THE REPAIR OF CONCRETE STRUCTURES

Second edition

Edited by
R. T. L. Allen, S. C. Edwards
and J. D. N. Shaw

BLACKIE ACADEMIC & PROFESSIONAL
An Imprint of Chapman & Hall

The Repair of Concrete Structures

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SECOND EDITION
Edited by

R.T.L.ALLEN
Consulting Engineer Cardiff
S.C.EDWARDS
Balvac Whitley Moran Ltd
Derby
and
J.D.N.SHAW
SBD Ltd
Bedford

BLACKIE ACADEMIC & PROFESSIONAL

An Imprint of Chapman & Hall

London • Glasgow • New York • Tokyo • Melbourne • Madras

Published by Blackie Academic & Professional, an imprint of Chapman & Hall, Wester Cleddens Road, Bishopbriggs, Glasgow G64 2NZ, UK

Chapman & Hall, 2–6 Boundary Row, London SE1 8HN, UK

Blackie Academic & Professional, Wester Cleddens Road, Bishopbriggs, Glasgow G64 2NZ, UK

Chapman & Hall Inc., One Penn Plaza, 41st Floor, New York, NY10119, USA

Chapman & Hall Japan, Thomson Publishing Japan, Hirakawacho Nemoto Building, 6F, 1–7–11 Hirakawa-cho, Chiyoda-ku, Tokyo 102, Japan

Chapman & Hall Australia, Thomas Nelson Australia, 102 Dodds Street, South Melbourne, Victoria 3205, Australia

Chapman & Hall India, R.Seshadri, 32 Second Main Road, CIT East, Madras 600 035, India

First edition 1987

This edition published in the Taylor & Francis e-Library, 2005.

Second edition 1993

Reprinted 1994

ISBN 0-203-97392-5 Master e-book ISBN

ISBN 0 7514 0086 6 (Print Edition)

A Catalogue record for this book is available from the British Library

Library of Congress Cataloging-in-Publication Data available

Preface to the second edition

Recent years have seen increased emphasis on the repair and refurbishment of all types of structures, in preference to demolition and rebuilding. Furthermore, faults are now becoming evident in some structures erected during the period of peak activity in the construction industry, some ten to twenty years ago. Concrete structures are no exception. As a result, new materials and methods of concrete repair have been developed, but much of this information has appeared in isolated papers and articles. This book brings the details together and provides a comprehensive guide to the subject. In addition to basic structural repairs, it covers underwater work, leak sealing, repairs to concrete floors and the use of surface coatings in the renovation and protection of concrete structures.

RTLA

Contributors

R.T.L.Allen	Consultant 54 Hollybush Road Cyncoed Cardiff CF2 6TA
R.D.Browne	Taywood Engineering Ltd. Southall Middlesex WB1 2QX
S.C.Edwards	Balvac Whitley Moran Ltd. Birchwood Way Cotes Park West Somercotes Derbyshire DE55 4PY
W.B.Long	Consultant 53 Berwick Road Little Sutton South Wirral L66 4PR
A.McLeish	W.S.Atkins Structural Engineering Woodcote Grove Ashley Road Epsom Surrey KT18 5BW
G.F.Masson	Blue Circle Cement Portland House Aldermaston Park Church Road Aldermaston Berkshire RG7 4HP
E.Mold	Consultant, 12 Clevehurst Close Stoke Poges Slough SL2 4EP

P.C.Robery Taywood Engineering Ltd.
Southall
Middlesex WB1 2QX
J.D.N.Shaw SBD Ltd.
Flitwick
Bedford MK45 5BH

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1
Damage occurring during construction

R.T.L.ALLEN

1.1
General

Cast in-situ concrete structures are hardly ever built under ideal conditions so, for a variety of reasons, defects may occur as the concrete is being cast or very soon afterwards. The cause may be unsuitable or defective materials, unsuitable construction methods, poor workmanship or failure to appreciate the hazards associated with a particular structural form or with prevailing weather conditions. Some structural details, such as congested reinforcement or very narrow sections, can greatly increase the risk of occurrence of defects. Unsuitable concrete mix design can cause a variety of defects ranging from variations in colour to severe honeycombing, and it must be remembered that a mix that achieves satisfactory strength may not be satisfactory in other respects. A mix that is richer in cement may be necessary in order to meet requirements of compactability, surface finish or long-term durability. Similarly, apparent savings in cost of labour or formwork may prove to be false economies. The majority of construction defects can be made good, but demolition and rebuilding of the affected members is sometimes a more economical solution. Certainly, if this has to be done it is easier to demolish and rebuild before the concrete has gained its full strength and while plant, labour and materials are ready to hand, rather than doing so after a long interval.

1.2
Cracks

Cracks that occur soon after concrete has been placed are often ascribed vaguely to 'shrinkage', but true drying shrinkage throughout the section of a concrete member may take months to become significant, so another cause must usually be sought (1).

If cracks appear in an exposed concrete surface very soon after it has been finished or even, in some cases, before finishing is complete, they are termed plastic shrinkage cracks. They are caused by rapid drying of the concrete surface while the body of the concrete is still plastic. They are usually

Table 1.1 Summary of defects occurring during construction

symptom	*Cause*	*Prevention*	*Remedy*
Cracks in horizontal surfaces, as concrete stiffens or very soon after	Plastic Shrinkage: rapid drying of surface	Shelter during placing. Cover as early as possible. Use air entrainment	Seal by brushing in cement or low-viscosity polymer
Cracks above form ties reinforcement etc, or at arrisses especially in deep lift	Plastic settlement: concrete continues to settle after starting to stiffen	Change mix design Use air entrainment	Re-compact upper part of concrete while still plastic. Seal Cracks after concrete has hardened
Cracks in thick sections, occurring as concrete cools	Restrained thermal contraction	Minimize restraint to contraction. Delay cooling until concrete has gained strength	Seal Cracks
Blowholes in formed faces of concrete	Air or water trapped against formwork Inadequate compaction Unsuitable mix design Unsuitable release agent	Improve vibration Change mix design or release agent Use absorbent formwork	Full with Polymer-modified fine mortar
Voids in concrete Honeycombing	Inadequate Compaction Grout loss	Improve compaction Reduce maximum size of aggregate Prevent leakage of grout	Cut out and make good Insect resin
Erosion of Vertical surfaces, in vertical streaky pattern	Scouring: water moving upwards against form face	Change mix design, to make more cohesive or reduce water content	Rub in polymer-modified fine mortar
Colour variation	Variations in mix proportions, curing conditions, materials, characteristics of	Ensure uniformity of all relevant factors Prevent leakage from formwork	Apply surface coating

	form face vibration release agent Leakage of water from formwork		
Powdery formed surfaces	Surface retardation, caused by sugars in certain timbers	Change form material Seal surface of formwork. Apply lime-wash to form face before first few uses	Generally none required
Rust strains	Pyrites in aggregates Rain streaking from unprotected steel Rubbish in formwork Ends of wire ties turned out	Avoid contaminated aggregates. Protect exposed steel. Clean forms thoroughly. Turn ends of ties inwards	Clean with dilute acid or sodium citrate/sodium dithionine. Apply surface coating
Plucked surface	Insufficient release agent. Careless removal of formwork	More care in application of release agent and removal of formwork	Rub in fine mortar, or patch as for spalled concrete
Lack of cover to reinforcement	Reinforcement moved during placing of concrete, or badly fixed. Inadequate tolerances in detailing	Provide better support for reinforcement More accurate steel-fixing Greater tolerances in detailing	Apply polymer-modified cement and sand rendering. Apply protective coating

discontinuous and they very seldom extend to a free edge. In an unreinforced slab they are typically diagonal (Figure 1.1) and not more than 300 mm or so in length but, in severe cases, they may join up. The pattern may be modified if reinforcement is present. The most effective way of preventing their occurrence is by sheltering the surface from wind and sun during construction and by covering it immediately after finishing. Changes in concrete mix design, and especially the use of air entrainment, may also be helpful. Remedial measures after the cracks have formed usually consist of sealing them against ingress of water by brushing in cement or low-viscosity polymers.

Concrete may continue to settle, especially in deep sections, after it has started to stiffen and anything that obstructs this movement, such as reinforcement or formwork tie-bolts, may act as a wedge so that a crack forms immediately over the obstruction (Figure 1.3). Cracks of this type are known as plastic settlement cracks. They may also form in vertical surfaces when friction against formwork hinders settlement of the concrete, and this is particularly likely to occur at the

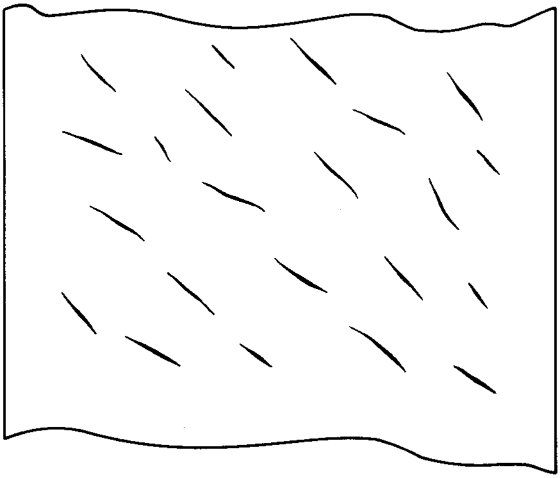

Figure 1.1 Typical plastic shrinkage cracks in unreinforced concrete slab

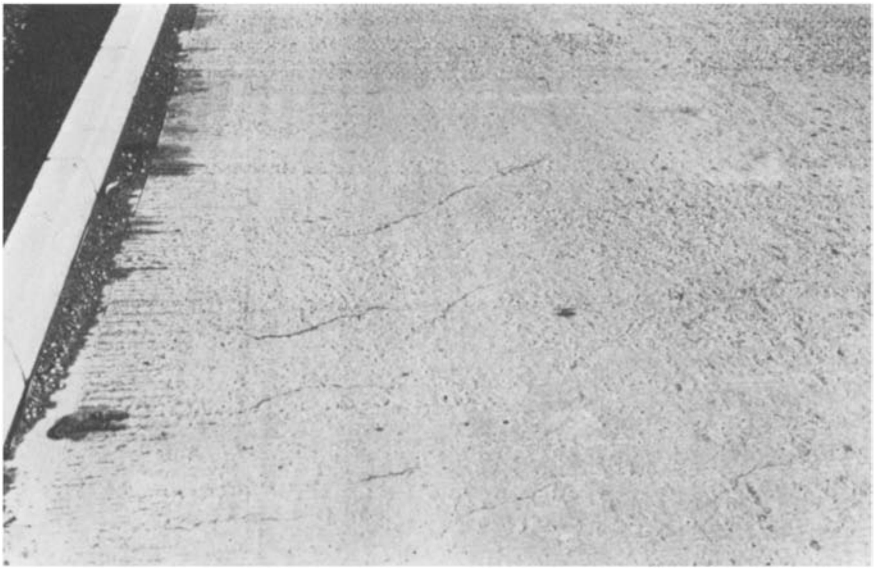

Figure 1.2 Plastic shrinkage cracks in concrete road

arrisses of columns or in narrow but deep members (Figure 1.4). They may sometimes be avoided by changing the concrete mix design and by using air entrained concrete and, if they do start to form, they can be closed by immediately recompacting the upper part of the concrete lift. Remedial measures after the concrete has hardened consist of sealing the cracks in order to protect the reinforcement, but it must be remembered that, as well as causing a crack to form above the obstruction, settlement of the concrete will usually cause a void

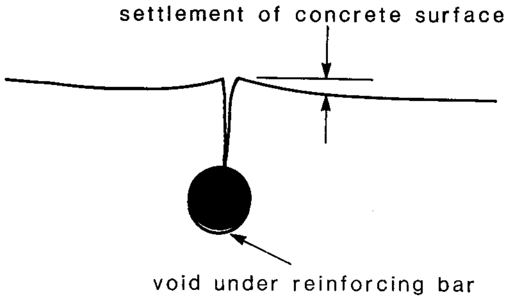

Figure 1.3 Typical plastic settlement crack over reinforcing bar

to form immediately below the obstruction. It is seldom possible to fill this void after the concrete has hardened, so recompaction immediately the cracks start to form is by far the best course of action.

Heat of hydration of cement raises the temperature of concrete (Figure 1.5) so that it is usually slightly warmer than its surroundings when it hardens, and in thick sections and with rich mixes the temperature rise may be quite considerable. As the concrete cools it will try to contract. If this contraction is restrained the concrete will be put into tension, and if the strain capacity of the concrete is exceeded, cracks will form. These thermal contraction cracks are often ascribed to drying shrinkage, but they form within a week or so of the concrete being placed, long before any appreciable amount of drying shrinkage has taken place. The risk of thermal cracking can be reduced by minimizing restraint to contraction and by delaying cooling until the concrete is strong enough to resist the stresses induced. This means that formwork and exposed surfaces should be insulated if there is considered to be a risk of too rapid cooling, and this is particularly important when ambient temperatures are likely to fall sharply overnight. If cracks do form, remedial measures are similar to those for cracks that form after a structure is in service.

Formwork should be rigid enough not to settle under the weight of concrete and plant but, if it is inadequately supported, tension cracks may form in the immature concrete. Here again, remedial measures are the same as those for cracks formed in service, but a structural check is usually advisable.

The causes, prevention and repair of cracks are discussed in more detail in a Technical Report entitled 'Non-structural cracks in concrete', issued by The Concrete Society (2).

1.3 Surface texture defects (3, 4, 5)

Blowholes in formed surfaces of concrete (Figure 1.6) are the result of bubbles of air or water becoming trapped against the face of the formwork. Their occurrence is particularly difficult to prevent on surfaces with top forms or

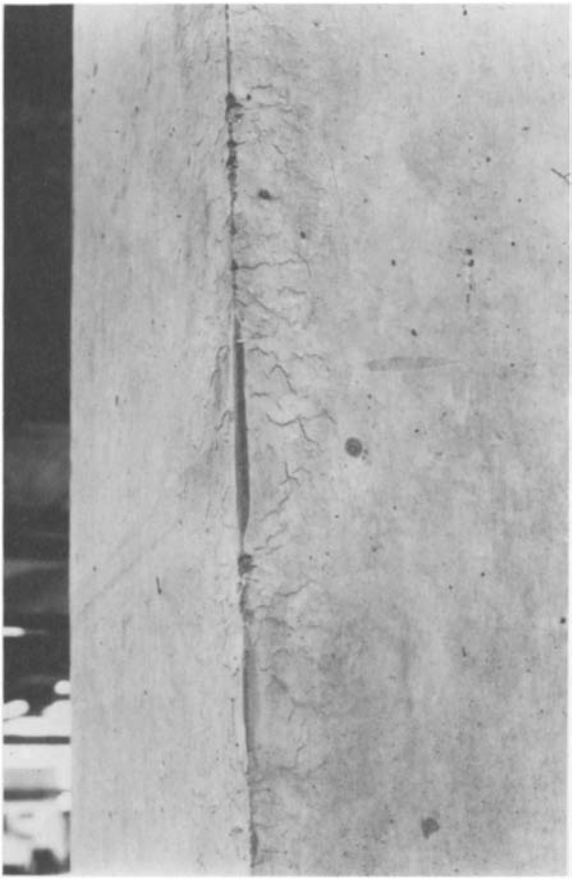

Figure 1.4 Plastic settlement cracks in arris of r.c. column

inwardly sloping formwork, but their incidence is reduced if the form face is slightly absorbent. With impermeable formwork, blowholes may be a sign of inadequate vibration of the concrete but, even with good compaction, it may be difficult to avoid them altogether. Both the type of release agent used and the concrete mix design have considerable influence on the formation of blowholes—a very cohesive mix tends to produce more than a less cohesive one.

Before deciding to fill blowholes, one should consider whether it is really necessary. Unless the blowholes are exceptionally large, or a smooth surface is required as, for example, in a reservoir, the decision will be based on the appearance of the concrete, and the viewing distance when the structure is in service may be much greater than when it is under construction. If blowholes must be filled, a mortar should be used consisting of cement and fine aggregate from which the coarser particles have been sieved out. Either a 600 μm or a 300 μm sieve should be used, depending on the smoothness of finish required.

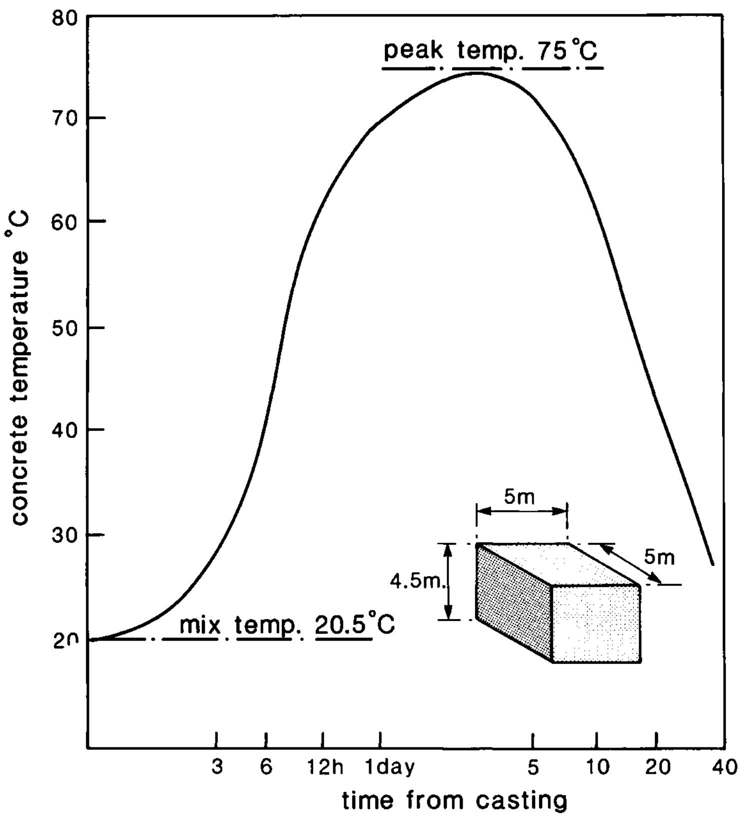

Figure 1.5

Natural sand can be used, after sieving, but crushed limestone fines are usually better. It may be necessary to blend a proportion of white with the normal grey Portland cement in order to achieve an acceptable colour, and it is advisable to treat a trial area first and to leave it to weather for as long as possible before embarking on the main part of the work. Mix proportions should be in the range 1:1 to 1:2, and it is advisable to incorporate a polymer admixture (see Chapter 4). The mortar should be rubbed over the whole area of the concrete with a rubber-faced float, and finally it can be rubbed down with a smooth stone or mortar block if a smooth finish is required (6).

Voids that penetrate more deeply, groups of interconnected voids, and honeycombing are normally signs either of inadequate compaction or of loss of grout through joints in the formwork or between formwork and previously cast concrete. The extent of poor compaction may be investigated by cutting back with a hammer and chisel or, in severe cases, with power tools. Ultrasonic pulse velocity measurements may also be used to detect the existence of regions of poor compaction (see section 2.3.3), but the presence of reinforcement may give rise to misleading results. Usually it is necessary to cut out the affected concrete

Figure 1.6 Blowholes in concrete under inward-sloping formwork

and to make good by the methods described in Chapter 6 for repairing spalled concrete. In some instances, however, such as when there is hydrostatic pressure on one side of the concrete, complete cutting out may not be possible and it may be necessary to form a seal by injecting a low-viscosity resin into the concrete as described in Chapter 9. The success of this technique will depend greatly on the extent to which the voids are interconnected, and the viscosity, rate of stiffening and other properties of the resin will have to be chosen to suit each particular set of circumstances. Resin injection alone, without any cutting out, may be adequate if the prevention of leakage or protection of reinforcement is all that is required, but a combination of both methods may be necessary for structural reasons or for the sake of appearance. It is important to realize that surface treatment such as bush-hammering or grit blasting will not mask regions of poor compaction of concrete—in fact they usually make the appearance worse (Figure 1.7).

Scouring of a vertical surface of formed concrete, so that it resembles a map of a delta of a river, is caused by water moving upwards against the face of the formwork (Figure 1.8). It is a sign of excessively wet or harsh concrete, and prevention is a matter of concrete mix design. It is a superficial defect so, unless it is unusually deep and the cover to reinforcement is unusually small, remedial measures consist of early facing up in the same way as suggested for filling blowholes. Here again, the need for remedial work should be clearly established first.

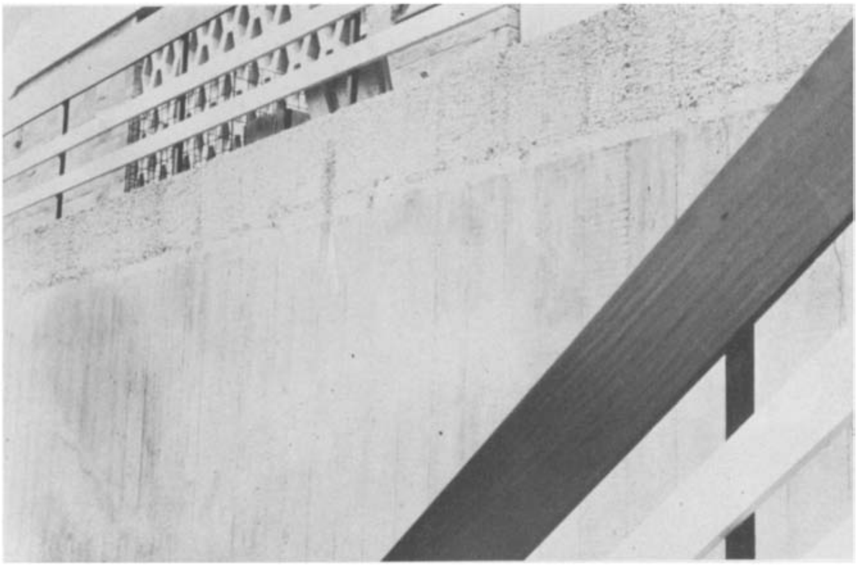

Figure 1.7 Marks of formwork joints still visible after bush hammering

1.4
Colour variation (3, 4)

It is practically impossible to produce a concrete surface that is completely uniform in colour. There will always be some variation, the acceptability of which will be a matter for subjective judgement. Variations in a supposedly uniform surface are bound to be conspicuous, but the same degree of variation in a profiled or textured surface will be far less obtrusive.

Colour variations may result from a number of factors, including concrete mix design, formwork surface texture, and variations in curing conditions, formwork absorbency or stiffness, vibration and release agent, and more detailed information is given by Monks (4). Leakage of water through joints in formwork usually causes dark discoloration in the immediately surrounding area.

If colour variations are judged to be unacceptable when formwork is struck, the probable pattern of weathering should be considered before anything is done to the surface, because weather staining may eventually mask the inherent colour variation. If some remedial treatment is considered to be necessary, however, the only practical course, short of demolition and rebuilding, is to apply some form of paint or surface coating which must be suitable for application to an alkaline surface. Treatment to expose the aggregate, such as bush-hammering or abrasive blasting, may produce a more uniform colour because the colour of the aggregate will predominate over the colour of the matrix, but it will completely change the nature of the surface, it will be costly, and the result may appear patchy if the concrete mix was not designed with the intention of providing an exposed aggregate finish.

Figure 1.8 Scouring of a vertical surface caused by upward movement of water (British Cement Association)

1.5 Other surface blemishes

If a formed surface of concrete is weak and powdery when the formwork is struck, it is a sign of surface retardation. Sometimes this may be caused by the use of an unsuitable release agent, or by misuse of a suitable one. Applying a release agent too thickly is a waste of money and may cause retardation or staining. A more frequent cause of this defect, however, is the release of natural sugars from new, unsealed timber formwork—particularly hardwoods. Some

Figure 1.9 Popouts, over unsound particles of coarse aggregate in r.c. column, caused by frost

timbers release sugars if they are left exposed to the sun, and these can retard the hydration of cement (4). After the formwork has been used a few times the surface becomes sealed and the trouble is unlikely to recur. For the first few uses of new formwork, retardation can be prevented by treating the surface of the formwork with lime-wash before use, or by applying a surface sealer. The effect does not penetrate the concrete to any appreciable depth, so it is seldom necessary to apply any remedial treatment apart from brushing down.

Rust-coloured stains may be caused by contamination of the aggregates with pyrites (iron sulphide) which oxidizes on contact with air. The only remedy is to cut out the offending particles and to make good the surface in the way recommended in Chapter 6 for spalled concrete. Rust stains may be caused if unprotected reinforcement is left projecting from partly completed reinforced concrete work for a period. Small stains may also be caused if the ends of wire ties for reinforcement are left projecting towards the face of the concrete instead of being turned inwards. These are unlikely to lead to spalling, because of the small diameter of the wire, but they may be unsightly, so a surface coating may be necessary in order to hide them. Rust stains on soffits of slabs or beams (Figure 1.10) may be a result of failure to clean the formwork out before placing concrete. Nails and ends of tying wire, if left lying in the formwork, will cause rust stains on soffits. If reinforcement is left exposed to the weather for some time, rain will wash rust from the steel on to soffit formwork (Figure 1.10) and it will stain the soffit if it is not removed before concrete is placed. Rust stains can be removed by treatment with dilute oxalic or hydrochloric acid (10% solution) or with sodium citrate followed by sodium dithionite (7), but all these chemicals

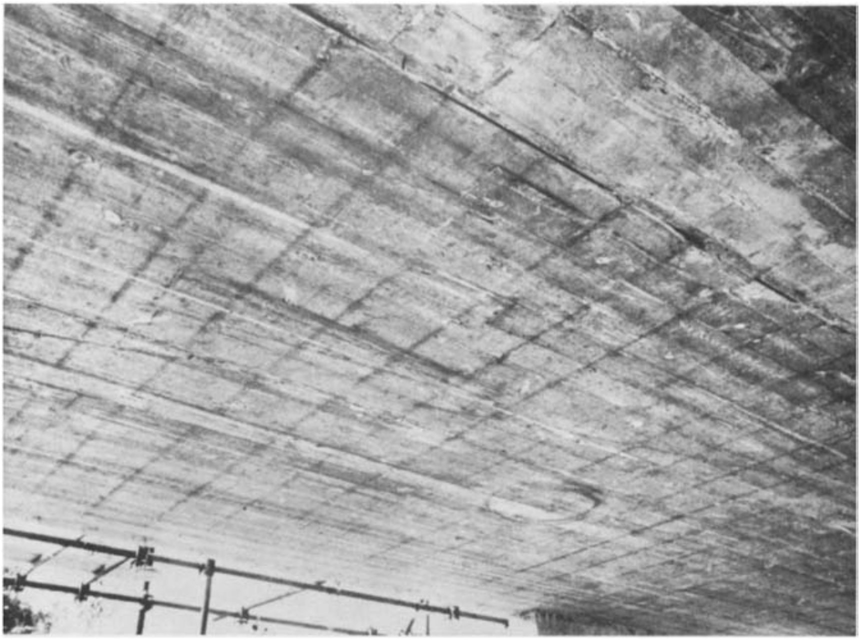

Figure 1.10 Stains on concrete soffit caused by rust from reinforcement being left in formwork (British Cement Association)

are potentially dangerous and suitable safety precautions are essential, especially eye protection and gloves. Treated surfaces must be washed thoroughly with water on completion. It must be remembered that the use of acids will etch the surface of the concrete, altering its texture and appearance. Treatments of this type can be applied to vertical or upward-facing surfaces but they are seldom practicable on soffits, and the alternative is a surface coating.

If insufficient release agent is applied to the formwork, the surface of the concrete may be plucked when the forms are struck. Careless removal of forms also may cause damage. It can be made good by rubbing in fine mortar, as recommended for filling blowholes, or by patching as for spalled concrete, according to the severity of the damage. If the surface is to be textured as, for example, with rough-sawn board marking, a skilled operative can usually produce a satisfactory effect by using small trowels, brushes and rubber-faced floats. If possible, trials should be carried out before the main remedial work is done, on a surface that will not be conspicuous.

1.6
Lack of cover

Sometimes reinforcement becomes displaced while concrete is being placed and compacted, with the result that there is less cover than desired on at least one face of the concrete. If this is suspected, a survey should be carried out with an electromagnetic covermeter in order to determine the extent of the fault. Sometimes it will be practicable to increase the cover by building out the face of the concrete with a rendering and, if a polymer-modified cement and sand mix is used, it may be possible to provide adequate protection for the reinforcement with a slightly reduced thickness of cover. Mixes for rendering should be similar to those recommended in Chapter 6 for repairs to spalled concrete, but it will be necessary to make sure that there is adequate key. If the face of the concrete is weak or coated with laitance, it should be scabbled or grit-blasted to provide a sound, roughened surface. If it is sound but smooth, it will usually be cheaper to apply a spatter-dash coat of polymer-modified cement and sand, in proportions of about 1 part of cement to 2 parts of sand, before applying the first coat of rendering (8, 9, 10). If it is not possible to increase the dimensions of the concrete the only available remedy, short of demolition and re-casting, is to apply a surface coating. It should be of a type having a low permeability to carbon dioxide and liquid water, but it should preferably allow water vapour to escape from the concrete.

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2
Investigation and diagnosis

R.T.L.ALLEN

2.1
General considerations

Before any repair work is put in hand, the cause of damage must be identified as clearly as possible. This principle may seem self-evident but it is surprising how often it is disregarded, with the result that further repairs have to be carried out within a short time. Sometimes the cause is obvious as, for example, in many cases of accidental damage but, more often than not, careful investigation is required.

The next step must be to consider the objective of the repair, which will generally be to restore or enhance one or more of the following:

Durability
Structural strength
Function
Appearance.

Of these four requirements, restoration of durability is by far the most common in repair work. One must also consider whether the repair is to be permanent or temporary.

Only after deciding on the most likely cause of damage, whether it is likely to recur, and the purpose of the work, should the method of repair be chosen.

2.2
Causes of defects

Latent defects may be caused by inadequacy of design, materials or construction which may not become evident until some time after completion. The immediate mechanism of deterioration may be, for example, chemical action or corrosion of reinforcement but, in a large proportion of cases, the fundamental cause can be traced back to something such as unrealistic detailing or poor workmanship.

Deterioration of concrete may be due to chemical or physical causes, or to corrosion of reinforcement. Rust on steel occupies a volume several times greater than that of the metal from which it was formed, and this expansion can cause cracking and spalling of the surrounding concrete.

2.2.1
Chemical causes

Chemical degradation is usually the result of attack on the cement matrix. Portland cement is alkaline, so it will react with acids in the presence of moisture and, in consequence, the matrix may become weakened and its constituents may be leached out. Acidic groundwaters are a potential cause of degradation of concrete foundations, and these may be derived from decayed vegetation (humic acid) or from contamination of the ground from external sources. Dense concrete will be attacked only at the surface so serious damage may be slow to occur, but an acid-resistant surface coating is the only complete protection. The use of sulphate-resistant Portland cement is not a solution.

Sulphates in solution can combine with the tri-calcium aluminate (C_3A) in Portland cement, to form a sulphoaluminate hydrate (ettringite) in the form of needle-like crystals, causing expansion of the matrix which turns white and becomes soft. Cementitious repairs in these conditions should use sulphate-resisting cement, which has a low C_3A content. Attack on dense concrete will be a surface effect so rich, well-compacted mixes must be used. The form of sulphate present in uncontaminated groundwater is normally calcium sulphate, which has limited solubility. Some other salts, such as magnesium sulphate, are much more readily soluble in water and can form stronger solutions, so they are more dangerous.

Old industrial sites may be contaminated with other chemicals, and specialist literature should be consulted in such cases (1).

Water containing carbon dioxide in solution may attack the surface of concrete, but such attack is usually very slow. In rare instances limestone aggregate may be attacked more rapidly than the surrounding mortar fraction, because the carbonic acid in the water converts the calcium carbonate to more readily soluble bicarbonate. Alkali-silica reaction (ASR) (Figure 2.1) is a possible but relatively uncommon cause of cracking of concrete, and other possible causes of cracking should be eliminated before ASR is seriously considered. Portland cement contains compounds of alkali metals (sodium and potassium), and their presence can lead to relatively high concentrations of hydroxyl (OH) ions in the pore fluid of the concrete. This highly alkaline solution can react with certain forms of silica, present in some aggregates, and produce an alkali-silicate gel. This gel will expand if it imbibes water and the expansive forces may be great enough to disrupt the concrete. Typical symptoms in unreinforced or lightly reinforced concrete are map-cracking, usually in a roughly hexagonal mesh pattern, and gel exuding from the cracks. The presence

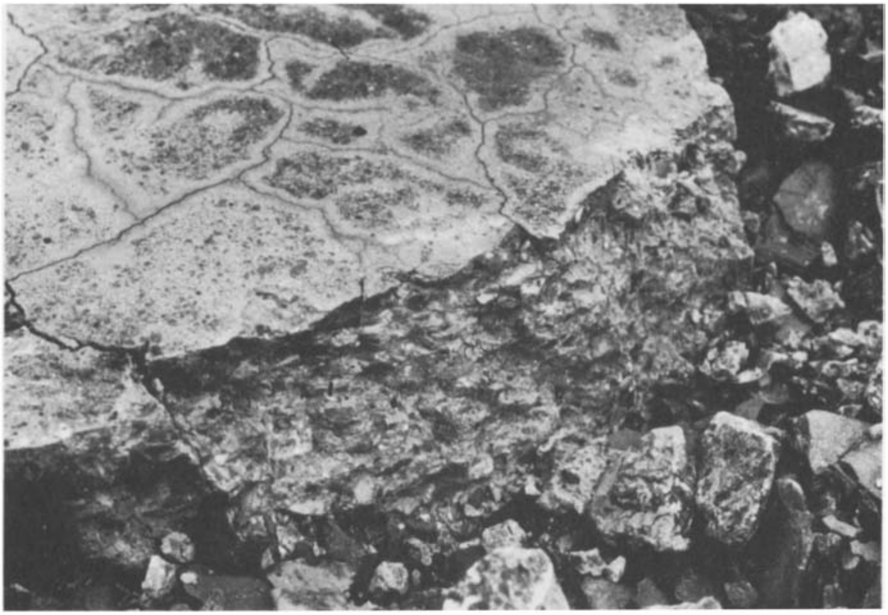

Figure 2.1 Cracking caused by alkali-silica reaction in unreinforced concrete. Note stains along cracks

of reinforcement or externally applied stress may modify the crack pattern: for example, cracks due to ASR in axially loaded columns are usually longitudinal. Not all forms of silica are reactive, and three factors must be present simultaneously for damage to occur:

(1) A sufficiently high concentration of alkali metals
(2) Reactive forms of silica
(3) Moisture. If any one of these is absent, damage will not occur. Alkalis in cement are usually shown in analyses as sodium and potassium oxides Na_2O and K_2O, and it is usual to express the alkali content as sodium oxide equivalent, the formula for which is

$$Na_2O \text{ equivalent} = Na_2O + 0.658 \times K_2O$$

It must be remembered that even though laboratory investigation may reveal signs of ASR in concrete, it does not necessarily follow that it was the cause of damage. Other forms of alkali-aggregate reaction have not been found to have caused significant damage to any concrete in the UK.

2.2.2
Physical causes

When concrete is damaged by impact or abrasion, the cause is usually obvious and protection may be necessary as well as repair. Cracks that occur some time after construction, however, are often more difficult to investigate. Overloading may produce cracks in tension zones of members, but other causes are probably more common. Drying shrinkage is a slow process in thick members, so it may lead to a gradual build-up of tensile stress if it is restrained. The use of excessively wet, high shrinkage concrete mixes will aggravate matters, as will the use of 'shrinkable' aggregates that occur in some regions. Restrained thermal contraction is a fairly frequent cause of cracking, and often designers do not make adequate provision for thermal movements. It must be remembered, too, that effects may be additive so that, even if one cause alone would not lead to cracking, a combination of causes may result in damage.

Concrete may be damaged by environmental factors such as fire (Figure 2.2a, b) or frost. Concrete gradually loses strength with increase in temperature above about 300°C (Figure 2.3), the damage being greater with aggregates such as quartzites with high coefficients of thermal expansion than with those such as limestone with lower thermal coefficients (2, 3).

Frost attack on concrete may take the form of spalling of the surface, or it may cause random cracking. Damage is made more likely by the use of deicing salts. Air-entrained concrete is far less susceptible to damage by frost than non air-entrained concrete, so it should be used for repairs when further frost attack is likely (4). Pockets (Figure 2.4) that can fill with water, or containing materials that can absorb water, are a source of trouble because the water in them will expand if it freezes, disrupting the surrounding concrete. Steps must be taken to prevent recurrence after any repairs have been carried out.

2.2.3
Corrosion of reinforcement

Probably the most frequent cause of damage to reinforced concrete structures is corrosion of reinforcement, and this is usually the result of carbonation of the concrete or the presence of chlorides. Normal concrete is alkaline (pH 12.5 or more) and a passivating layer of oxide quickly forms on the surface of steel embedded in it. If the alkalinity falls below about pH 10 the passivating layer is destroyed and, in the presence of oxygen and moisture, the steel will corrode. If chlorides are present in the concrete, passivation is lost at a higher pH value, depending on the chloride ion concentration.

Carbonation occurs as a result of penetration of carbon dioxide from the atmosphere. In the presence of moisture this forms carbonic acid which neutralizes the alkalinity of the cement matrix. The depth of penetration of carbonation into concrete is proportional to the square root of time so that, even

Figure 2.2(a) Reinforced concrete structure damaged by fire

if the surface layer of concrete carbonates quickly, the rate of penetration will slow down with increasing depth (5). The penetration rate depends also on the cement content and permeability of the concrete, so that an adequate depth of well-compacted cover of good quality concrete will protect the reinforcement for many years. Trouble occurs when the depth of cover is inadequate or its quality is not what it should be. Carbonation penetrates more rapidly into dry than into wet concrete, but both oxygen and moisture are needed for corrosion of steel to occur. Consequently reinforcement corrosion caused by carbonation is found most frequently in concrete exposed to the weather or to condensation.

With the restrictions on chloride contents of materials that are laid down in present-day codes of practice (6), chloride-induced corrosion of reinforcement occurs principally in older structures or in those that are exposed to chloride-containing materials such as sea water or de-icing salts. It is not possible to specify a limiting chloride content below which corrosion will not occur because a number of factors are involved. A survey by the Building Research Establishment (7) has suggested that corrosion is unlikely if the chloride content

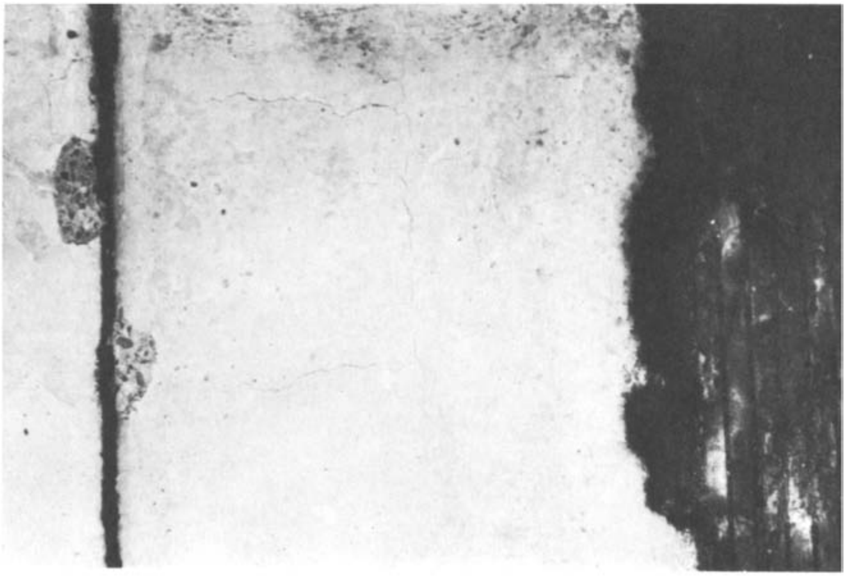

Figure 2.2(b) Fire damage to prestressed box section soffit beams. The repair method involved local repair of spalling, injection of the cracks with epoxy resin, followed by application of an anti-carbonation coating

of concrete is uniformly less that 0.4% by weight of cement and highly probable if it exceeds 1%, but these figures are not clear limits. The risk of corrosion depends partly on the variability of chloride concentration within a reinforced concrete element, on the hydroxyl ion concentration (i.e. the alkalinity) and its variability, and the presence of oxygen and moisture without which corrosion will not occur. The chemical composition of cement also has an effect, and chlorides that enter the concrete after it has hardened as, for example, de-icing salts are more harmful than those that are present in the concrete from the start as admixtures or contamination of aggregates (8, 9). This is so because a proportion of any chloride ions present in freshly-mixed concrete will combine with tricalcium aluminate in the cement and will not be available for initiating corrosion.

If two dissimilar metals, electrically connected, are immersed in an electrolyte a current will flow between them, the rate of current flow being dependent on the relative nobility of the two metals on the electrochemical scale (10) and the electrical resistance of the circuit. The anodic metal, at which electrons pass from the electrolyte into the metal, will be dissolved at a rate proportional to the current flow. In a similar way, anodic and cathodic areas will be set up on the surface of a single metal that is immersed in an electrolyte of varying composition, with electrons leaving the metal at cathodic areas and entering it at anodic areas. Moist concrete will act as an electrolyte and, if passivity of the reinforcement is lost, anodic and cathodic areas will be set up. Iron ions will be

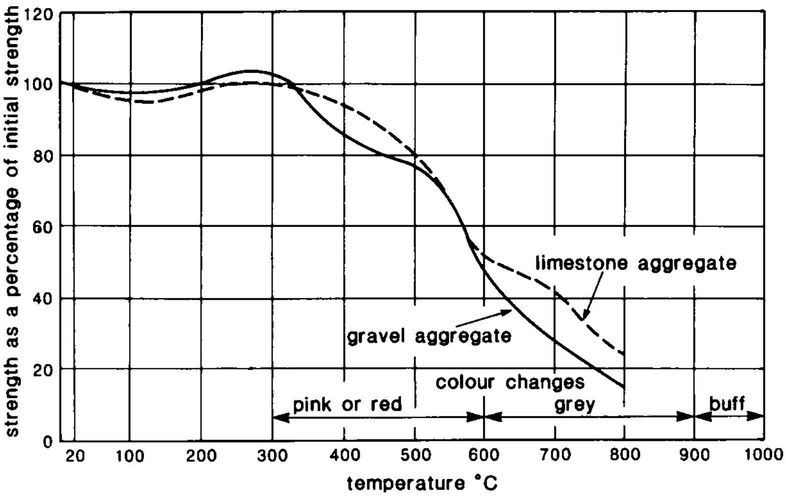

Figure 2.3 Strength *v*. temperature relationships for gravel and limestone aggregates

Figure 2.4 Cracking caused by freezing of water in bolt pockets

liberated at anodic areas and, in the presence of adequate supplies of oxygen, they will react to form rust. The rate of corrosion will depend on the electrical resistance of the circuit and the relative sizes of anodic and cathodic areas. The most harmful situation will be that of a small anode and a large cathode because the corrosion will then be concentrated at a small area. The need for an adequate supply of oxygen is the reason why serious corrosion of reinforcement seldom occurs in reinforced concrete structures that are permanently submerged in water.

2.3 Investigation

The investigation of reasons for damage to structures is largely a matter of gathering information by observation, studying records and asking questions, supplemented if necessary by a certain amount of testing, and then interpreting the information thus obtained.

2.3.1 *Observation*

The texture of a concrete surface may suggest the possibility of chemical attack by a general softening, leaching of the matrix or, in the case of sulphate attack, whitening of the concrete. Rust stains often indicate corrosion of reinforcement but they may be caused by contamination of the aggregates with iron pyrites. If cracked concrete is broken out, the state of the crack surface gives useful information: dirt or discoloration show that the crack has been there for some time although it may only recently have been noticed. General flaking of an exposed concrete surface suggests frost damage. In fire-damaged structures, the colour of the concrete gives an indication of the maximum temperature reached (11) (Figure 2.3).

When concrete is cracked, the crack pattern can be informative. A mesh pattern suggests drying shrinkage, surface crazing, frost attack or, in some cases, alkali-aggregate reaction. Exudations from cracks may be the result of water passing through the concrete and washing out calcium salts, or they may be gels from alkali-aggregate reaction. Relatively straight cracks usually indicate excessive but fairly uniform tensile strain, and they should be studied in relation to the probable stress pattern in the member concerned. Cracks caused by unidirectional bending will be widest in the zone of maximum tensile stress and will taper along their length, while cracks caused by direct tension will be of roughly uniform width. Continuing movement at a crack often produces crumbling at the edges.

Popouts in concrete (see Figure 1.9) are usually associated with particles of coarse aggregate just below the surface. Highly absorptive particles may expand if severe frost occurs while they are saturated. Occasionally, coarse aggregates are contaminated with particles of lime or clay that expand with weathering. In some countries, popouts are associated with alkali-aggregate reactions, but they have been seen in few if any of the known cases of alkali-silica reaction in the UK.

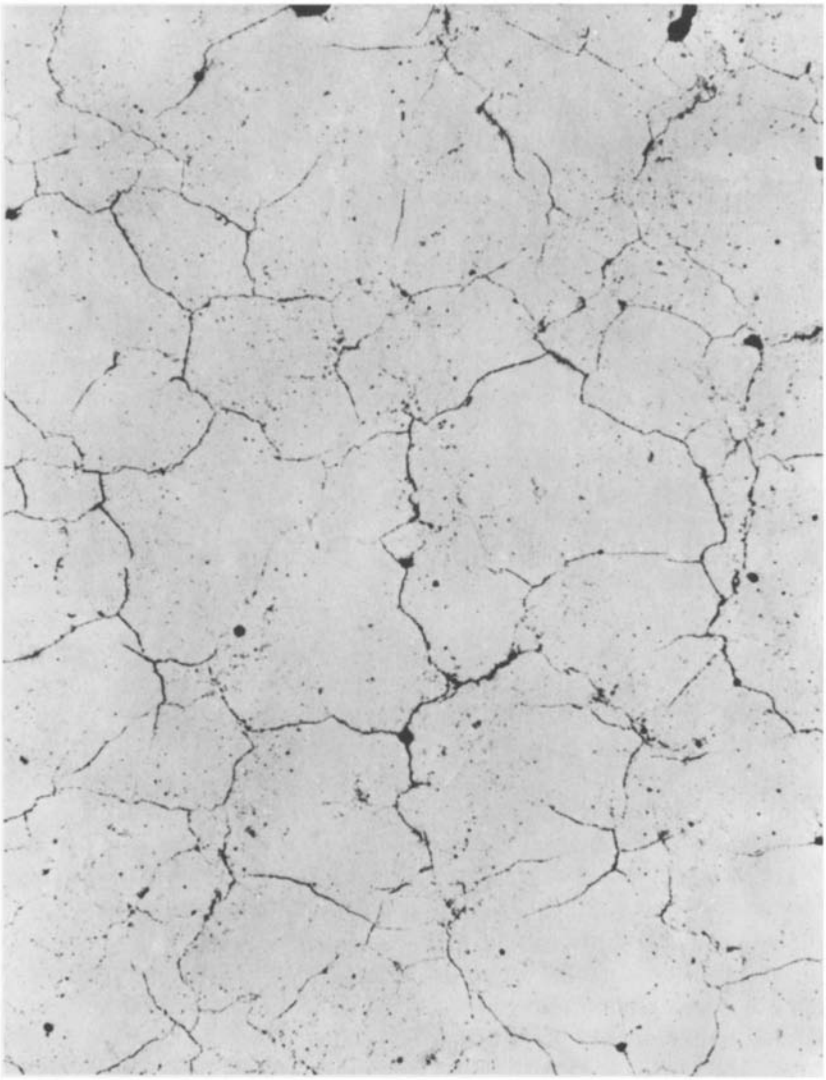

Figure 2.5 Surface crazing of concrete cast against a smooth polished form face, accentuated by accumulation of atmospheric dirt (British Cement Association)

2.3.2
Questioning

Records of mix proportions, sources of materials, cube test results, weather conditions, etc. may be available, particularly for recently-built structures but, even with these, reliable information may be difficult to obtain. The proposal that 'log books' should be provided for newly-built structures has much to commend it.

It is always useful to ask questions of as many as possible of the people who were concerned with the design or construction. Their recollections may not be completely accurate and their accounts of events may conflict but, by questioning, one can often find out what actually happened as distinct from what should have happened. This applies not only to work on site during construction but also to subsequent use or misuse of the structure.

2.3.3
Testing in the field

There are no truly non-destructive tests that give a direct measurement of compressive strength of concrete but there are some, such as rebound hammers and ultrasonic pulse velocity measurements, that enable comparisons to be made between suspect concrete and similar concrete that is known to be satisfactory (12a).

Useful information can often be obtained by sounding the surface of the concrete with an ordinary hammer. The difference in sound when the concrete is struck may identify areas of delamination or of concrete that has been damaged by, for example, fire.

In the rebound hammer (Schmidt hammer) (Figures 2.6, 2.7) a mass strikes the concrete surface at a constant velocity and the distance through which it rebounds depends upon the hardness of the concrete near the surface. Calibration curves are available that give an indication of the relationship between rebound and compressive strength. In order to get a reliable result, however, readings should first be taken on a cube of similar concrete that is then crushed in order to provide a reference point (Figure 2.8). A recording type of Schmidt hammer is available in which the rebound numbers are automatically recorded on a roll of paper (Figure 2.7) (12b).

The velocity of sound in concrete is related to its density and elastic modulus, which are related in turn to compressive strength. Here again it is necessary to obtain a reference point by taking readings on a standard specimen such as a cube. In practice, pulses of ultrasound are transmitted through the concrete between two transducers and the time taken for the pulses to travel from one to the other is recorded electronically. If the path length also is measured, the pulse velocity can be calculated. If possible, measurements should be taken with the transducers directly opposite each other on opposite sides of the member under test (direct transmission). It is possible to obtain readings with the transducers on two faces at right angles (semi-direct transmission) or side by side on the same face of the member (indirect transmission) but the amount of energy received and the accuracy of measurement will be very much less. Care should be taken, also, to choose transmission paths that do not contain reinforcement because the velocity of sound in steel is higher than that in concrete (12c, 13).

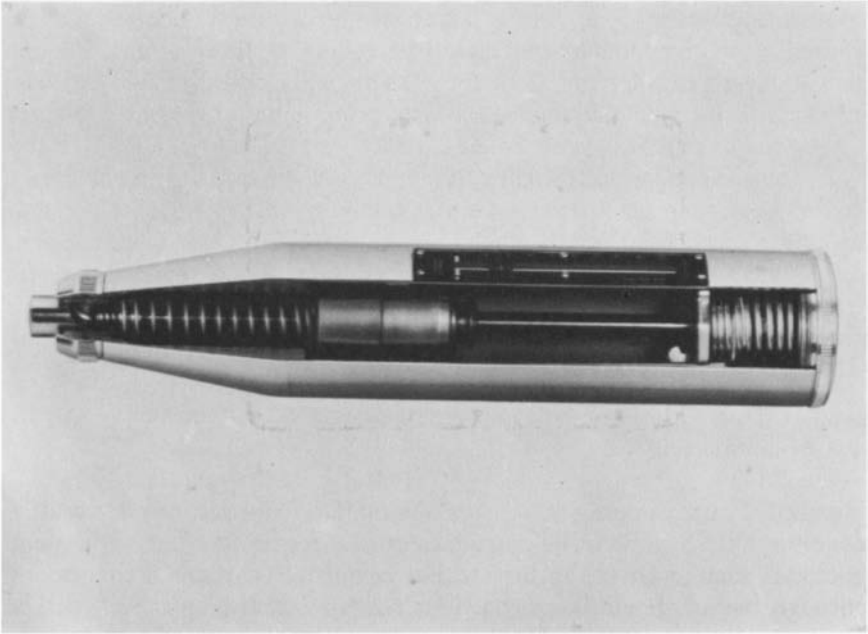

Figure 2.6 Sectional view of Schmidt rebound hammer (Proceq SA, Zurich)

Non-destructive tests such as these have the merit that a large number of readings can be taken fairly quickly. Statistical analysis will give an indication of the variability of the concrete, and contours of equal value can be plotted. In this way one can locate particularly low results. Experience in using these methods is very helpful, and anyone considering them should consult specialized literature on the subject (14).

There are also a number of semi-destructive tests available such as pull-off tests, probes fired into the concrete, core-drilling etc and, here again, specialist literature should be consulted (14).

Whatever tests are done, it must be remembered that the strength of concrete in a structure will not be the same as the standard cube strength of concrete sampled at the mixer, and it will not be constant from one part of a structure to another (15, 16).

In order to assess the strength of a structure, the position and size of reinforcement must be known. A knowledge of reinforcement details is also of great assistance in the interpretation of crack patterns. In the absence of records, or as a check on their accuracy, the depth of cover can be measured by electromagnetic cover-meters (Figure 2.9), and these will also show the positions of individual bars if they are not too close together. Some types of instrument can also indicate the approximate bar diameter (12d). Gammaradiography can be

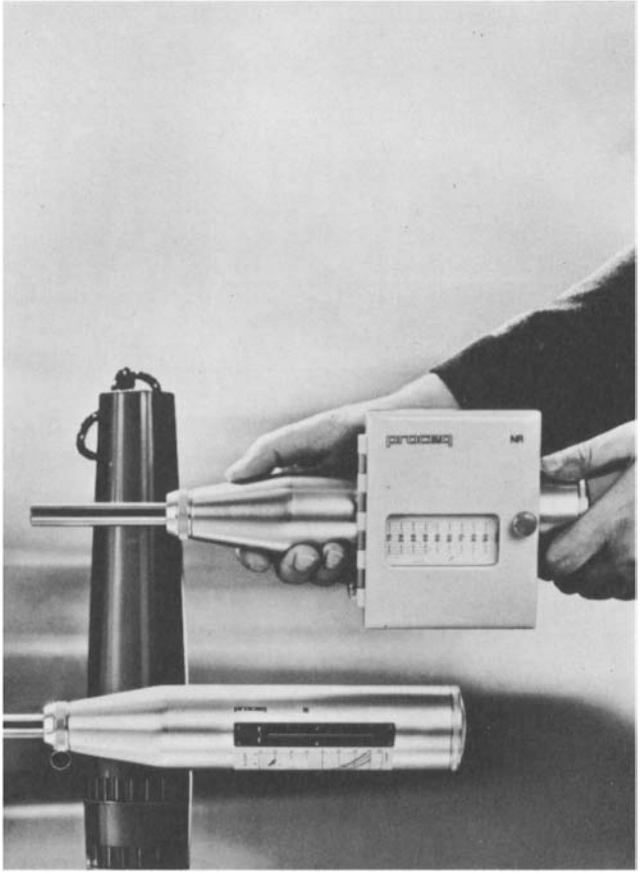

Figure 2.7 Schmidt rebound hammers: recording type (upper) and non-recording type (lower) (Proceq SA, Zurich)

used to detect deeply embedded reinforcement but it is considerably slower and more costly. It can also detect hidden voids in the concrete (12e).

An idea of the state of reinforcement in a structure can sometimes be obtained by measuring electrical potentials by means of standard half-cells, provided that the reinforcement is electrically continuous. The usual procedure is to connect one terminal of a high-impedance millivoltmeter to a point on the reinforcement and the other terminal to a half-cell which, in practice, consists usually of a copper electrode immersed in an electrolyte of copper sulphate solution as shown in Figure 2.10. Other types of half-cell such as silver/silver chloride can be used, but copper/copper sulphate is the most common. The tube containing the electrolyte is closed by a permeable pad that is saturated with either the electrolyte or some other conductive liquid, and this is placed in contact with the surface of the concrete. By moving it about on the member under examination it is possible to draw equipotential contours.

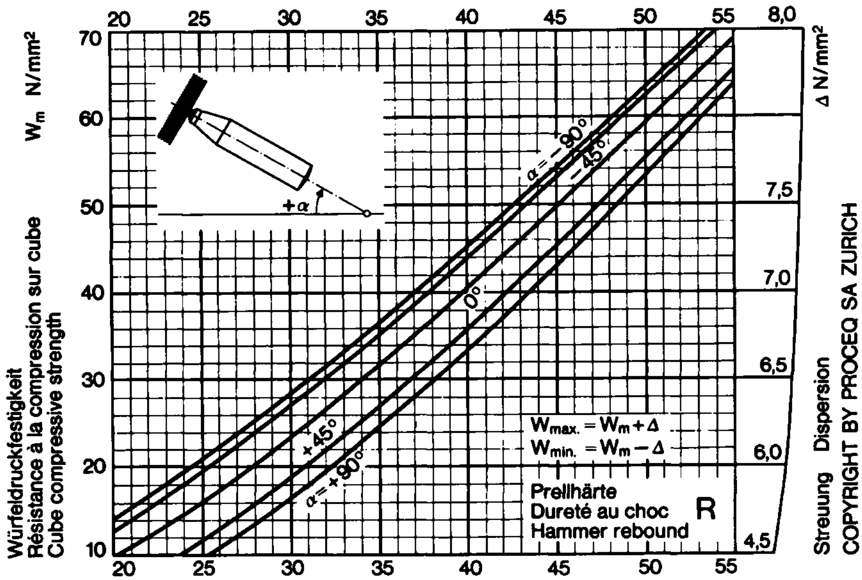

Figure 2.8 Example of Schmidt hammer calibration curves for well-compacted Portland cement concrete with smooth dry surface—note effect when the impact plane is not horizontal (Proceq SA, Zurich)

Areas showing potentials more negative than—350 mV relative to the copper/copper sulphate electrode are generally considered to be those in which the steel is anodic and no longer passive, so it may be actively corroding. Corrosion is likely to be negligible in areas showing potentials less negative than—200 mV. Different investigators have assigned different values to these criteria, and at intermediate potentials the state will be uncertain. The equipotential contours will also show areas which, although still passive at present, may develop into active anodes later (17). The general pattern of equipotential contours provides useful information to an experienced observer, and it will often be of more use than absolute values of potential. It is important to realize that, while potential measurements may show where steel is no longer passive, they do not show the rate of corrosion. Steel may be corroding but at a negligible rate. In order to get an idea of the rate of corrosion it is necessary to determine the resistivity of the concrete as well as potentials. This is usually measured by Wenner's method, in which four probes are embedded in the concrete as shown in Figure 2.12. A known current is passed between the two outer probes and the potential difference between the inner ones is measured. The resistivity of the concrete can be calculated and an experienced operator can form an opinion about the probable rate of corrosion of the steel. A 'state of the art' survey of these methods is given by Figg and Marsden (18).

There are a number of other electrical techniques for detecting corrosion of reinforcement but, as yet, they are more suitable for use in the laboratory than in

Figure 2.9 Profometer metal reinforcement detector and cover measuring instrument (Proceq SA, Zurich)

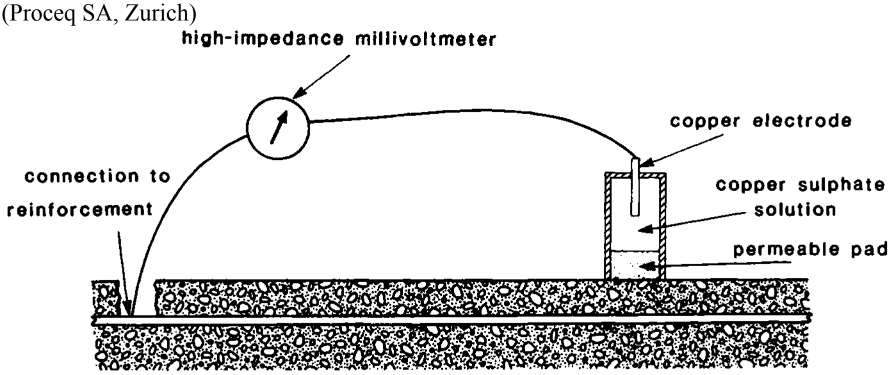

Figure 2.10 Schematic diagram of equipment for electrode potential measurement

the field (19, 20). All of them, including the methods of potential and resistivity measurement outlined above, require experienced operators for their success and interpretation because there are a number of factors that can introduce serious errors.

The measurement of depth of carbonation of concrete is, fortunately, a relatively simple matter. If a freshly exposed surface of concrete is sprayed with a chemical indicator, the difference in alkalinity between carbonated and uncarbonated concrete is shown by a change in colour. The indicator most commonly used is a solution of phenolphthalein in diluted ethyl alcohol which

Figure 2.11 Colebrand's Multicell for half-cell potential measurement. The machine reads and records the potentials and displays the values numerically and in graphical format. (Photograph courtesy Colebrand Ltd)

changes from colourless to purple-pink as the pH value rises above 10. Consequently the outer, carbonated layer of concrete remains its natural colour while uncarbonated concrete is stained pink. In the absence of chlorides, steel becomes depassivated about pH 11, but the carbonation front normally is sharply defined, so the change from pH 12.5 or thereabouts to pH 11 is a negligible distance ahead of the position of pH 10 or less. This test must be applied only to freshly exposed surfaces, because reaction with atmospheric carbon dioxide

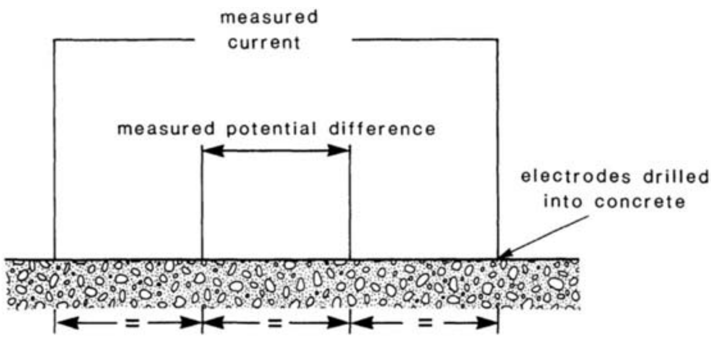

Figure 2.12 Schematic diagram of Wenner method of measuring resistivity

starts immediately. Also, one must ensure that the carbonated surface is not contaminated with dust from uncarbonated concrete. The technique is described in detail by Roberts (21).

The presence of chlorides in concrete may be a contributory factor towards corrosion of reinforcement. They are readily detected and measured in a laboratory and there are some simple chemical tests that have been developed for site use (22, 23). Samples of powdered concrete are obtained by drilling, and are then dissolved in a chemical reagent. Strips of special indicator paper are dipped into the solution and the chloride content is shown by the height to which a colour change rises. This gives the result as percentage by mass of concrete: in order to obtain a percentage by mass of cement, the cement content must be determined but it can usually be estimated accurately enough for practical purposes.

2.3.4
Laboratory tests

Sometimes as, for example, when concrete has appeared to be less durable than might have been expected, samples of hardened concrete are analysed in order to determine mix proportions.

To give an accurate result for cement content of a batch of concrete, four independent samples are required and the samples are best obtained by coring. When a large mass of concrete containing a number of batches is to be tested 10–20 samples, taken at random, are needed to give a good estimate of the average quality.

Cement content can be determined by chemical analysis for soluble silica or calcium using the methods described in BS 1881: Part 124 (24). Whenever possible both calcium and soluble silica methods should be used although calcium cannot be used when limestone aggregates are present. Accuracy of the results is greatly improved if samples of the cement and aggregates can also be provided. Much depends on conscientious sample preparation in the laboratory, which is a tedious job.

Other tests possible include the assessment of original water/cement ratio and of aggregate grading, but these tests require great care in their performance. Chemical attack on concrete is usually suggested by the appearance of the concrete and by information about its environment, and most common forms of attack are readily confirmed by chemical laboratory tests.

Microscopic examination of concrete can be used for the identification of aggregate types, to detect the presence of cement replacement materials such as pulverized fuel ash (pfa), to identify cement type, to measure air entrainment including bubble size and spacing, and to detect alkali-aggregate reactions. For the latter purpose, thin sections of concrete must be made and viewed by transmitted light. The preparation of thin sections is slow and costly, but it is the only certain way of identifying alkali-aggregate reactions and assessing their significance.

2.4 Assessment

In the great majority of cases, enough information for a satisfactory diagnosis can be obtained by careful observation and diligent questioning, and the amount of testing required is usually small. If the load-bearing capacity of a structure is in question calculations will have to be undertaken and guidance has been given by The Institution of Structural Engineers (25). All observations should be recorded, preferably on drawings of the structure. Localized and distinct variations in material properties often indicate weakness, and records in graphical form make their positions more readily distinguishable.

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3
Cements and aggregates

G.F.MASSON and R.T.L.ALLEN

3.1
Portland cements

The cements most frequently used in concrete repair work are ordinary Portland cement (OPC) and rapid-hardening Portland cement (RHPC), which should comply with BS 12(1). This recently published Standard classifies cements according to standard strength classes which are given in Table 3.1. Ordinary Portland cement (OPC) will be Class 42.5 and rapid-hardening Portland cement (RHPC) will be Class 52.5. BS 12(1) also includes requirements for initial setting time, soundness, loss on ignition, insoluble residue, sulphate and chloride.

A common misapprehension refers to setting times. The stiffening and hardening of cement paste is the result of the continuous chemical reactions of hydration; these start as soon as cement and water are mixed and continue at a gradually decreasing rate for a considerable period of time. Setting times are purely arbitrary states of stiffening that are determined by needle penetration tests on standard specimens of cement paste and defined in British Standard EN 196-3 (2); they do not represent any sudden change in properties, and they refer to cement paste only, not to mortar or concrete. Sulphate-resisting Portland cement (SRPC), complying with British Standard

Table 3.1 Strength requirements of BS 12:1991 Specification for Portland cement

	Compressive strength (determined in accordance with BS EN196-1)			
	Early strength		*Standard strength*	
Strength class	*2 days*	*7 days*	*28 days*	
32.5N	–	≥ 16	≥32.5	≤52.5
32.5R	≥10	–		
42.5N	≥10	–	≥42.5	≤ 62.5
42.5R	≥20	–		
52.5N	≥20	–	≥52.5	≤72.5

	Compressive strength (determined in accordance with BS EN196-1)			
	Early strength		*Standard strength*	
Strength class	*2 days*	*7 days*	*28 days*	
62.5N	≥20	–	≥ 62.5	–

Table 3.2 Typical proportions of principal constituents of Portland cement

	Tricalcium silicate C_3S %	*Dicalcium silicate C_2S %*	*Tricalcium aluminate C_3A %*	*Tetracalcium aluminoferrite C_4AF %*
OPC and RHPC	53	18	10	8
SRPC	60	15	1	13

4027 (3), may be used when the structure under repair was built with SRPC concrete, or deterioration has occurred due to sulphate attack. The principal difference between SRPC and OPC is in chemical composition: the maximum permitted content of tricalcium aluminate in SRPC is 3.5%, while no limit is given for OPC. Typical proportions of the principal constituents of present-day Portland cement are given in Table 3.2. It is important to remember that while SRPC is more resistant than OPC to attack by sulphate ions, there is little difference between the resistance of the two types of cement to acid conditions. British ordinary, rapid-hardening and sulphate-resisting Portland cements are approximately equivalent to American Types I, III and V respectively (4).

White Portland cement complying with BS 12 may be used for reasons of appearance. It is made from selected raw materials and its composition is adjusted so as to reduce greatly the proportion of iron compounds in it. The proportion of tetracalcium aluminoferrite (C_4AF) is typically less than 1% in white cement compared with about 8% in OPC.

Coloured Portland cements are no longer available in Great Britain, but coloured mortars or concretes can be made by incorporating inorganic pigments complying with British Standard 1014 (5) in the mix. White cement is often necessary when pigments are used. If such a mix is correctly designed, all the aggregate particles will be coated initially with coloured cement paste and the colour will be governed by the cement and pigment. On exposure to the weather, however, the film of coloured cement on exposed particles will tend to disappear and the colour of the fine aggregate will become more evident. Consequently, it is advisable to choose a fine aggregate that has a colour resembling that desired.

3.2
High-alumina cement

High-alumina cement is sometimes used when rapid gain of strength is important, but its use for load-bearing structures is prohibited by current Codes of Practice (6). This is because of its susceptibility to 'conversion', which is a change of crystalline form with time that leads to a serious reduction in strength (7). This phenomenon occurs particularly when the concrete is stored under warm or in humid conditions. Carefully controlled mixtures of high-alumina and Portland cements produce rapid setting properties for non-structural applications such as temporary repairs or sealing leaks, but have little strength or long-term durability.

3.3
Aggregates

Aggregates should generally be natural concreting aggregates, complying with BS 882 and, unless proprietary pre-packed materials are used, the selection of type will depend largely on what is available within a reasonable distance from the site (8).

Generally speaking, coarse aggregates are used only in the larger repairs, and 10mm maximum sizes are used more frequently than they are in new construction. Rounded particles are preferable to very angular ones, because compaction is often more difficult in repair work than in new construction, but angular coarse aggregates may have to be used in some localities and it will seldom be worth paying higher prices for rounded coarse aggregates. Flaky and elongated particles should be avoided because they make the concrete difficult to compact.

With sands, particle shape has a greater effect on workability because of their greater surface area, so the use of rounded pit sands rather than crushed rock fines has distinct advantages by reducing the amount of water required, and hence the likelihood of shrinkage. Grading is important, however, in order to produce a dense concrete that can be compacted readily without segregation or bleeding, and it may be necessary to blend natural sands with crushed rock fines in order to get the best results. Sands containing excessive amounts of silt or clay should be avoided because their very great surface area increases the amount of water required and they interfere with the bond between cement and aggregate particles, and limits laid down in BS 882 should be adhered to (8). Building sands complying with BS 1199 or 1200 are not generally suitable for concrete repair work because of their finer gradings (9). The choice of sand may be affected by its colour, for reasons already stated.

Special aggregates may be needed in some circumstances. Lightweight aggregates to British Standard 3797 (10) are used occasionally in overhead work, because the thickness of mortar that can be built up in one layer, using normal aggregates, may be restricted by its weight. Lightweight fillers are used in some proprietary repair compounds for this reason. Specially hard metallic aggregates may be used when the work will be subject to severe abrasion, as in floors in heavy industrial premises.

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4
Polymers for concrete repair

J.D.N.SHAW

4.1
Introduction

In virtually all cases of concrete deterioration, the problem is associated with corrosion of steel reinforcement. It is well established that steel reinforcement well embedded in good-quality concrete is protected from corrosion by the passivating nature of the highly alkaline cement matrix. Therefore, whenever possible, it is desirable for both technical and economic reasons that deteriorated reinforced concrete should be repaired with impermeable highly alkaline cement-based materials closely matched in properties to the parent concrete. However, there are many instances where repair compositions containing polymers, either as admixtures for cementitious systems or as high strength binders (for adhesives, mortars and grouts), are the most appropriate (1).

Over the past twenty years, many different polymers have been used in a range of applications in the repair and maintenance of buildings and other structures. Without the unique properties of some of the polymer systems, many of the repairs undertaken would, without doubt, have been much more costly and have taken much longer to carry out (2).

The polymers used in concrete repair consist principally of two different types of materials:

(i) Polymers used to modify cementitious systems
(ii) Reactive thermosetting resins, mainly epoxy and unsaturated polyester resins, but also unsaturated acrylic resin systems.

4.2
Polymer modified cementitious systems

Since the early 1950s, it has been known that certain polymers can be added to cementitious mortars and renders to help overcome many of the problems of using unmodified mortars etc. as concrete repair materials. The polymers used as admixtures for cementitious systems are normally supplied as milky white dispersions in water (latex) and are used to gauge the cementitious mortar as a whole or as partial replacement of the mixing water (3, 4).

Such mortars afford the same alkaline passivation protection of the steel as do conventional cementitious materials, and can readily be placed in a single application at 12–15mm thickness which gives adequate protective cover (1, 3, 4–8). The polymer latex acts in several ways:

(i) It functions as a water-reducing plasticizer, producing a mortar with good workability and lower shrinkage at lower water/cement ratios
(ii) It improves the bond between the repair mortar and the concrete being repaired, providing, of course, that it is applied and used properly
(iii) It reduces the permeability of the repair mortar to water, carbon dioxide and oils and also increases its resistance to some chemicals
(iv) It acts, to some degree, as an integral curing aid, but careful curing is generally still essential
(v) It increases the tensile and flexural strength of the mortar.

Work by Isenberg and Vanderhoff (9) indicates that when a polymer latex is incorporated in a cementitious mortar, it forms a network of polymer strands interpenetrating the cement matrix. This has been shown using photomicrography (Figures 4.1–4.4) (9).

These figures show that when an unmodified cementitious mortar sets and the excess water evaporates, shrinkage occurs, causing microcracking of the cement matrix, some ‘deep’ cracks 4–5 µm wide being formed. When a polymer latex is incorporated, the water/cement ratio is lower and hence shrinkage is lower so that the microcracks are less wide (1–2 µm). In addition, the polymer forms ‘elastic bands’ across these microcracks, increasing tensile and flexural strengths and further reducing permeability of the mortar.

There are several different types of polymer latexes which have been used as modifiers for cementitious systems, most of which have been manufactured specifically as admixtures for cementitious materials. These include polyvinyl acetates (PVAc), styrene butadiene (SBR), polyvinylidene dichloride (PVDC), acrylics and modified acrylics (generally styrene acrylics).

Polyvinylidene dichloride (PVDC) latexes are not recommended for repair mortars for reinforced concrete because there is a slight possibility of free chlorides being released in the long term. Polyvinyl acetate (PVAc) ‘homopolymer’ latexes, which are widely used as general-purpose bonding aids/ admixtures for the building industry, are *not recommended* in external applications or under wet service conditions as there is a danger of the polymer breaking down under wet alkaline conditions (this also applies to their use as bonding agents). Recently, modified polyvinyl acetate polymers in which vinyl acetate is reacted during manufacture with other monomers such as ethylene, vinyl propionate and vinyl ‘Versatate’ to produce ‘copolymers’ and ‘terpolymers’

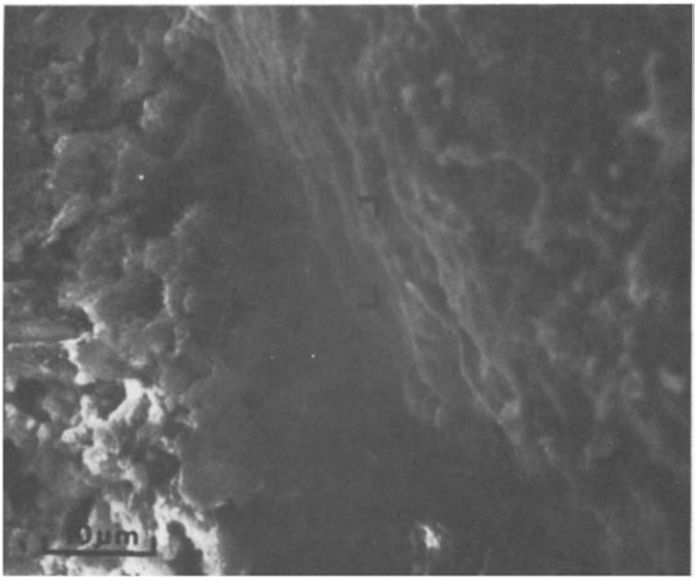

Figure 4.1 Cementitious matrix without SBR latex

have been developed to overcome this sensitivity to wet alkaline conditions, but to date they have not been widely used in concrete repair compositions in the UK.

Styrene butadiene (SBR), acrylic and modified acrylic latexes are most commonly used as admixtures in concrete repair mortars and, when they are properly formulated for compatibility with cement, there do not appear to be any significant differences in the long-term performance of the repair mortars based on the three latex types for general concrete repair (3). The work by Isenberg and Vanderhoff (9) was carried out with an SBR latex, but similar polymer strands are probably formed with other polymers.

In the early 1980s polymer modified repair mortars were blended on site from sand, cement, latex and water. This resulted in some problems of unsatisfactory mortars due to the lack of adequate quality control (poor sand, inadequate labour, unsatisfactory mixes, etc.). To overcome this problem, there are now available complete 'bag and bottle' mixes of latex and pre-blended sand and cement which eliminate on-site blending. These packs are generally designed to be complete, requiring no further additions. A further development has been the use of redispersible spray-dried polymer powders which may be factory blended with graded sand, cement and other additives to give mortars and bonding coats simply by the addition of water on site. These polymer powders are generally based on copolymers of vinyl acetate and other 'monomers' such as ethylene or vinyl 'Versatate'. Over the past two years redispersible acrylic powders have become available. Some of the acrylic powders would appear to offer technical improvements to offset their higher cost and are likely to be used increasingly in

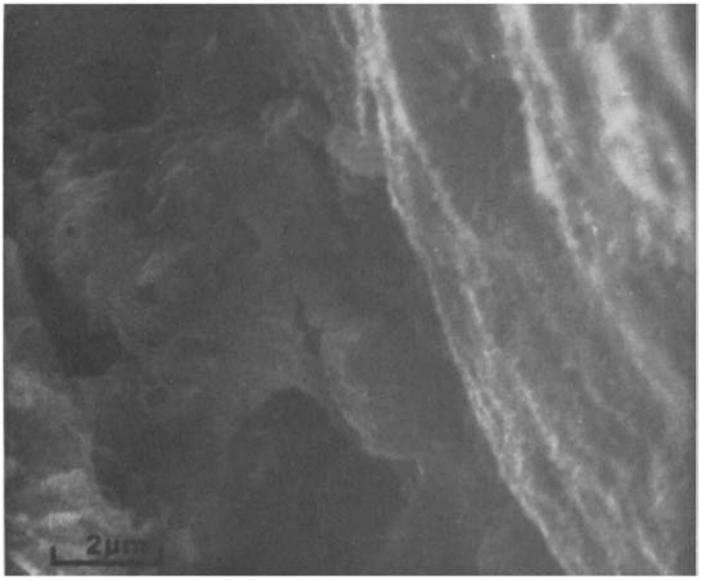

Figure 4.2 The same matrix as in Figure 4.1, enlarged×5

the future. The 'all in the bag' factory blended, quality controlled repair mortars incorporating redispersible polymer powders are rapidly becoming more popular and are more cost effective than the 'bag and bottle' mixes. Formulations incorporating lightweight fillers are also available for vertical and soffit repairs. Such lightweight repair mortars can be applied approximately 75 mm deep without any formwork and may be used as an alternative to replacement concrete.

Polymer modified cementitious mortars are mainly used for the repair of reinforced concrete where the cover to be replaced is more than 12 mm in thickness. In some instances they are used in conjunction with a protective coating in lower cover situations (down to approx. 6 mm). Where the cover is less than 12 mm, and no protective coating is to be applied, then resin repair mortars are normally recommended (3, 4).

4.3
Resin repair mortars

Where the cover is less than 12 mm and the areas to be repaired are relatively small, resin mortars are being used extensively. However it is important to note that unlike polmer modified cementitious repair systems, whose alkalinity helps prevent steel reinforcement corrosion by passivation, the protection afforded by resin mortars is achieved by encapsulating the steel reinforcement with an impermeable 'macro' coating which exhibits excellent adhesion to both the steel and concrete substrate. This protective mortar/ coating will give good long-term

Figure 4.3 Cementitious matrix with SBR latex

protection of steel reinforcement at thicknesses far less than is possible with cementitious repair materials. This protection depends entirely on the impermeability of the envelope and thus it is essential that the formulation and application of resin mortars, including surface preparation of the steel reinforcement (generally by grit blasting to Swedish Standard SA 2 1/2 or equivalent), are of a high standard (1, 3, 4).

Resin repair mortars are based on reactive resins filled with carefully graded aggregates. Epoxy resins are most commonly used, but polyester and acrylic resins are also used especially where rapid strength development is required.

Epoxy, polyester and acrylic resins are classed as thermosetting materials because, when cured, the molecular chains are locked permanently together and, unlike thermoplastics, they do not melt or flow when heated but become more rubbery and gradually lose strength with increases in temperature. They are generally supplied as two or three component systems: resin, hardener (either or both may contain fillers) and fillers. The chemistry of the resin is, however, significantly different for each type (2, 4).

4.3.1 *Epoxy resins*

Epoxy resins consist of a reactive resin which can, in much simplified non-chemical terms, be considered as a material with reactive 'hooks', and a hardener (also called curing agent) with reactive 'eyes' (Figure 4.5). To achieve the full properties of the cured resin system, the right number of 'hooks' must be

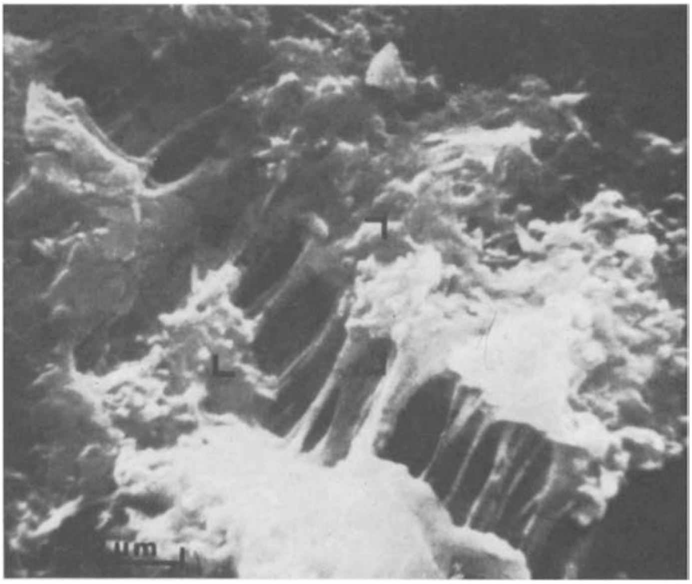

Figure 4.4 The same matrix as in Figure 4.3, enlarged × 5 and showing polymer strands. (Photomicrographs by courtesy of Professor J.W.Vanderhoff Emulsion Polymers Institute, Lehigh University, Pennsylvania, USA)

intimately mixed with the right number of 'eyes' so that in the pot of mixed resin a 'hook' is immediately adjacent to an 'eye'.

The properties required for a specific application are achieved by careful attention to the chemistries of both the resin and hardener which are influenced by the precise chemical nature of the chemical grouping structures between the chemical 'hooks' and 'eyes'. The nature of these structures and also the nature of the other additives in the formulation will influence the ultimate strength, rate of cure at different temperatures and also whether the formulation will bond under damp conditions (or even under water). Correct proportioning and thorough mixing are, therefore, imperative when using epoxy resin systems. The curing (hooking up) of epoxy resin systems is an exothermic reaction (i.e. heat is given off) and the rate of cure is temperaturedependent. As a rule, the rate of cure doubles as the temperature increases by 10°C. Many formulations stop curing altogether as the temperature drops below about 5°C, although there are available epoxy formulations which will cure down to approximately 0°C. In warm weather, the exothermic heat developed during cure with epoxy resins can be excessive and give rise to problems. It is for this reason that alternative formulations are often necessary in winter and in tropical climates.

In the cure of epoxy resins, maximum heat evolution due to exotherm occurs whilst the resin is still in a fluid state. Nevertheless, in some conditions the resin composition will set rigid whilst it is at a temperature significantly above the adjacent substrates, and therefore thermal contraction can occur causing stresses

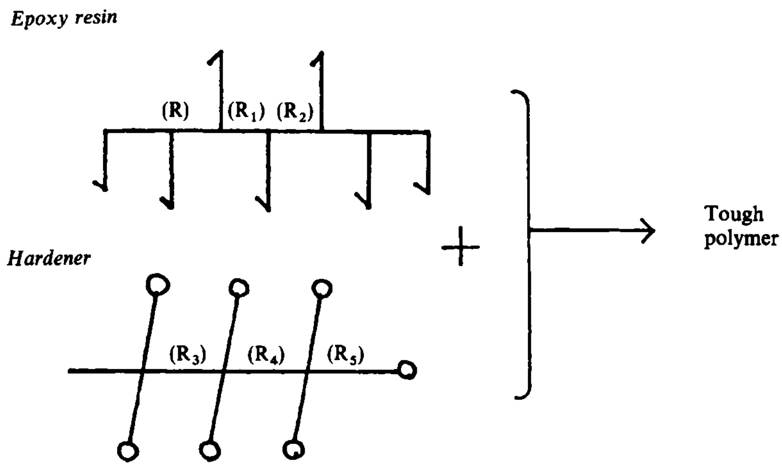

Figure 4.5 Reactive hooks and eyes

to be built up at the interface between the resin composition and the substrate. The change in volume between the mixed uncured epoxy resin/hardener and the fully-cured polymer is low and, if the material is carefully formulated, carefully mixed and applied according to the formulator's instructions, can often be considered to be negligible. However, for each application, the volume of epoxy resin to be placed, thickness, temperature of mixed resin system and cure temperature all need to be carefully considered to avoid shrinkage due to thermal contraction.

4.3.2 *Unsaturated reactive polyester resins*

Polyester resin systems are chemically much more simple in that the liquid resin component contains both the 'blocked hooks' and the 'eyes' in the right proportion intimately mixed together (Figure 4.6). The hardener (or catalyst) component is based on organic peroxide, which can be in the form of a fine powder, a low-viscosity liquid, or paste. The hardener is required purely to initiate the 'unblocking' of the hooks which, once initiated, is to some extent a chain reaction which continues throughout the mass of the polyester resin. Mixing and proportion of the hardener component is, therefore, less critical than for epoxy resin formulation. It is important to note that the curing of the polyester resin at the interface with the substrate may be inhibited under certain, not always well defined, conditions, resulting in loss of adhesion. Because of the nature of the curing mechanism it is possible to formulate polyester resin repair materials with a usable life of 45 min but which develop a compressive strength of 40 N/mm^2 within 2 h at temperatures down to 4°C. Polyester resin systems are formulated for specific application temperatures and generally winter and summer grades are marketed by the formulator.

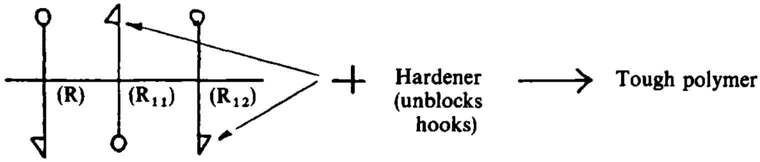

Figure 4.6 Polyester resin

Like the epoxy resin systems, the cure of polyester resin systems is also exothermic but, unfortunately, the maximum heat evolution occurs after the resin has set and this can result in significant thermal contraction inducing high stress build-up at the interface with adjacent substrates. This can cause adhesive failure at these interfaces.

In addition to this possible thermal contraction of polyester resin systems, there is also a change in volume between mixed, uncured polyester resins and the fully cured, set polymer (curing shrinkage). Because of these two factors, polyester resin formulations must, in general, belimited to application in relatively small areas at one time, and most formulators do make recommendations on the maximum areas/thickness that can be applied for a particular polyester formulation at one time (2).

Polyester resin mortars and concretes with aggregate/binder ratios up to 11/1 by weight have been used for more than 20 years for airport runway repairs and the installation of runway lights and similar applications where their rapid strength gain properties are essential (2, 12).

Low modulus polyester resin mortars, with similar rapid curing properties, have recently been developed. These have been used to fill cable slots cut across asphalt runways and also to fill over PVC cable ducts installed in concrete runways and taxiways (12).

4.3.3
Unsaturated acrylic resins

Acrylic resin systems form high-strength materials by similar chemical cure mechanisms to the unsaturated resins described in 4.3.2. In general, acrylic resins are based on monomers of very low viscosity or blends of monomers with methyl methacrylate monomer, the most commonly used. Because of the very low viscosity of the uncured acrylic resins, very high filler loadings are possible, so that the mortars tend to exhibit less shrinkage than mortars based on unsaturated polyester resins. There are also available acrylic resins based on monomers such as 2-ethylhexacrylate. These produce mortars with significantly lower modulus which are, therefore, able to absorb the stresses due to their inherent shrinkage without causing bond failure with the concrete substrate.

4.3.4
Safe handling of resins

All epoxy, polyester and acrylic resins require handling with care. Contact with resins, especially epoxy resins, can cause skin irritation if correct handling procedures are not followed (13). Most people are less sensitive to polyester and acrylic resins but nevertheless careful handling is essential.

Polyester and acrylic resins contain volatile constituents which are flammable. Most acrylic resins are highly flammable with flash points below 10°C, and the vapours given off can cause toxic reactions. Safe handling precautions are recommended by all responsible suppliers and should be strictly followed (13).

4.3.5
Selection of resin

Of the resin systems, epoxy resin mortars are the most widely used in concrete repairs. Polyester and acrylic resin-based mortars are also used, generally for small-area repairs where their very rapid development of strength is required. High-modulus, rigid polyester and acrylic mortars are not suitable for larger repairs because of dangers of shrinkage and subsequent cracking or debonding. However, low-modulus polyester and acrylic mortars capable of absorbing these stresses have been used to a limited extent in rapid-setting repair mortars. Epoxy resin mortars are available which give excellent handling and cure characteristics at high ambient temperatures, and systems based on lightweight fillers are available which can be applied up to 30 mm thickness in a single layer on soffits and vertical faces without problems. Comments have been made that epoxy resin mortar repairs have not always proved durable even in the short term. It is, therefore, most important to understand that the generic name 'epoxy resin' covers a very diverse range of chemically and physically different polymers. To achieve good durable repairs, careful selection of the resin composition and grading of the fillers appropriate to the application and service conditions is essential.

4.4
Properties of polymer-based repair materials

In most repair situations, the polymer-based repair material is bonded directly to concrete or other cementitious material. It is, therefore, important to be aware of the similarities and differences in mechanical and physical properties of polymer repair compositions and concrete. Typical properties of polymer compositions are given in Tables 4.1 and 4.2. Until recently, there were no recognized test methods for measuring the properties of polymer compositions which reflect their use in construction applications. There is now a range of test methods BS 6319, parts 1–8, which were initially drafted by FeRFA (13).

4.5 Polymer bonding aids

When applying conventional concrete, sprayed concrete or sand/cement repair mortars, bond is often a problem. In particular, where the repairs are to

Table 4.1 Physical properties: a comparsion typical products used in concrete repairs

	Epoxy resin grouts, mortars and concretes	*Polyester resin grouts, mortars and concretes*	*Cementitious grouts, mortars and concretes*	*Polymer modified cementitious systems*
Compressive strength (N/mm^2)	55–110	55–110	20–70	10–80
Comprressive modulus *E*-value (kN/mm^2)	0.5–20	2–10	20–30	1–30
Flexural strength (N/mm^2)	25–50	25–30	2–5	6–15
Tensile strengthe (N/mm^2)	9–20	8–17	1.5–3.5	2–8
Elongation at break (%)	0–15	0–2	0	0–5
Linear coefficient of thermal expansion per °C	$25–30 \times 10^{-6}$	$25–30 \times 10^{-6}$	$7–12 \times 10^{-6}$	$8–20 \times 10^{-6}$
Water absorption, 7 days at 25°C (%)	0–1	0.2–0.5	5–15	0.1–0.5
Maximum service temperature under load (°C)	40–80	50–80	In excess 300° dependent upon mix design	100–300
Rate of development of strength at 20°C	6–48 hours	2–6 hours	1–4 weeks	1–7 days

Table 4.2 Materials selection for concrete repairs

	Large spalls, cover (mm)			*Small spalls cover (mm)*		*Crack sealing*	*Structural crack repair*	*Bonding aids*	*Honeycomb concrete*	*Permeable concrete*
	25	*12–25*	*6–12*	*12–25*	*6–12*					
Concrete Sprayed concrete Sand/cement mortars with/without admixtures and/or bonding aids	×									
Polymer modified cementitious mortars		×	×[1]	×						
Epoxy resin mortars			×		×					
Polyester resin mortars					×					
Moisture-tolerant epoxy resins								×		
SBR, acrylic and co-polymer latices						×		×		Depends on permeability
Low viscosity polyester and acrylic resins						×			×	Depends on permeability
Epoxy resin low viscosity							×		×	Depends on

	Large spalls, cover (mm)			*Small spalls cover (mm)*		*Crack sealing*	*Structural crack repair*	*Bonding aids*	*Honeycomb concrete*	*Permeable concrete*
	25	*12–25*	*6–12*	*12–25*	*6–12*					
										permeability
Penetrating polymer systems, ‘in surface’ sealers										×
Special coatings and penetrating ‘in-surface’ sealers										×
Universal bonding aids, PVA, PVA modified mortars						not suitable for external repairs				

[1] Depending upon service conditions the application of an anti-carbonation protective coating may be required

be carried out at high ambient temperatures, water loss at the interface between the repair material and the prepared concrete may prevent proper hydration of the cement matrix at this interface. The use of an epoxy resin or polymer latex bonding aid can assist in achieving a reliable bond. With an epoxy bonding system specifically formulated for bonding green uncured concrete to cured concrete, a bond is achieved which is significantly greater than the shear strength of good-quality concrete or mortar. In the UK and continental Europe, polymer latex bonding aids which are applied to the prepared concrete either as neat coats of latex or as slurries with cement are widely used, since they are simpler to use than epoxy resin bonding aids and give a good tough bond which is less ‘structural’ than that achieved using the right epoxy bonding aid (14).

However, under severe drying conditions, the ‘open time’ for polymer latex bonding coats can be too short for this to be a practical method of ensuring a good bond between the repair mortar and the parent concrete. For this reason, epoxy resin bonding aids with adequate pot life and open time for the application conditions are also widely used (14, 15).

As an alternative to polymer latex slurry bond-coats, there are now available factory-blended polymer modified cementitious bonding aids based on special spray-dried copolymer powders blended with cement, fine sand and other special additives which are simply gauged with water on site and applied to the prepared parent concrete to give a ‘stipple’ finish. Even when allowed to set overnight, this type of bonding aid gives a good ‘key’ for the repair mortar and prevents rapid loss of water from the repair mortar which may result in inadequate hydration and thus poor bond. However, application of the repair mortar whilst this key coat is still tacky is recommended wherever practicable (14). In some instances, the epoxy bonding aid is also required to function as an impermeable barrier between the repair mortar and the parent concrete. In these cases, two coats of the bonding aid are applied and whilst still tacky are dressed with clean sharp sand. This ensures an excellent mechanical key between the two coats and the repair mortar. Even when using a high-performance epoxy bonding aid, it is essential that the parent concrete is cut out to a minimum depth of 5 mm at the edge of the area to be repaired (1, 3, 14).

4.6 Repair of cracks/resin injection

Reinforced concrete structures are designed so that the inevitable cracking of the concrete is restricted such that no cracks at the surface should exceed approx. 100 microns thickness. For many reasons, cracking in excess of the design acceptance limits occurs rather too often either during construction or during the service life of the structure. If such cracks are not sealed or structurally bonded, further deterioration may occur. Before deciding the most appropriate methods/materials for repairing/sealing cracks, it is imperative to establish the cause of the cracking and, where a permanent structural bonding of the crack is required, to carry out any other strengthening which may be necessary. It is possible to restore the structure to the original tensile/shear strength of the uncracked concrete by injection with low-viscosity epoxy resins specifically developed for repairing cracks, providing the bonding surfaces of the concrete at the crack interface are clean and sound. Cracking is caused by tensile stresses and, if these stresses recur after crack repair, the concrete will probably crack again (3, 11, 16, 17). If it is not possible to establish and rectify the cause of the original cracking, it is recommended to cut out along the surface of the crack and treat it as a normal movement joint or, alternatively, to cut out a normal straight movement joint adjacent to the crack and then repair the crack by resin injection. Alternatively the crack can be converted into a movement joint as described in Chapter 5, section 5.4. The use of a very low-modulus system to fill the crack, as a cheaper alternative, is not recommended for filling fine cracks liable to movement, since the filling material is required to exhibit virtually infinite elongation over a very short width, which is, to all practical purposes, impossible (3).

Low-viscosity epoxy resin systems (viscosity below 6 stokes at 20 °C) are generally used for the structural repairs of cracks. Low-viscosity acrylic or polyester resins are also used, but in general give lower bond strengths and do not bond under damp conditions as reliably as epoxy resin injection systems specifically developed for the purpose (18).

Using pressure injection techniques, it is possible to completely fill cracks finer than 50 microns with epoxy resin systems. It is important to note that when injecting very fine cracks, the ‘back pressures’ as the resin penetrates can be significant, and if the work is not carried out skilfully can ‘blow’ surface seals, making successful injection impossible. Controlled pressures sustained for several minutes may be required to completely fill a fine crack. In such instances, the volume of injection resin required is minute (a few millilitres) and the premixing of packs of resin and hardener prior to injection can be very wasteful due to the limited profile of the mixed resin. For injection into very fine cracks, sophisticated metering and mixing equipment is often used by specialist contractors. Such specialized equipment generally uses special static mixing heads with complex flow patterns which ensure thorough mixing of very small volumes of resin/hardener at any one time.

When repairing cracks of 1–2 mm, the use of a low-viscosity injection resin is sometimes impracticable as it is not always possible to seal all the outlets to the crack so that the resin simply ‘drains away’ and does not fill and repair the crack. In these instances, modified resins are used which flow readily into relatively fine cracks under low pressures but stop flowing immediately the pressure is released. Such resins are termed ‘thixotropic’ and are produced by adding small quantities of special additives which induce ‘thixotropy’.

In cases where it is required to fill/bond a network of cracks with ‘dead ends’, voids behind tiles or honeycombed concrete, a combination of vacuum, to remove the majority of air in the cracks etc., and pressure injection has proved most effective in some instances (10, 11, 18, 19).

The concept of using epoxy resin injection systems as a means of repairing cracked concrete so that when repaired, the concrete again acts monolithically has been established for over 20 years and during that time some major ‘rescues’ have been carried out (20).

In some cases it is required to seal cracks to prevent ingress of water etc. and to achieve a reasonable, but not structural, bond. Specially formulated low-viscosity aqueous acrylic resin dispersions are available to seal such cracks in concrete provided it is dry. The water in the dispersion is gradually absorbed into the concrete and by several applications the crack is filled with a water-resistant rubbery acrylic resin which can accommodate a small degree of movement. Such materials are ideally suited for sealing narrow cracks up to 1 mm width and are very commonly used to fill/rebond hollow floor screeds which have ‘curled’ during curing (3).

4.7
Grouting under heavy-duty crane rails

Over the past 20 years the use of epoxy resin compositions for the installation and repair of support systems for heavy-duty crane rails has become a standard procedure (2).

The excellent mechanical properties and volume stability of the epoxy resin systems has allowed precision placement and long-term serviceability against the high compressive, tensile and flexural forces induced under acceleration and braking.

The general practice is to cast a concrete support beam with its upper surface as level as possible and then mount the rail and soleplate using metal shims or levelling screws to level and align it, giving a 10 mm—30 mm bed. The filled epoxy resin grout is then pumped into the void and allowed to cure. In the past crane rail systems were installed with site mixed sand/cement or proprietary cementitious grouts. Both suffered from a number of limitations including long cure times, low tensile and flexural strengths and poor resistance to chemical attack. These inadequacies have often led to costly repair works after only short periods of service (2, 20).

The first major UK crane rail epoxy resin grouting job was the grouting of the rails for the Goliath Krupp Crane at the Harland and Wolff Shipyard, Belfast, Northern Ireland, in 1967 (21). This large dock permits the construction of giant oil tankers under enclosed workshop conditions. The tankers are built in sections, each weighing approximately 800 tonnes, which are lined up by the giant crane for joining together in the 140 m by 800 m dry dock. The crane, which is 70 metres high, runs on steel rails on both sides of the dock. The load of the laden crane is distributed over 16 bogies on each side of the dock (2, 20, 21).

For this contract, a special high-strength epoxy grout was developed and some 280 tonnes of the grout were used. During the development of this grout, problems of entraining air in the grout during mixing were encountered which, if not eliminated, would have resulted in the weakness in the most critical part of the grout, the top 1–2 mm in contact with the soleplate. This was overcome by mixing all 280 tonnes of sand-filled grout in a vacuum mixer on site. However, epoxy grouts now available do not in general suffer from the same problem of air entrainment and vacuum mixing is very rarely used.

A more recent development in the repair of concrete support beams for crane rails in the UK has been the use of epoxy resin concrete to fill any large voids beneath the rail caused by disintegration of the concrete, and voids in excess of 100 mm thickness have been filled in a single application. By careful grading of selected silica sands and gravels, it has been possible to achieve high-strength resin concretes with compressive strengths in excess of 85N/mm^2 with high filler/binder ratios (10:1 to 11:1 by weight). These resin concretes can be readily mixed in a forced action mixer and compacted into place with little effort. Using these materials, a major repair of concrete support beams and relevelling of crane rails can be carried out within a few days, which would be virtually impossible with more conventional cementitious materials (20).

4.8 Strengthening of reinforced concrete structures by external bonding of steel plates

The use of epoxy resin adhesives in the strengthening of loadbearing reinforced concrete structures by bonding on steel plate reinforcement externally has been established for more than 25 years. From published literature, it would appear that the concept was developed almost simultaneously in South Africa and France in about 1965 (17, 22). In South Africa, resin-bonded reinforcement was used for the rapid emergency repair of a road overbridge damaged by the impact of a mobile crane which ruptured some of the steel reinforcement in several beams (22).

Since 1965, extensive testing has been carried out in South Africa, France, Switzerland, Japan, Belgium and the UK (11, 17, 22–24). This has demonstrated that resin bonding of flat steel plates to the external surfaces of structural concrete beams, columns, etc. can be a practicable and economic way of strengthening highway bridges and buildings. However, in the UK there has been a considerable reluctance to use this method partly because the UK Standing Committee on Structural Safety, both in their 5th Report (1982) and their 8th Report (1989), expressed their reservations of this strengthening method due the lack of information on the long-term performance of resin adhesives (25).

Because of gradual loss of strength of ambient cured resin adhesives at temperatures above about 60°C the use of resin bond steel reinforcement has been restricted in the UK to the strengthening of highway bridges or other structures where the risk of fire is minimal or to strengthen buildings where the inherent strength of the structure prior to strengthening is considered adequate in the short term under fire conditions (11). Other countries, notably Belgium and Japan, have used the technique much more widely than the UK and no major structural problems due to the failure of the resin adhesives used in this strengthening technique have been cited in published literature (26).

The first structure in the UK to be strengthened using resin-bonded steel plates was an eight-storey building in Harlow, Essex in 1966. Strengthening was required as a result of a revision of building regulations following the Ronan Point disaster. The regulations required greater stability under very high winds. This increased stability was achieved by bonding steel plates with an epoxy resin adhesive to the vertical columns and central lift shaft (11, 17).

Several bridges including M5 Quinton Bridges 1974 (27–30), M20/M25 Swanley Interchange Bridges 1977 (31), M1 Brimsworth Road Bridge 1983 (32) A.10 Brandon Creek Bridge 1986 and an overbridge at M2 Farthing Corner Service Station 1987 (30) have been strengthened by the use of steel plate bonded on externally using epoxy-resin-based adhesives. In addition to bridges, steel-plate bonding strengthening techniques have been used on a number of other structures including the decks of a multi-storey car park in 1985 and a number of other buildings, most of which have not been reported in literature.

The strengthening of Quinton Bridges was undertaken whilst adjacent lanes of the bridge were in service, which meant that inevitably the adhesive would be subject to some minor load cycling during curing. Laboratory tests were therefore undertaken to investigate the effect of strain cycling on epoxy-resin-bonded steel to steel lap shear test specimens during cure of the adhesive. It was found that the shear strength was reduced by approximately 30%. However, the shear strengths achieved were still significantly higher than the shear strength of good quality concrete which is the limiting factor in strengthening concrete structures by steel plate bonding (11, 28).

One aspect which short-term and accelerated testing could not fully prove was whether external bonded plates would prove durable in service over many years. It is now 18 years since Quinton Bridges were strengthened and apart from some very small areas of corrosion, the externally bonded reinforcement is still performing well. The adhesives used are no longer available because of the potential handling hazards of some of the constituents of the adhesive formulations. However, safer formulations of very similar compositions with equivalent performance are available (11).

Mays (33) has summarized the main performance criteria for epoxy resin adhesives for steel plate bonding, which include:

(i) At least as strong in shear as high-strength concrete, i.e. at least 8 N/mm^2. In practice, the shear strength of concrete in a repair situation is seldom greater than 4 N/mm^2.
(ii) Stiff enough not to creep significantly under sustained load yet flexible enough so that no high stress concentrations can arise. Flexural modulus should be in the range 2-8kN/mm^2.
(iii) Have long-term durability for a service life of at least 30 years at service temperatures from −20°C to +40°C, and subjected to the many wet/dry cycles typical of the British climate.

Accelerated test procedures are currently being evaluated in which the performance of proprietary adhesives of proven performance in service over more than 10 years will be compared with other formulations. It is considered that this should give comparable if not superior performance.

4.9 Improving the abrasion resistance of concrete floors by polymer impregnation

There has been considerable interest in materials which can improve the serviceability of industrial concrete floors, which for a variety of reasons are very prone to dusting and rapid deterioration of the surface due to abrasive wear. Many industrial property owners require remedial treatments which can

Table 4.3

Water/cement concrete mix	Depth of abrasion (mm) cement (15min.cycle)			
A	B	C	0	
0.65	0.26	0.14	0.28	1.18
0.52	0.12	0.14	0.22	0.78
0.44	0.08	0.06	0.12	0.54

A= 10% solution of fully reacted methyl methacrylate/ethylacrylate copolymer in aromatic solvents applied in 2 coats.

B = 20% solution of low molecular weight aliphatic isocyanate prepolymer based moisture curing polyurethane resin in aromatic solvents, applied in 2 coats.

C = 30% solution of a bisphenol A/F resin and blended polyamine hardeners in aromatic solvents, applied in 2 coats.

0 = Controls—no surface treatment.

eliminate these problems and which, moreover, can be applied cheaply over a weekend allowing floors to be back in service on the following Monday.

A recent research programme by the University of Aston has investigated the possibility of improving the abrasion resistance of concrete floor slabs of three different qualities (the differences achieved by keeping the concrete mix the same but varying the water/cement ratio) (34). In this work, the concrete surfaces were treated with two coats of different polymer solutions. The abrasion resistances of the impregnated concrete surfaces were compared with untreated controls using an abrasion wear machine developed by Chaplin. The results are given in Table 4.3.

The results demonstrate a marked reduction in abrasive wear under controlled conditions achieved by different polymer solution impregnants. The conclusion is that, in some cases, a substandard industrial floor can be upgraded to an acceptable level by impregnation with a polymer solution. The technique has been used to 'rescue' many substandard concrete floors so that their wearing properties are at least equivalent to good quality concrete (35, 36).

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5
Repairs to cracked concrete

R.T.L.ALLEN and S.C.EDWARDS

5.1
Purpose of repair

Repairs to cracked concrete should not be embarked upon without full consideration of all the factors involved. All too often, specifiers call for inappropriate or unnecessary work to be carried out because they have not given enough preliminary thought to the causes of cracking and the reason for repair.

The commonest reason for repairing cracked concrete is in order to prevent corrosion of reinforcement. Cracks may provide a path for ingress of carbon dioxide and/or water containing dissolved salts through the concrete cover, so it appears at first sight that they must form a corrosion hazard. Research has shown, however, that this is not necessarily true. A number of Codes of Practice specify maximum permissible crack widths for various conditions, but they do not agree with each other (1, 2, 3, 4). A fundamental weakness of this approach lies in the fact that the crack width at the surface of the concrete will nearly always be greater than the width at the reinforcement, and the difference will depend largely on the thickness of cover.

It has been shown (4) that cracking at right angles to a reinforcing bar is often relatively unimportant. In this case the cracking will have an effect on the time that elapses before corrosion is initiated but it usually has little effect on its subsequent progress. Cracking along the length of a bar is far more serious because a larger proportion of the bar is exposed.

Crack injection may also be used to restore structural integrity. In such cases, the physical adhesion of the injection resin to the internal surfaces of the cracks has to be very good. This may require flushing of the cracks with water in order to remove loosely adhering contaminants. It is also necessary for the resin to penetrate to the full depth of the cracks. It has been demonstrated (5) that injection of a suitable resin into cracked concrete can restore its physical properties.

Cracks may be repaired in order to prevent leakage of fluids into or out of a structure. Before this is done, the possibility of autogenous healing should be considered, especially if the fluid concerned is water (6). Reference should be made to Chapter 9 where the sealing of leaks is discussed in more detail.

In many cases, fine cracks are unsightly but they do not affect the durability or performance of the structure. When considering the appearance of cracks, the distance and circumstances of viewing during the service life of the structure should be taken into account. British Standard 8110 suggests that, as a guide, a design maximum crack width of 0.3 mm may be acceptable (1). Attempts to hide cracks by filling them nearly always fail, and the only really successful method is to apply some form of surface coating which usually has to be applied to the whole of the surface. Coating materials vary in their crack bridging properties and in their elasticity so it may be necessary to fill the cracks first, and the amount of subsequent movement that can be tolerated may be very small. This subject is dealt with more extensively in Chapter 10.

5.2
Classification and diagnosis

Cracks may be classified broadly as either 'live' i.e. those where the width varies with time, or 'dead' cracks where no further movement is likely. They may also be subdivided into progressive cracks that are expected to become longer, and static cracks that are unlikely to do so. If repairs do not have to be carried out immediately, observation over a period of time will enable cracks to be classified and will assist diagnosis of the cause. In any case thorough investigation and diagnosis, as described in Chapter 2, are essential before repairs are carried out (7, 8, 9, 10). The most suitable method of repair will depend on the classification and diagnosis.

5.3
No further movement expected

Dead cracks are generally the result of an event that has passed, such as accidental overload, and they may usually be 'locked' in such a way as to restore the structure as nearly as possible to its original uncracked state. Cracks wider than about 1 mm in horizontal surfaces can usually be sealed by filling them with cement grout. It must be remembered, however, that cracks often taper as they progress into the concrete, and the width at the surface may be greater than the width at the reinforcement. Finer cracks and those in soffits or vertical surfaces may be sealed by injecting a polymer. Epoxy resins are most frequently used when the repair is being carried out in order to restore structural integrity, or when moisture is present. Cheaper polymers, a good example of which would be polyester resin, can often be used when the purpose of the repair is to protect reinforcement from corrosion. In both cases the resin may be injected under gravity or positive pressure; better penetration can be achieved, however, by using vacuum assisted injection.

5.3.1 *Cement grout*

Cracks wider than about 1 mm in the upper surfaces of slabs etc. can often be sealed by brushing in dry cement followed, if necessary, by light spraying with water. This treatment will seal the upper part of a crack against ingress of moisture and carbon dioxide, but the depth of penetration of the cement will be variable. It will not hide the cracks completely but they will be less conspicuous than they would be if they were filled with a material not based on Portland cement. For cracks wider than about 2 mm it may be preferable to use a cement and water grout but this is far more likely to leave marks on the surrounding concrete. Alternatively, cracks can be chased out to a width of 5– 10 mm and pointed up with cement and sand mortar. Clearly, this will be more costly because of the additional labour required but it will be possible to ensure that the seal penetrates at least to the depth of the chase. The cracks are likely to be conspicuous after sealing because it will be very difficult to match the colour and texture of the mortar filling to that of the surrounding concrete: it may match reasonably well at first, but the colour will change as the mortar cures.

5.3.2 *Polymer sealing, without applied pressure*

Low-viscosity liquid polymers can be used in a similar way to cement grout. It may be possible to obtain an adequate seal by brush application or, on level surfaces, temporary bunds can be formed with clay, plasticene or similar material to surround a crack so that it can be flooded with polymer. When no further liquid will penetrate the crack, the surplus material and the bunds are removed. Some of these materials will penetrate cracks down to about 0.1 mm width but, in general, the repair will not be structural. It will seldom be necessary to seal cracks that are narrower than this.

5.3.3 *Polymer injection*

5.3.3.1 *General principles.* When it is necessary to ensure, as far as possible, that the sealant penetrates to the full depth of a crack, injection of polymer grout under pressure is the method most commonly used. For relatively wide cracks that are unlikely to be blocked by debris, it may be enough to use a gravity head of a few hundred millimetres, but in other cases hand-operated or mechanical pumps or pressure pots are used. A theoretical treatment of the flow of liquids in cracks is given in Chapter 9, section 9.5.

The general principle in sealing cracks by injection is to start at one end and work progressively along the crack. For cracks in vertical or inclined surfaces, injection should start at the lowest point and proceed upwards. A series of injection points are formed at intervals along the length of the crack and grout is injected into each point in turn until it starts to flow out of the next one. The point in use is then sealed off and injection is started at the next point, and so on until the full length of the cracks has been treated. It has been argued that material will travel into the concrete and along the joint to subsequent inlets at similar rates. It is for this reason that recommended intervals between injection points are normally equal to the depth of penetration required. The view is oversimplified, however, since the resin will favour the least obstructed or easiest route. The most suitable spacing of injection points depends on a number of factors, including depth of crack, width and how it varies with depth, viscosity of grout, injection pressure, etc. The choice must therefore be based on experience.

5.3.3.2 *Injection points.* These can be formed in various ways, but it will be necessary to surface seal the cracks temporarily between them. Polymer-based materials are available for this purpose, with rapid curing properties, and it is these which are most often used. Sometimes holes are drilled into the crack at intervals and injection nipples grouted in but, with normal drilling, there is some risk that the crack may become blocked by drilling dust. This risk can be reduced if hollow drills with an applied vacuum are available. (Experience has shown that these are difficult to obtain.) Further to this, the method assumes the crack to run perpendicular to the surface, and this is not always the case. The injection point might not necessarily connect with the crack in some situations, so this method is limited in its application. A more suitable technique is to use flanged injection nipples that can be fixed temporarily to the concrete surface with an adhesive. Yet another method is to form gaps in the temporary surface seal at intervals along the crack and to use an injection nozzle that can be sealed adequately to the concrete by pressing it against the surface. This cannot be done if the surface is too rough or if the crack is wide enough to allow resin to run out afterwards. Gaps in the temporary seal can be formed by applying strips of adhesive tape across the crack, at intervals, applying the temporary sealant to the full length, and then peeling off the strips of tape.

5.3.3.3 *Material properties and pressure.* The properties of the grout and also the injection pressure should be determined by experience and the factors governing these and the spacing of injection points are interrelated. When treating vertical and inclined surfaces or soffits, the injection methods may take advantage of thixotropic grout, in order to prevent its flowing out again. Experience has shown that thixotropic materials are also suitable for injecting cracks through concrete walls where the back face may not be accessible for face seals to be applied. This technique has been used sucessfully for repairing concrete cooling towers and secondary containment walls for effluent tanks.

Injection pressures are usually governed by the experience of the operative, and it is common practice to increase the injection pressure during the course of the work. The resistance against flow increases progressively as the crack is filled with material, firstly because of the relatively high viscosity of repair materials and also, in the case of vertical cracks, because of the hydrostatic pressure exerted. In long and relatively wide vertical cracks, it may be necessary to inject in stages or to use a thixotropic repair material to avoid the possibility of rupturing the face seal.

It is always preferable to inject fine cracks under low pressure in order to allow material to be drawn into the concrete by capillary action. In these cases ‘gravity feed’ is the normal method of injection but this is slow, and where cracks are wider, i.e. above 0.5 mm, it will be more cost effective to inject under pressure.

It is important to understand that the pressure used to propel the material through the concrete will not act significantly on the structure while it is flowing freely. If the flow is reduced or stops completely, and pressure is maintained, forces acting from within the system will increase proportionally up to the full value of the pressure applied. This is known as the Bernoulli principle, which postulates that: the sum of pressure, kinetic and potential energies is constant along a specified streamline. It is important to bear this principle in mind when injection pressures are recommended, since the internal surface areas of cracks are normally quite large. Injection pressures must therefore be kept to a minimum where low flow rates are expected.

5.3.3.4 *Equipment.* The most basic type of injection equipment consists of a small reservoir or funnel attached to a length of flexible tubing, so as to provide a gravity head, but the simplest piece of mechanical equipment is a hand-held gun that holds a cartridge of resin grout, similar to the guns used for applying mastic sealants. These may be hand or pneumatically operated. When very small quantities of material are required, this is usually the most economical type of equipment to use. Their main advantage is that a steady pressure can be maintained, which reduces the chance of damage to face seals. The next in order of size and cost is a hand pump with the end of its suction hose immersed in a container of resin grout. This is suitable for use in relatively small works or when a number of small cracks have to be grouted up. They have the advantage that the pressure is easily controllable and an experienced operative can get a ‘feel’ for the progress of injection. For larger schemes, a pressure pot may be used. The mixed resin grout is placed in a closed vessel that is pressurized with compressed air, and the flow of resin through the delivery hose is controlled by a valve at the nozzle end. This also has the advantage of maintaining constant pressure. Pressure pots are in fact designed for feeding paint into air-assisted spray systems, which require a steady flow of material at a constant pressure. In this respect they are suitable for injection of moderate amounts of resin. The major limitations of both pressure pots and pneumatic guns are, primarily, that their maximum working output is only as high as that of the compressor, and also that they are difficult to clean thoroughly, and can easily become blocked.

Power-driven reciprocating pumps are often used for resin injection although they are not specifically designed for the purpose. Injection pressures are typically several times higher than the input value. This depends on the mechanical ratio of the pump. A five to one ratio pump, for example, with an input pressure of 20 lb/in2 will deliver 100 lb/in2. This type of pump, though, is not recommended where low pressures are required. This is because the lowest output will be a multiple of the minimum pressure which is needed to operate the pump. The other main disadvantage of reciprocating pumps is that the delivery pressure fluctuates quite considerably when the piston changes direction. This is likely to cause problems with adhesive face seals, which are less able to cope with cyclic variation than with constant pressure.

Unfortunately, high pressures at a constant value are difficult to attain; rotary pumps can achieve this, but are only suitable for specific materials, and where high flow rates are expected. These pumps impart heat to slow-moving fluids, and grouts will cure more quickly under such conditions. The end result in such a case will be blocked injection lines and a seized pump.

All the equipment described above operates on a batch principle—a batch of grout is mixed and injected, after which injection must stop while another batch is mixed and placed in the equipment. It was explained in Chapter 4 that resin grouts consist primarily of a resin and a hardener or catalyst, and the chemical reaction starts as soon as the components are mixed together. This means that the viscosity of the grout will gradually increase while each batch is being used and, depending on the rate of cure of the particular formulation, it may make an appreciable difference to the way in which the grout penetrates the crack. Also, it is essential to clean out all equipment, including delivery lines, immediately work stops for any appreciable length of time, in order to prevent its becoming blocked with hardened resin. This may cause problems in the event of a breakdown.

It is now increasingly common practice on all but small jobs to use powerdriven equipment in which the resin and hardener do not come into contact with each other until they reach the injection head. The two materials are contained in separate reservoirs and are fed through separate metering pumps and hoses to a self-mixing injection head. The rates of delivery through the pumps can be adjusted, and the flow is controlled at the point of injection. Consequently, the only part of the equipment that is at all likely to become blocked is the nozzle, which can either be removed and cleaned in solvent, or discarded. Until recently few machines had been designed specifically for resin grouting; reciprocating pumps and pressure pots are normally tools for paint application. They are suitable for resin injection on account of their components' being able to resist attack from organic cleaning solvents. Further to this, they are powered by compressed air, which is a preferred power source within the construction industry. Injection pumps are now available which are specifically designed for resin injection. These range from specially modified paint and process pumps to suit the range of pressures required for resin injecton, to *state of the art* machines (an example of which is shown in Figure 5.1), which have been developed for resin injection.

Where cementitious grout is preferred, the range of purpose-designed machinery is quite extensive. Equipment does not have to cope with organic

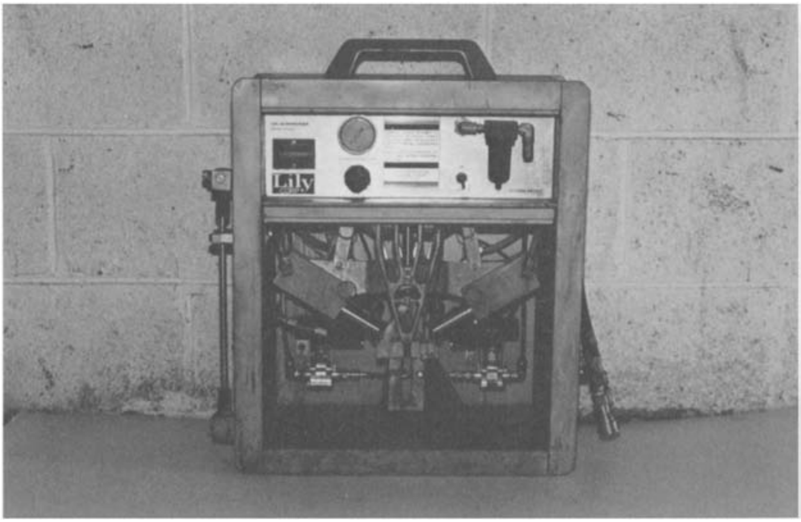

Figure 5.1 Two-component, air-driven metering pump. (Photograph courtesy of Balvac Whitley Moran)

solvents, but it must be able to withstand quite a high level of abrasion. Reciprocating and rotary pumps are both commonly used, and these are linked directly to twin mixing vessels to ensure a constant flow. Cementitious grouts are often used in vast quantities and, compared with resins, the flow rates encountered may be many times higher.

5.4 Further movement expected

If there are signs of continuing movement at a crack, it is usually necessary to make provision for it to continue after repair. The crack can be regarded as an unplanned movement joint and, if it is locked solid, another crack will often form nearby. The movement must be considered in terms of strain rather than absolute magnitude, and the strain capacity of the sealant must be at least as great as the strain that has to be accommodated. At anything other than a very wide crack, a small amount of movement represents a considerable strain if it all occurs within the width of the crack, and the strain capacity of any practicable sealant can easily be exceeded (Figure 5.2). Consequently, the movement must be spread over a greater width so that the resulting strain is compatible with the sealant to be used (11, 12, 13, 15, 16).

One way of achieving this is to cut a chase along the line of the crack. The sealant must then be adhered to the sides of the chase but debonded from the bottom so that the movement is spread over the full width of the chase as shown in Figure 5.2. A debonding strip of a material such as smooth plastic is laid in the

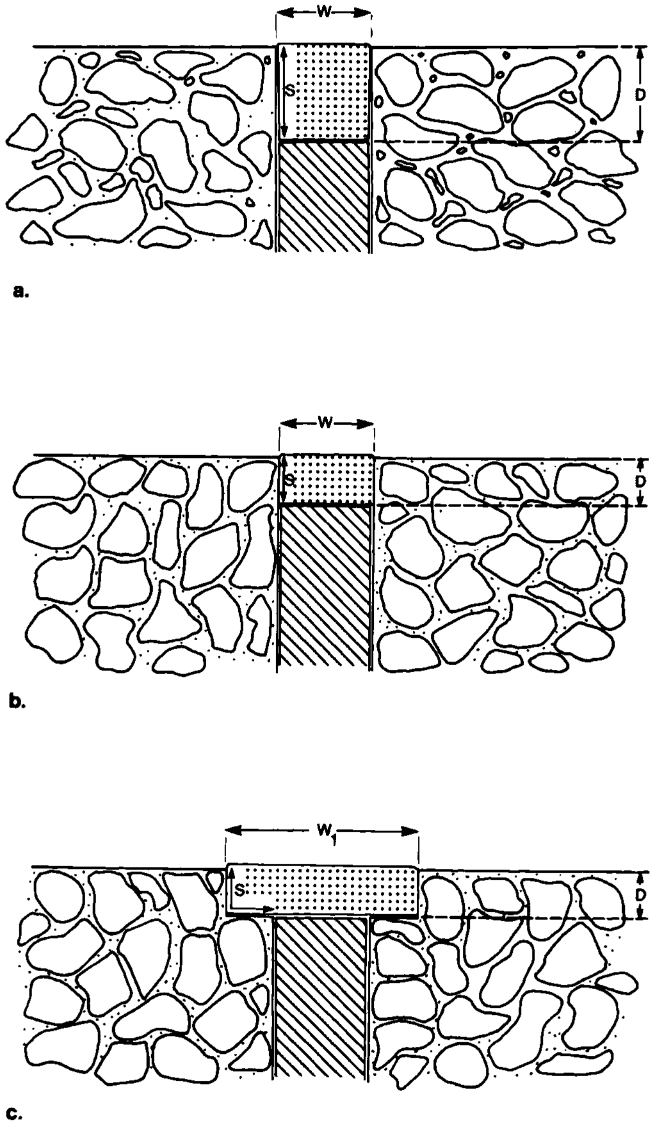

Figure 5.2 Expansion joint detail

bottom before the sealant is applied. The dimensions of a seal are integral to its performance. Consider the case shown in Figure 5.2 which represents a sectional view through a typical movement joint. The depth of the sealant *D* is equal to *S* which is the surface available for adhesion on either side of the joint. *W,* the width of the joint, is equal to *D,* so any movement which places the sealant in shear or tension will exert considerable stress on the adhesive interface with the concrete. If movement is excessive, the seal will probably fail. The second diagram shows a better situation where, although *D* is still equal to *S,* the width of the sealant is twice that value. This means that for any one situation, the force exerted will be considerably reduced. In the third diagram, *S* has been doubled, and the top surface of the sealant W_1 is twice the value of *W*. The depth of the seal is half the width of the joint, half of the area available for adhesion and a quarter of the top surface measurement. In this situation the face seal will cope with extensive movement without exerting excessive stress on the adhesive surfaces. Alternatively, the sealant may consist of a surface bandage of elastic material which adheres to the concrete at its edges only. This may be a pre-formed strip, or it may consist of several layers of a high-build coating material with suitable elastic properties. In either case it is applied over a slightly narrower strip of debonding material.

The colour of the sealant can be chosen so as to be relatively inconspicuous, but it is not practicable to hide a crack at which provision is made for movement.

5.5 Vacuum impregnation

This is a patented process, known in Britain as the Balvac process.

In cases where a large number of cracks occur over an area, the affected part of the structure is enclosed within an air-tight plastic cover that is sealed to the surface of the concrete at its edges, and a vacuum is applied so that air is exhausted from all cracks and crevices in the concrete within the cover. Resin grout is then admitted and atmospheric pressure forces it into cracks and pores in the concrete surface. In order to ensure that the resin can flow into the whole of the area under the cover it is usual to fix a layer of net material first so as to provide a slight space between the cover and the concrete surface. On completion of impregnation, the cover and net are removed before the resin hardens. Clearly, any cracks that pass right through the concrete must be sealed first in order to prevent unwanted ingress of air.

This process must be carried out by experienced operators who can select appropriate impregnants and degrees of vacuum for any particular circumstances. It is particularly applicable for treating concrete surfaces that contain a large number of cracks, such that it would not be an economical or practical proposition to attempt to seal them individually. It is also used extensively as a means of reducing the permeability of weak concrete or masonry and sometimes as a preliminary to patching spalled concrete.

Vacuum can also be used to assist with conventional resin injection. When normal pressure injection methods are used for sealing cracks that do not pass right through the concrete, there is a danger that pockets of air may become trapped at the back of a crack. This risk is greatly reduced with vacuum impregnation because all except a very small amount of residual air is exhausted from the cracks first. Another problem that occurs occasionally during pressure

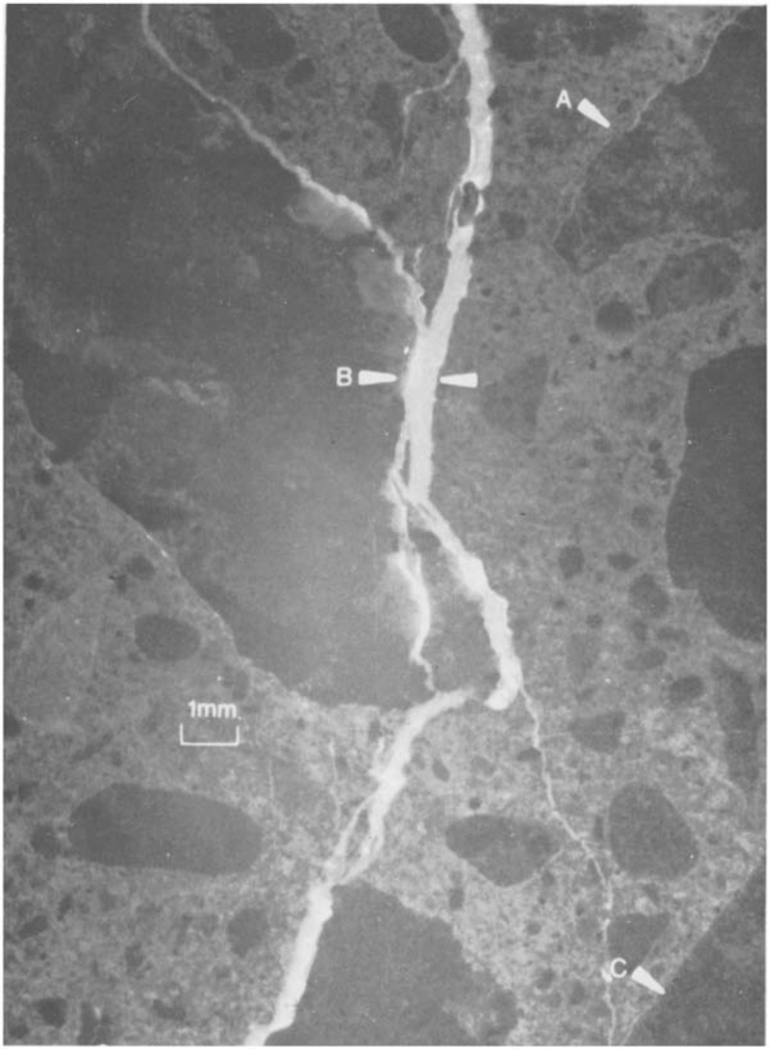

Figure 5.3 CXL 600 low-viscosity epoxy resin injected into cracked concrete. Crack widths: A, 0.015 mm; B, 0.5 mm; C, 0.02 mm. (Photograph courtesy Colebrand Ltd)

injection is leakage of grout into movement joints. Repair materials suitable for concrete are rigid when cured and may be capable of bridging movement joints. This is unlikely to occur with vacuum impregnation because a vacuum will not be established in an open joint.

When very fine cracks have to be sealed it is necessary to use a resin with very low viscosity, and some of these are moisture-sensitive. If the cracks pass right through the structure they can be dried out by drawing dry gas through them with the vacuum equipment before the resin is introduced.

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6
Spalled concrete: hand-applied repairs

R.T.L.ALLEN

6.1
Diagnosis

Before any repair is carried out the causes of the damage must be identified. There may be more than one factor involved, and the probable sequence of events leading up to the damage must be established. In the case of spalled concrete it is particularly necessary to distinguish between mechanical damage and spalls caused by corrosion of reinforcement. Mechanical damage is usually relatively simple to repair. Corrosion of reinforcement, however, may be caused by contamination of the concrete with aggressive ions such as chlorides or by reduction in alkalinity of the concrete (1, 2, 3) and in either case restoration of the damaged member to its original state may be inadequate.

Once the cause of damage has been determined, the objective of the proposed repair must be considered. This may be one or more of the following:

Restoration of durability
Restoration of structural strength
Increase of structural strength
Restoration or improvement of appearance
Restoration of fitness for use.

This list does not imply any order of importance, but it is probable that durability will figure prominently in the objectives of most repairs.

6.2
Preparation

Whatever the cause of damage, preparation of the structure for repair is vitally important. Application of a sound patch to an unsound surface is useless because the patch will eventually come away, taking some of the unsound material with it. Similarly, contamination that has once caused trouble must not be allowed to

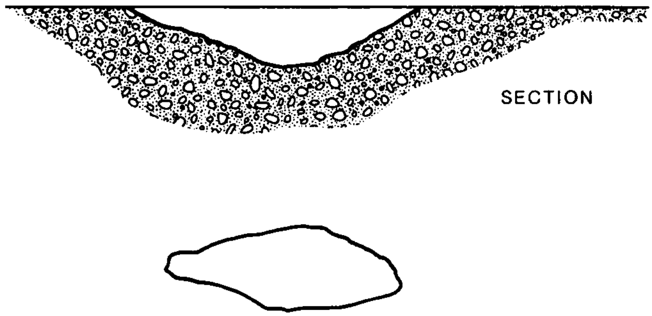

Figure 6.1 Incorrect method of cutting out

remain where it is likely to cause trouble again. Any attempt to take short cuts over preparation is a false economy.

The first step must be to remove unsound concrete. The area to be cut out should be delineated with a saw cut to a depth of about 5 mm in order to provide a neat edge but the remainder of the cutting out can be done with percussive tools. Feather edges should be avoided if at all possible—edges should be cut normal to the surface or slightly undercut, for a depth of at least 10mm as shown in Figures 6.1 and 6.2. If any corroded reinforcement is present the concrete should be cut back far enough to ensure that all corroded areas are exposed so that they can be cleaned, and with bars of small diameter this will usually involve exposing the full perimeter. In case of doubt it is better to remove more concrete than strictly necessary rather than too little. If the cause of reinforcement corrosion was an inadequate depth of cover, it may be possible either to move the reinforcement back from the face or to build out the concrete when it is repaired.

Carbonated concrete will not protect reinforcement from corrosion, so the concrete must be cut back far enough for carbonated concrete in contact with the reinforcement to be replaced with something that will protect it, such as fresh concrete or an impermeable resin compound. Quite extensive cutting out may be required and temporary structural support must be provided if necessary. The concrete can be tested for carbonation as cutting-out proceeds by means of a phenolphthalein spray, as described in Chapter 2, section 2 but care must be taken to ensure that the surface being tested is not contaminated with dust from other parts of the concrete, which could give misleading results. Ideally, all concrete that is contaminated with chlorides should be removed, but that would often involve complete removal of a structural member or even demolition of the structure. No clear safe limit for chloride content can be laid down, but work carried out at the Building Research Establishment indicates that a chloride ion content of not more than 0.4% by weight of cement is unlikely to cause damage for a considerable number of years (4). In practice, all chloride-contaminated concrete that has clearly caused trouble should be removed, together with as much other contaminated concrete as is practicable, and the probability of further

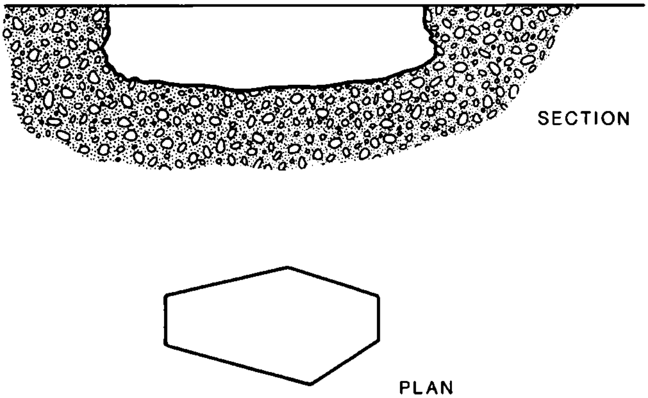

Figure 6.2 Correct method of cutting out

corrosion in the future must be accepted. It may be possible, by electrical potential mapping techniques, to identify areas where future corrosion is most probable, in which case they also should be cut out and repaired if possible (5). This technique is described in Chapter 2, section 2.3.3.

Some practitioners recommend the application of corrosion-inhibiting chemicals such as phosphates to exposed reinforcement after it has been cleaned. These materials form part of some commercial systems that have been shown to be successful in the hands of experienced operatives, but the non-specialist would probably do better not to use them because of possible harmful effects on the bond of the repair material. It is advisable, however, to provide some form of protection for reinforcement as soon as reasonably practicable and the type of material to be used will be governed largely by the repair material selected. A slurry coating of polymer latex and cement can be used if a cement-based repair is to follow. Resin-based coatings are obtainable that are suitable for use with cement-based and with resin-based repair materials, and these are sometimes blinded with coarse sand in order to provide a key for the subsequent patch. Unless the patch is to follow immediately, these coatings should be applied to the reinforcement only and not to the concrete, because they reduce the strength of the bond between old and new concrete if they are allowed to dry out.

Dust should be removed, as far as possible, from the surface of the concrete before patching material is applied, especially when resin-based compounds are to be used. Oil-free compressed air jets are effective on small areas but they tend merely to redistribute dust on large areas. For these, industrial vacuum cleaners can be more effective.

6.3 Choice of material

The basic choice of repair systems is between those based on Portland cement and those based on synthetic resins. In reinforced concrete, they protect the reinforcement from corrosion in different ways. Cement-based materials provide an alkaline environment for the steel (pH of the order of 12) and, in these conditions, a passivating film forms on the surface of the steel. Corrosion will occur if the alkalinity of the concrete surrounding the steel is reduced by carbonation—i.e. a penetration of carbon dioxide from atmosphere—or if aggressive ions such as chlorides are present (1). Consequently, the provision of an adequate thickness of dense concrete cover is important. Resin-based materials do not generally provide an alkaline environment: they normally rely for their protective effect on providing cover that will exclude oxygen and moisture, without which corrosion will not take place.

It is usually desirable that the mechanical properties of the repair material should resemble as closely as possible those of the structure being repaired. This means that, as a general rule, careful consideration should be given to the use of cement-based repairs. They can be made relatively inconspicuous although it is very difficult to hide them altogether without using an overall coating. They can provide fire resistance, while resins soften at relatively low temperatures. Cement is cheaper than resins but this is seldom the deciding factor because labour usually accounts for a large proportion of repair costs. Most building operatives are more familiar with the use of cement-based material than with resins.

For some applications, however, resins are more suitable. Their properties can be adjusted within fairly wide margins by suitable formulation so that they can, to some extent, be tailored to fit the job in hand. This is particularly valuable when working time is limited and rapid curing is required. Sometimes the thickness of cover to reinforcement is less than it should be and it may not be possible to increase the dimensions of the member or to move the reinforcement. In these cases resin mortars may provide less permeable cover then cement mortar although the permeability of the latter can be reduced by incorporating polymer admixtures. Sometimes feather edges cannot be avoided and, although polymer admixtures may make it possible to use cement mortar patches, resin mortars are often more suitable. Some compounds are not suitable for use in confined spaces and good ventilation is always desirable (6, 7).

Heat is evolved while resin compounds cure and, in general, the faster the cure the greater the rate of heat evolution. This may not be important in the case of a small patch from which heat can escape easily, but there may be a considerable temperature rise in a patch with a small ratio of surface area to volume, and this may give rise to unacceptably high thermal stresses as the material cools. For a similar reason too great a volume of material should not be mixed in one batch. The rate of reaction is both exothermic and temperature-dependent so the rate of stiffening will gradually accelerate as the temperature rises and the result can be that the resin solidifies in the container before it can all be used.

6.4 Application: cement-based material

After the work has been prepared as described above a bonding coat should be applied to all exposed surfaces. This should be done with a minimum of delay but if necessary the surfaces should be cleaned again immediately before the bonding coat is applied.

The greatest concrete-to-concrete bond strength can be achieved under laboratory conditions by placing concrete against a prepared surface that is saturated with water but surface dry (8) but in addition to this, the use of a bonding coat is advisable under site conditions. It can consist of a slurry of cement and water only, but it is nearly always desirable to incorporate a polymer admixture.

Typical proportions would be 2 parts (by volume) of cement to one part polymer latex, but the supplier's advice may vary. Alternatively, some polymers are used alone, without any cement addition. With most polymer materials it is advisable to wet the exposed concrete beforehand and allow the surface to become just dry, but the supplier's instructions should be followed. Whatever material is used, it must be worked well into the exposed surface. It is possible to achieve satisfactory results without using a polymer, given thorough workmanship and close attention to detail, but a polymer provides some additional adhesion. It must be remembered however that no admixture will compensate for inadequate preparation or poor workmanship.

The first layer of patching material should be applied immediately after the bonding coat, while the latter is still wet. This is most important because a bonding coat that has been allowed to dry out will reduce bond instead of increasing it. If there has been an unavoidable delay it may be necessary to repeat the final stages of preparation in order to expose a fresh surface but, if a polymer admixture has been used and the delay has not been too long, it may be possible to proceed by applying a second polymer-modified bonding coat, although usually there will be a reduction in bond strength. This will depend on the particular material used, and the supplier's advice should be followed.

If some delay is inevitable there are some resin-based bonding agents that have a longer 'open time' than cement slurry. There are also some resin coatings that are blinded with coarse grit while they are still sticky and then allowed to harden, in which case the grit provides a key for the subsequent patch. These have the advantage of permitting greater flexibility of timing. Resin coatings do not in themselves provide an alkaline environment in immediate contact with steel reinforcement and hence do not cause the formation of a passivating layer as described in section 2.2. There are some proprietary systems in which a resin containing ground Portland cement clinker is used, which may provide some alkalinity.

If reinforcing bars cross the repair they may provide a good mechanical anchorage for the patch, especially if the concrete has been cut away behind them. If this is not the case, however, it is often advisable to provide some mechanical anchorage for the patch by means of dowels drilled and grouted into the surrounding concrete or by fixings fired in with a cartridge gun, depending on the size of the repair. There should be a good bond between repair and existing concrete if the work is executed correctly, but some shrinkage will occur and provision of a positive anchorage is a wise precaution, especially when the repair is some distance above ground level.

Hand-applied repairs usually consist of cement and sand mortar in proportions of about 1:2.5 or 1:3, using a sharp concreting sand in grading zone M of table 5 of British Standard 882 (9) for the bulk of the work. If a smooth surface finish is required it may be necessary to use a finer sand for a final layer. Lightweight fine aggregates are sometimes used, especially in overhead work, and some proprietary pre-packed materials are available that contain cement and specially-graded sands in correct proportions. It is usually beneficial to incorporate a polymer admixture such as styrene-butadiene rubber (SBR) or an acrylic emulsion, because they improve adhesion to the substrate and increase the strain capacity of the repair mortar, thus reducing the risk of debonding or cracking as a result of shrinkage or thermal stresses. They also reduce the permeability of the mortar, so giving it some self-curing ability and increasing its ability to protect reinforcement. A commonly-used concentration is 10% polymer solids in the mortar but, as usual, the suppliers' instructions should be followed. Many of the pre-packed materials contain a polymer in addition to cement and sand.

Polymer-modified mortars should usually be mixed using a forced action mechanical pan mixer, often known as a cretangle mixer, because of the tendency for the polymers to entrain air in the mix. They increase workability, and any addition of water must be made very carefully in order to prevent the production of an over-workable mix. Repair mortar should be as stiff as possible consistent with full compaction, and it should be rammed into place as forcefully as possible. An experienced operative can judge the degree of workability that is best suited to a particular job.

Repairs should be built up in layers, and each layer should normally be applied as soon as the preceding one is strong enough to support it. The thickness of each layer should not normally exceed 20 mm. If there is likely to be a delay between layers, the first should be scratched as in normal rendering practice in order to provide a key (10, 11), and a fresh bonding coat should be applied when work is resumed. Here again, experience is valuable.

6.5
Application: resin-based material

The requirements for preparation for resin-based repairs are generally similar to those for cement-based repairs. Removal of dust is particularly important and it must be remembered that the repair material will have mechanical properties that differ from those of the substrate. Consequently, stresses may be set up at the interface as the resin cures, so the provision of a clean, sound substrate is essential.

Resin based materials are usually supplied as two or three constituents that must be mixed together immediately before use. This must be done really thoroughly, especially when epoxy resins are involved, and the use of mechanical mixers or stirrers is advisable. If hand mixing is unavoidable, flat stirrers must be used. The use of lengths of reinforcing bar or round dowel is invariably unsuccessful. It is essential, also, that the materials should be correctly proportioned, and it is common practice to supply the constitutents in pre-batched packs so that the use of a full pack of each constituent will give the correct proportions. This means, also, that care must be taken to ensure that the complete contents of each pack are used. Stirrer heads are available designed so that they will scrape the sides and base of a cylindrical can and ensure that nothing is left unmixed. A very large proportion of failures of resin-based repairs have been traced to incorrect proportioning or inadequate mixing, and any attempt to use parts of packs is likely to lead to failure.

Resins include such a wide range of materials that, inevitably, there will be exceptions to every rule. General guidelines can be given, but the formulator's instructions should be followed in any particular case. It is usually necessary to apply a primer or tack coat of unfilled resin to the freshly-exposed surfaces of concrete and reinforcement as soon as possible after preparation has been completed. In general one coat will be enough, but two may be needed in some cases, especially if the substrate is porous. If two coats are applied, the first must not be allowed to cure too much before the second is applied, and the formulator's instructions should be followed.

With the majority of resin-based systems the patching material must be applied while the primer is still tacky, and each successive layer of patching material must be applied before the previous one has cured too much. Here again there are exceptions and some systems require certain minimum curing periods between priming and patching, or between successive patching layers.

Resin-based materials cure by chemical reaction which starts immediately the constituents are mixed, so they have a limited 'pot life'. In general, the pot life decreases with increasing temperature and, since the reaction is exothermic, the temperature of the material will gradually rise and its rate of stiffening will increase. This must be borne in mind when repair work is being planned, and the quantity of material to be mixed in any one batch must be chosen so that it can be used before it becomes too stiff. It is essential that resin-based patches should be well compacted and impermeable: they do not provide an alkaline environment for the reinforcement so they must protect it by excluding oxygen, moisture and any other corrosive influences.

Tools must be cleaned occasionally during use and again immediately afterwards, because it is extremely difficult to remove hardened resin. Normal safety precautions for the use of resins and hardeners should be taken: gloves should be worn, splashes should be washed off the skin but solvents should not be used for this purpose, adequate ventilation should be provided, and smoking, eating or drinking should be prohibited. More detailed advice on safety precautions is obtainable from the Federation of Resin Formulators and Applicators (6, 7).

6.6 Curing

Resin-based repairs do not generally need any protection during their curing period, which is usually quite brief. Cement-based repairs usually do require some initial protection, because rapid drying out could halt the hydration of the cement and lead to shrinkage cracking, delamination and weakness.

Repairs consisting of cement, aggregates and water without any polymer addition are particularly vulnerable because they are often relatively thin and could dry out quickly if unprotected. Careful curing is essential by covering with absorbent material that is kept damp, preferably covered in turn by polythene or similar sheets which are sealed at the edges. Shading from the sun may be necessary. Above all, alternate wetting and drying must be prevented because of the alternating stresses that it would cause. Sprayed-on curing membranes can be used after the complete patch has been applied, but they cannot be used between layers of a multi-layer repair because they would prevent bond between layers. For the same reason, they should not be used on a completed repair if a surface coating is to be applied later (12).

If repairs are to be carried out during hot weather it is advisable to shade the work from direct sunlight in order to prevent drying out of cement-based repairs or over-rapid stiffening of resin-based materials. It may be possible to time the work so as to follow the sun round but, in other cases, shading may be necessary.

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7
Sprayed concrete

W.B.LONG

7.1
Introduction

An American big-game hunter and naturalist, Carl Akley, developed a cement gun apparatus before 1900 for the purpose of spraying plaster on to wire mesh models of animals. This led him to take out a patent in 1911. Although the technique was unsuccessful for this purpose, the possibility of being able to spray thin layers of fine concrete on to existing structures was soon realized, and its use rapidly developed. By the 1930s, considerable expertise had been developed in the use of the gunite technique as it became generally called, for repair and new construction work both in the USA and Europe. These included major repairs to buildings and structures, and waterproof linings to new tunnels in Berlin and under the River Mersey. From 1945 onwards, a big upsurge in repair work took place brought about by a need to catch up with repairs necessarily held over and those resulting from war damage. There was also an increased volume of maintenance work required on concrete structures built from the 1920s onwards. The gunite process was undoubtedly one of the most satisfactory repair methods then available.

Careful study of earlier repair works carried out, and of the engineering principles involved, enabled the basic specification principles still in use today to be developed, although we had to wait until recent years for a more precise understanding of the causes of deterioration, particularly of the effects of carbonation of concrete, and of the presence of chlorides, enabling the full significance of these factors to be clearly investigated and documented.

Today, the essential principles to be followed are well understood. A thin layer of high quality fine concrete can be sprayed on to the surface of a structure to which it will bond strongly, restoring the protective cover to the steel reinforcement, making good concrete that has spalled or become abraded, and producing an acceptable appearance.

7.2
Definitions of terms used

The following terms are used in referring to sprayed concrete and may have different meanings from those commonly ascribed.

Sprayed concrete, gunite and shotcrete. Gunite and shotcrete are variously used to refer respectively to sprayed concrete where the aggregate is less than 10 mm, and 10 mm and upwards maximum size. They also apply respectively to Dry Process and Wet Process sprayed concrete. Probably the terms are best avoided, except in the traditional use of 'gunite' to refer to Dry Process Sprayed Concrete where the maximum aggregate size is less than 10mm.

Layer. Layer is a discrete thickness of sprayed concrete built up at one time by a number of passes of the nozzle, and allowed to set. 'Flash coat' is a thin layer of sprayed concrete applied to protect, prime or finish the surface.

Rebound and overshoot. Rebound and overshoot is all material which, having passed through the nozzle, has not been compacted into a dense homogeneous mass by compaction on the interface in accordance with the definition of sprayed concrete.

Interface. Interface is the surface on to which sprayed concrete is being applied —that is a prepared surface of a structure or a previously applied layer of sprayed concrete.

Sprayed concrete. Sprayed concrete is a mixture of cement, aggregate and water projected at high velocity from a nozzle into place against an existing structure or formwork where it is compacted by its own velocity to produce a dense homogeneous mass. Sprayed concrete is placed by either the Dry or Wet Process.

Profile guides. These are rigidly fixed timbers or stretched wires positioned as guides to the line and thickness of the placed sprayed concrete.

7.3
The dry and wet processes

7.3.1
Dry process sprayed concrete

Dry process sprayed concrete is that technique whereby a pre-determined ratio of cement and aggregate is batched and mixed without added water. The mixture is loaded into a purpose-designed machine wherein it is pressurized; an even flow of the mixed material is introduced into a high velocity air stream and conveyed through flexible hoses to a discharge nozzle (see Figure 7.1). At this nozzle a finely atomized spray of water is added to the stream of materials in sufficient quantity to hydrate the mix and to provide the right consistency so that the uninterrupted stream of materials can be projected at high velocity into place (see Figure 7.2). The impact compacts the material to form the required quality

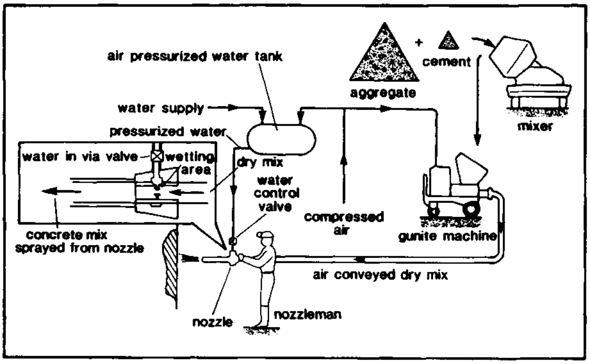


Figure 7.1 The gunite process

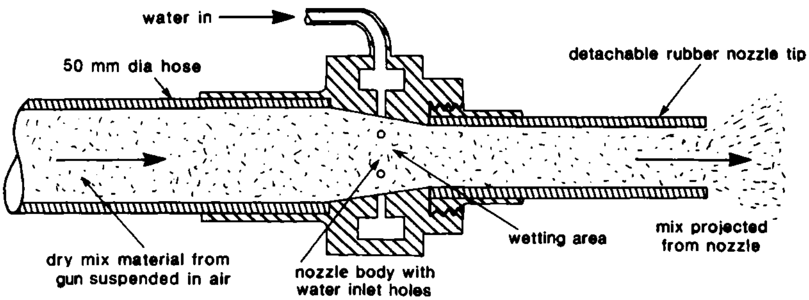


Figure 7.2 Typical dry mix nozzle

concrete. As no water or admixtures are required to give workability during transporting or to achieve compaction, dry process sprayed concrete with suitable aggregates and aggregate: cement ratio can be placed at low water: cement ratios, with no-slump characteristics that enable it to be placed to limited thicknesses on vertical and overhead surfaces.

Admixtures can be introduced in powder form into the dry pre-mix, or in liquid form with the added water at the discharge nozzle or as a separate injection at that nozzle. Steel and other fibres can be incorporated in the premix.

Equipment offering a wide range of throughputs is available, allowing a range from carefully controlled low rates for application in thin layers or on awkward or intricate structures, to high rates of application of considerable thicknesses on larger areas and straightforward configurations.

The application nozzle is generally hand-held and the stream of materials is directed by the nozzleman, who can also adjust the amount of added water. It should be noted that added water can only be varied within a limited range, as too little water will prevent the mixture compacting into a homogeneous mass, and too much will make it over-workable and it will slump off. Remotely-controlled nozzle assemblies are available and are particularly used in tunnelling work where they enable the sprayed concrete to be placed in situations that would be potentially hazardous for a nozzleman. They also avoid the need for temporary access in order to place the material at a height above the tunnel invert.

7.3.2
Wet process sprayed concrete

Wet process sprayed concrete is that technique whereby a pre-determined ratio of cement, aggregate and water is batched, mixed and loaded into a standard or purpose designed concrete pump. The suitably workable concrete is pumped along flexible hoses to a discharge nozzle, where a supply of high pressure compressed air is introduced so as to project the concrete at high velocity into place where it compacts to form the required quality concrete.

Admixtures can be introduced into the premix to improve the workability or modify the setting properties of the concrete. A rapid setting admixture is commonly used to facilitate build-up of thick layers of material and this is usually introduced as an additional spray at the discharge nozzle; otherwise early set might take place within the delivery hoses.

The equipment used generally has medium to high throughput, as there are problems in pumping concrete for any distance through the small-diameter hoses which would be needed for low throughput work.

The application nozzle is generally hand-held as for the dry process but the nozzleman controls the placing of material only, the mix proportions and added water being predetermined at the batching and mixing plant.

7.4
Plant and equipment

Conventional concrete weigh batching and mixing plant is used, usually of the reversing drum or tilting drum type. Cement silos for bulk handling may be used on larger contracts, although the use of bagged cement for site mixing is more usual. Suitable facilities for off-ground storage and protection of cement and aggregates from rain and frost are required. Alternatively, bagged premixed cement and aggregates are available for the dry process, with or without admixtures such as rapid setters and steel fibres. Ready-mixed concrete may be used for the wet process, to obviate the need for site batching and mixing.

Equipment used for the dry process includes both double-chamber and rotating-barrel machines. In double-chamber machines, the lower chamber is pressurized to a constant level and contains a rotating feedwheel. The material in the lower chamber falls into the rotating feedwheel which carries pockets of material round in its spokes until each pocket comes opposite the outlet. At this point the pocketful of material is picked up by a high pressure air stream and carried into and along the delivery hose.

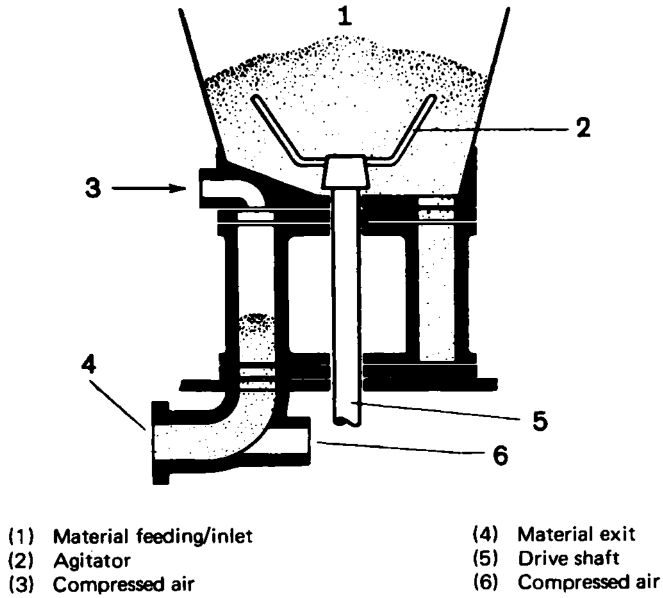


Figure 7.3 Rotating barrel machine: detail of barrel (Aliva Ltd)

The upper chamber can be isolated from the lower by a valve, so that it can be de-pressurized and loaded with mixed material, then re-pressurized to equal pressure with the lower, when the valve can be opened and the material allowed to fall through to re-charge the lower chamber. In rotating-barrel machines, which have now largely superseded double chamber machines, a series of chambers in a rotating barrel are filled in sequence with mixed material by gravity from an overhead hopper, are pressurized as they rotate under a compressed air inlet, discharge their material into the delivery hose as they rotate over the discharge port, and finally are de-pressurized ready for reloading and a repeat of the cycle (see Figures 7.3, 7.4).

Machines available from reputable manufacturers each have different characteristics and applications. All are capable of transporting and placing satisfactory sprayed concrete or mortar and the choice of machine can be left to the experienced contractor.

Special nozzle assemblies are available from the same manufacturers, which ensure compatibility with the machines and efficient control and injection of the added water into the stream of dry material. Water is supplied to the nozzle through small diameter flexible hoses, the pressure being maintained at 1.0 to 1.5 atmospheres above the pressure in the material delivery hose, either by supplying from a pressure tank maintained at a suitable pressure, or by a constant pressure pump.

Wet process plant is similar to standard concrete pumping equipment and some purpose-designed plant is available. A steady flow of concrete, rather than

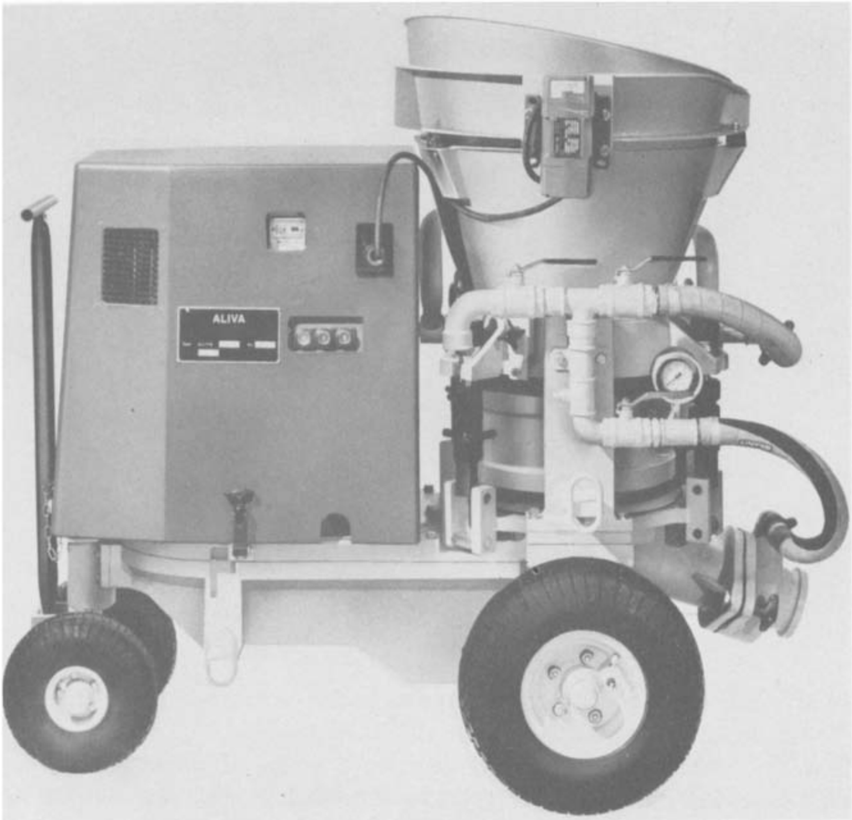


Figure 7.4 Aliva-260 conveyor (Aliva Ltd)

a pulsating flow, is desirable so that the nozzleman has a constant feed to handle. Delivery hoses of flexible construction are typically 50 mm to 75 mm diameter and the discharge nozzle looks similar to the dry process nozzle, except that there is a separate air supply to the nozzle instead of a water supply. Some nozzles have provision for the introduction of admixtures such as rapid setters in addition to the air supply.

7.5 Properties of the two processes

7.5.1 *Dry process sprayed concrete*

Dry process sprayed concrete is a very flexible technique, capable of wide variation in throughput, able to handle virtually all types of cement and a wide variety of conventional and lightweight aggregates up to 10 mm or even 20 mm maximum size, but there is usually no advantage in using material over 10 mm.

The range of aggregate: cement ratio mixes that can be sprayed is limited and the range typically used in repair work is 3.5:1 to 4.0:1 by weight. Because the rebound is mainly aggregate, the placed mix will be richer in cement than the pre-mix.

Characteristics of dry process sprayed concrete when in place are good density, high strength (typically 40 to 50 N/mm^2) and very good bond to a suitable substrate. Properties tend to be more variable than conventional concrete or wet process sprayed concrete. Dry process sprayed concrete is suitable for both large and small jobs and the equipment does not take long to set up on site and get into production, being simple and light in weight. With good quality control, experienced contractors and operatives can achieve excellent results and it is the process most commonly used in repair work.

7.5.2
Wet process sprayed concrete

Wet process sprayed concrete is probably more suited to the application of relatively large quantities of sprayed concrete, typically in new construction work. It is necessary to provide a supply of concrete of uniform workability to an appropriate mix design for pumping and this is often done from ready-mix plants. The range of cements, aggregate: cement ratios, maximum aggregate size and grading is limited to what will give a pumpable mix with the equipment to be used. A higher water: cement ratio than that in the dry process will be necessary to achieve pumpability. The placed mix is normally similar to the pre-mix.

Characteristics of the placed wet process sprayed concrete are good density, average strength (typically 20 to 40N/mm^2) and good bond to a suitable substrate.

7.6
General specification for repair work

Where a concrete structure is in need of repair, the cause of deterioration must be identified before the repair can be specified.

The object of the repairs will be to replace concrete that has been lost or cut away and to increase effective cover to the steel reinforcement or against future damage by adding additional concrete if required.

Where the concrete itself has contributed to the corrosion of the steel, i.e. it has become carbonated or contains an unacceptable amount of chlorides, such concrete must generally be removed back to unaffected material, even though it is physically sound. This removal is often difficult and very costly but can only be omitted after careful consideration of the potential effect on the durability of the repairs. Nevertheless, in some cases where removal of all such concrete would effectively demolish or seriously weaken a structure, or where it would be very difficult to replace with sound material, a decision may have to be taken to limit the cutting out. In any case, it should be realized that carbonated concrete is not in itself harmful. It will no longer inhibit corrosion if the other factors causing corrosion, i.e. oxygen and water, are present, but the presence of carbonated concrete within a repaired structure, especially when adequate additional protection has been applied, may be totally harmless.

Unless the defective portions of the structure are only a small part of the whole, the recommended method or repair will be to encase the whole of the accessible, external surfaces with a specified minimum thickness of sprayed concrete, which is brought out to a uniform profile and eyeable lines by additional infilling of the areas of defects cut away.

To achieve this, the sprayed concrete may be applied over areas of undamaged concrete, and the surface of this must also be prepared by thoroughly roughening to remove all original cement laitance, surface deposits and impurities. Particular care must be taken to remove all traces of coatings or the like which may have been applied, especially if these have had water-repellent properties, as these would prevent a bond developing. In all cases, in order to develop as good a bond as possible, the prepared interface must be sound, rough and homogeneous (i.e. free from shattered or laminated concrete).

Experience has shown that sprayed concrete without polymer or other modifying admixtures should incorporate a welded steel fabric, or steel or other fibres, to minimize the risk of cracks of sufficient size developing to allow penetration of air and water, by encouraging a large number of very fine, insignificant cracks.

A typical fabric for this purpose would be of high tensile steel, 75 mm or 100 mm square mesh, 3 to 4 mm dia. bars, and with such a fabric the sprayed concrete thickness should be 50 mm minimum, which will provide adequate cover to the fabric itself.

The fabric reinforcement should be securely fixed by being tied to shot-fired pins, or by nails driven into plugs set in the parent concrete and bent over to grip it, with spacers to hold it at least 12 mm from the surface. Fixings should be spaced at sufficiently close centres that the mesh cannot belly out during the concrete spraying with consequent lack of cover. The spacing will vary, depending on the mesh stiffness, between 400 and 750 mm (Figures 7.5, 7.6).

The sprayed concrete thickness may be reduced where galvanized or non-rusting steel fabric is used, as less concrete will be needed to provide protection to the fabric itself. The practical minimum thickness, so that the sprayed concrete fully covers the fabric at overlaps and allows for tolerance in fixing, etc., will be found to be 30 or 35 mm.

In the case of sprayed concrete incorporating steel or other fibres, or where a suitable admixture such as styrene butadiene rubber is incorporated in the mix to modify and improve the protective properties of the placed concrete, the specified thickness can be judged by other considerations such as

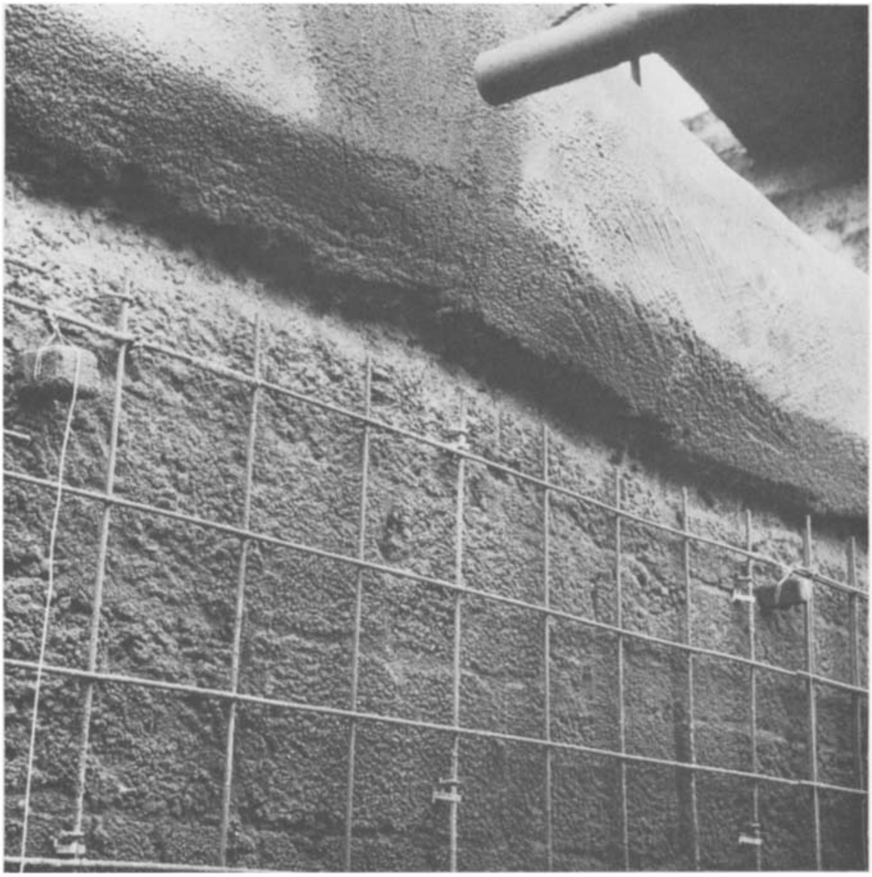


Figure 7.5 Concrete face of dam prepared for sprayed concrete repair with spaced-off mesh and wire profiles

durability, added protection to the original structure, practicability of placing, etc. A thickness of 15 to 20 mm minimum will be found to be the least that can be employed, but greater thicknesses are usual. Additional bar reinforcement can be introduced if necessary, by lap welding on to exposed existing steel, or by other fixing methods as explained in (2). Profiles should always be used as a guide to thickness and to provide eyeable lines on all main arrisses, as without them the thickness of concrete applied can only be judged by eye and considerable variations will occur. Light timbers or stretched high-tensile wires must be securely fixed in the correct position (Figure 7.7), so that they cannot be dislodged by the concrete spray or any hand trimming or finishing operation. A typical method of using timber formers is shown in Figure 7.8.

Chases at least 20 mm wide × 20 mm deep should be cut with pneumatic tools at the perimeter of the sprayed concrete into which the edge will tuck to provide a sound finish at that point. It is important to avoid feather edges.

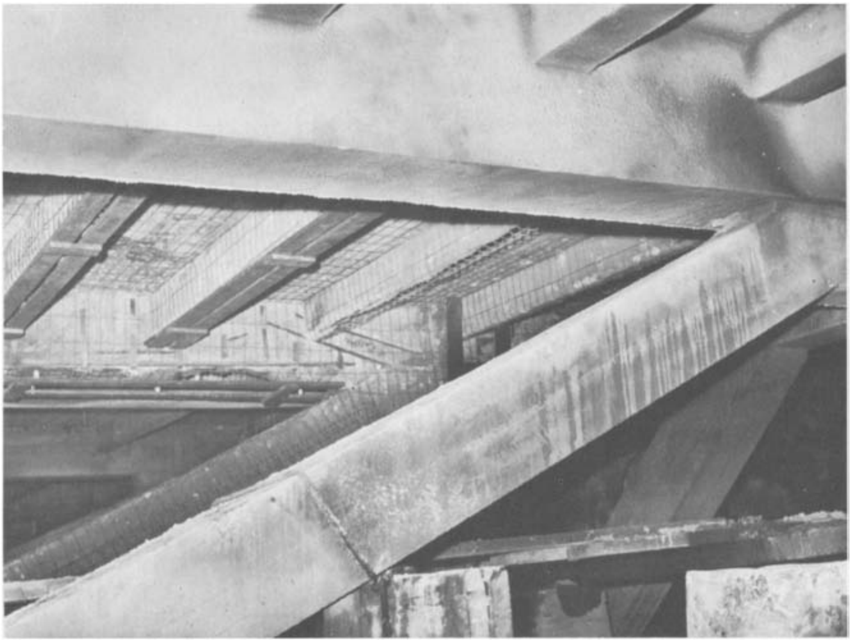


Figure 7.6 Sprayed concrete repairs to quay substructure in progress and completed

The sprayed concrete will normally be specified by type of cement and aggregate, and mix proportions, or by strength. All materials must comply with relevant British, American or other Standard specifications. Ordinary Portland cement is adequate for most repair contracts, but almost any kind of cement can be used where the circumstances require.

Aggregates should be clean, well graded from 10mm to fines, without an excess of fines, clay, silt or dust, and have suitable characteristics for the wet or dry process being used. Typical mix proportions will be 3.5:1 or 4:1 aggregate: cement ratio, and typical specified strengths 30 N/mm^2 at 28 days, with higher figures being required only in special situations. Other characteristics such as flexural strength, absorption and permeability may be of interest and are sometimes specified although there is a lack of standard test methods as yet, and insufficient information on these characteristics and their significance in repair work.

Construction joints are formed at a slope wherever possible, not at right angles as in cast concrete, and typical recommendations are shown in Figure 7.9. The face of the sprayed concrete is normally carried forward at a slope, so that a construction joint of this kind is formed naturally. The interface of the joint must be cleaned of rebound, overshoot and laitance so that a good bond is achieved at the joint.

Figure 7.7 Concrete column with reinforcement and timber formers fixed for sprayed concrete repair

7.7 Particular specification requirements

7.7.1 *Repair of concrete damaged by reinforcement corrosion* (4, 5)

The importance of correctly identifying the cause of the problem cannot be over-emphasized. Wherever possible and practicable, all chloride-contaminated and carbonated concrete must be cut away together with loose, weak, honeycombed or otherwise defective material. Where a significant loss of steel section has occurred, it may be necessary to add new steel, as described in section 7.6.

Concrete should be cut away from corroded steel at the ends of defective patches until at least 75 mm of uncorroded steel is exposed. The exposed steel should be cleaned by abrasive blasting or other appropriate means to remove all rust and scale, so that it is as clean as would be required in new reinforced concrete construction.

The repair should preferably be overall; that is the full length and perimeter of members should be encased in the specified minimum thickness of sprayed

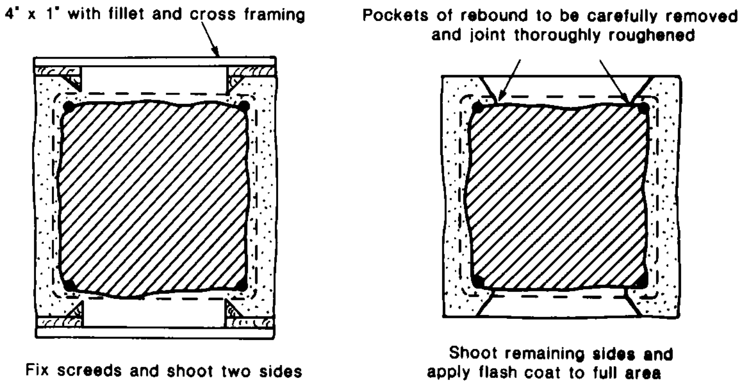


Figure 7.8 Use of timber formers

concrete, with additional infilling to build concrete back to original profile where it has been cut away.

Where the defects are in isolated areas and patchwork repairs are justified, these should extend at least 300 mm on to sound concrete at the perimeter of the defective area and terminate in chases. Rectangular patches are preferable to irregular shapes.

The thickness of the sprayed concrete repair will take account of the need to restore adequate protection to the steel for the anticipated life of the structure.

7.7.2
Repairs to fire-damaged concrete (2)

In this case, it is necessary only to cut away all concrete weakened by the fire, which can be judged satisfactorily by physical strength, i.e. reasonably cut away all concrete that can be so removed with light pneumatic tools.

The repair will be to restore lost strength, which may mean adding steel and further preparation work in order to link this to the existing steel, and adding cover to steel for protection in any future fire and against the environment.

The thickness of sprayed concrete to be applied will be judged on these grounds, but in practical terms it is not worth applying less than 30–40 mm, and 50 mm is the usual amount specified, when a light steel fabric is incorporated.

7.7.3
Repairs to mechanical or physical damage

Chemicals, abrasion, impact, overloading can all damage concrete. In the case of chemical attack, all affected concrete must be identified and cut away; otherwise all weakened or damaged concrete must be cut out, and the repair carried out as described above.

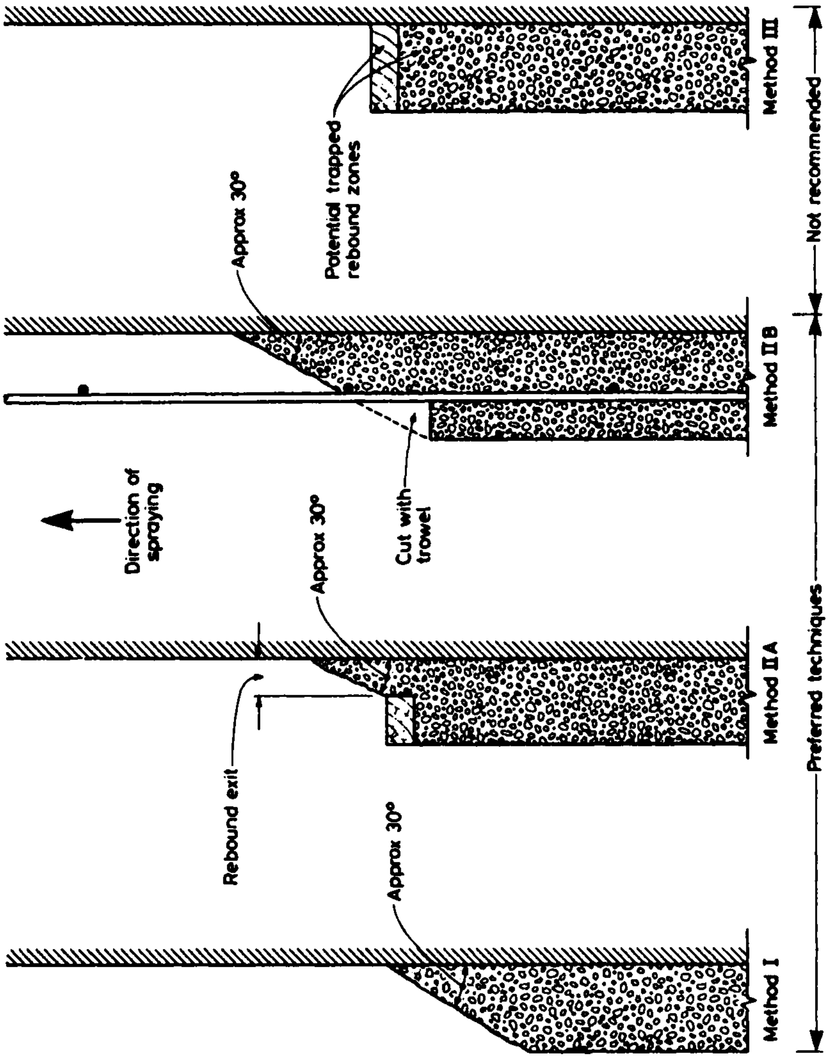


Figure 7.9 Formation of construction joints (Concrete Society, ref.6)

7.8
Quality control and workmanship

Quality of the product commences with the selection of plant and equipment and design of mix. The plant and equipment must comprise an integrated outfit where the batching and mixing plant, concrete delivery machine, delivery hose and nozzle assembly form a smoothly working and balanced combination. All plant must be regularly checked, working efficiently, free from leaks and with worn parts regularly replaced.

The batching and mixing plant must be checked for accuracy of weigh-batching and efficiency of mixing. The air supply to the dry process machine must be adequate in volume and pressure, clean and dry, and free from pressure fluctuations. The air supply to the wet process nozzle may be less critical but in both cases it must correspond with the plant manufacturer's recommendations. Nozzle assemblies must be regularly checked for leakages, uniformity of water supply and worn liners, any of which may cause variability of placed material.

Cement and aggregates will be checked for compliance with the relevant standards. In the case of the dry process, the water content, fines content and grading of the aggregate can be critical, and should comply with the Specification.

Where required, pre-construction test panels will have been sprayed to confirm that the properties of the placed material are adequate for the requirements of the work. These test panels are usually sprayed into test boxes 600 or 750 mm square and 100 mm thick, placed in the attitude in which the concrete will be sprayed in the work, i.e. vertical, sloping, overhead etc. They are valueless unless identical materials, mixing and placing plant are used to those proposed for the work and for this reason they are quite expensive to provide. Previous experience with similar plant and materials is often accepted in lieu of such pre-construction tests except on the largest of jobs. 100 m diameter cores are taken from the test panels at a suitable age for testing for specified standards of crushing strength etc.

Test panels can also be used to judge the competence of nozzlemen. The ability of a nozzleman to place uniform, well-compacted sprayed concrete to the required tolerances or finish can be judged immediately from a freshly placed test panel. Strength tests can be taken on cores from another panel later.

The standard of finish to be provided in the work may similarly be set by a test panel which is to the required appearance and is kept as the standard to be achieved in the work itself. When the work commences, the first important control for the supervisor or inspector to make is of the standard of interface preparation. Ideally, although this may not be practical on many contracts, no spraying on to an interface should be allowed until that interface has been checked and approved, so that a clean, sound, rough surface to which a good bond can develop is achieved. Care is needed to ensure that prepared areas are not contaminated by overspray or rebound from adjacent areas being sprayed.

Mesh or bar reinforcement must be checked for security of fixing, correct positioning and overlaps, spacers, and cleanliness.

Profile guides, whether pins, timber formers or stretched piano wires, must be firm, tight and correctly positioned because the tolerance achieved in the placed concrete will depend upon them. As already stated, without such profiles it is difficult to achieve any acceptable tolerance in the line or thickness of the placed material.

Figure 7.10 Spraying concrete to repair and strengthen settlement tank

Prior to commencing spraying, the interface must be wetted so that it does not absorb water from the sprayed concrete, but at the same time is not so wet that there is excess free water on it. This is usually done with the spraying nozzle itself, using air and water only.

Spraying should be carried out with the nozzle approximately at right angles to the interface, and at such a distance that the concrete compacts effectively (Figure 7.10). If the nozzle is too close, the spray of material will dislodge material already placed. If it is too far away, poor compaction will be achieved (see Figure 7.11). The nozzle should be 'fanned' from side to side and up and down so that a layer is evenly built up over the area in front of the nozzleman that he can reach without moving himself, not built up to full thickness in each spot in turn. It may be found helpful in building up around reinforcement to make the mix a little wetter and to alternate spraying from side to side at a slight angle.

If there is any unevenness in the spray of material as it leaves the nozzle, the nozzleman must turn the nozzle away from the work until the spray becomes even again.

Where the full thickness has to be built up in more than one layer—it may be inadvisable to apply more than 50 mm or so at a time on vertical surfaces or 25 mm or so overhead—the surface of each layer may be lightly trimmed with the edge of a steel float, and must be wetted again once set before applying the next layer.

The nozzleman must have the skill and experience to be able to avoid trapping rebound in the placed concrete. This is a particular risk in corners and recesses and behind reinforcement, and regular inspection should be made to check that a sound result is being achieved. An air-line to blow out trapped rebound may be advantageous. Test panels may be called for during the course of the spraying. These will be of similar size to the pre-construction test panels and should be sprayed adjacent to the working area and in the same attitude as the work, i.e. vertical working or overhead etc.

Curing of the sprayed concrete, as specified, is probably even more important than of conventional cast concrete because the thinner sections may make water loss easier and more serious, and the standard of curing should be regularly checked. Methods used can include a fine water spray, wetted hessian and curing compounds. With the latter, care is needed to avoid spraying any interface or intermediate layer to which further sprayed concrete is still to be applied.

On all other than the smallest contracts, there should be a full time supervising foreman who has adequate experience of all aspects of the work and who has preferably been a skilled operator himself.

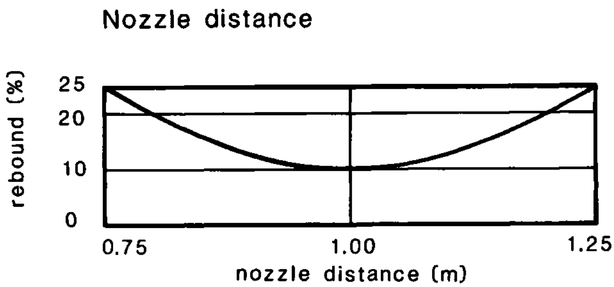
There should also be an assistant nozzleman, who is usually a trainee nozzleman, who moves the delivery hoses, clears rebound, trims the surface and uses an air line to clear rebound where required.

7.9 Practical aspects

Access for the work, whether by fixed scaffolding, mobile towers, suspended cradles, hydraulic platforms or other means, must take account not only of the safe legal requirements, but of the particular needs of repair work. To prepare the surface, fix reinforcement and profiles, carry out finishing, trimming etc., the operatives must be able to comfortably reach the interface. To do the spraying, the nozzleman must be able to stand back so that the nozzle is at the right distance from the interface, between 0.6 and 1.5m, average 1 m or so (Figure 7.11). The nozzleman is controlling a noisy, dusty and heavy hose and nozzle assembly exerting a strong thrust and also has to move about as the work proceeds, to a preconsidered sequence, so he must have an uncluttered floor area where he will not trip or stumble.

Adequate light is essential and, in dark areas, strong artificial lighting will be needed so that operatives—particularly the nozzleman—can see what they are doing. In confined spaces with poor natural ventilation, artificial ventilation may be necessary both for vision and for safe and tolerable working conditions.

Protection of the working areas by screening against wind and weather may be desirable in exposed conditions; also screens to confine dust, debris, spent abrasive, sprayed concrete, overshoot and rebound and protect adjacent



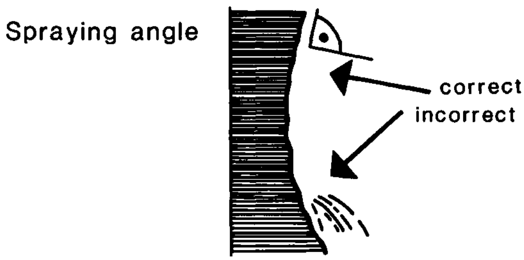


Figure 7.11 Nozzle distance and spraying angle for sprayed concrete

structures, equipment, machinery, the public, etc. may be needed. Alternatively, such adjacent structures etc. may themselves be wrapped or screened for protection. In windy conditions, sprayed concrete rebound and cement dust can blow around for surprising distances, if unconfined.

Cutting away defective concrete is best done using light hand-held pneumatic tools. Those around 5 kg weight will be found to have adequate power and be of reasonable weight to handle. If compressed air or tools are not available, electric tools can be used. Hand tools are ineffective except for very small local areas. However, as has already been stated, it is very difficult to cut away sound concrete from around and behind reinforcement, and it may be necessary to try different types and weights of power tools in order to determine the least expensive method. Very high pressure water jetting can be an effective alternative. Preparation of sound surfaces for overcoating with sprayed concrete can be effectively done by purpose-made abrasive blasting equipment, using coarse grit; by high pressure water jetting; pneumatic scabbling or more rarely by chemical or other methods.

Spraying is usually commenced at the bottom and progresses upwards. An important point to remember is that the rebound will fall downwards and should be kept as far as practicable off the completed work and any that does fall should be cleaned off as soon as possible.

Layer thickness will be determined as that which can be properly applied in one application without slumping off. Interfaces must be carefully cleaned of any surface deposits, and dampened before subsequent coats.

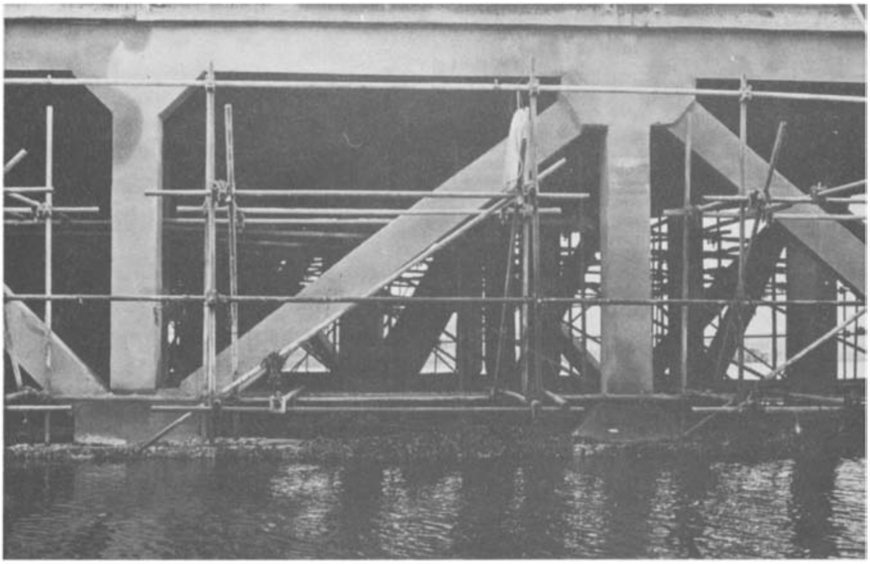


Figure 7.12 Completed sprayed concrete repairs to wharf substructure

The final surface of sprayed concrete should be left as sprayed by the nozzle if possible, as this is the most durable finish. However, it takes great skill by the nozzleman to achieve uniformity of line and texture without any hand trimming or finishing work, and variations in colour will almost certainly occur, especially between individual areas sprayed from each separate lift of scaffolding, or from work sprayed on different days.

A more common treatment is to spray the main coats of concrete to say 5 mm below the required final profile, trimming off to a uniform profile with the edge of a steel float or with a special tool. A final 'flash' coat about 5 mm thick is then sprayed, usually over the whole area of work done that day, in one operation, giving a good degree of uniformity of profile and texture (Figure 7.12). This flash coat, for which a finer sand is sometimes used, must be applied while the main coat is still 'green' and certainly not later than the following day. If a smoother surface is required, this can be achieved by rubbing up the flash coat with a wooden float, and/or closing the surface with a wetted brush. Such treatment must be done as little as possible, as there is a risk of breaking the bond with the substrate because the sprayed concrete is so dry and stiff and has coarse sand aggregate which will not produce a surface like trowelling mortar. Examples of completed sprayed concrete repairs are shown in Figures 7.13 and 7.14.

A further alternative if a very high cosmetic standard of finish is required, is therefore to trim the main coat of sprayed concrete to profile, as above, and to then trowel on a render coat of mortar which is suitable for the degree of finish required. This should be done as soon as possible, and preferably the next day, while the sprayed concrete is still 'green'.

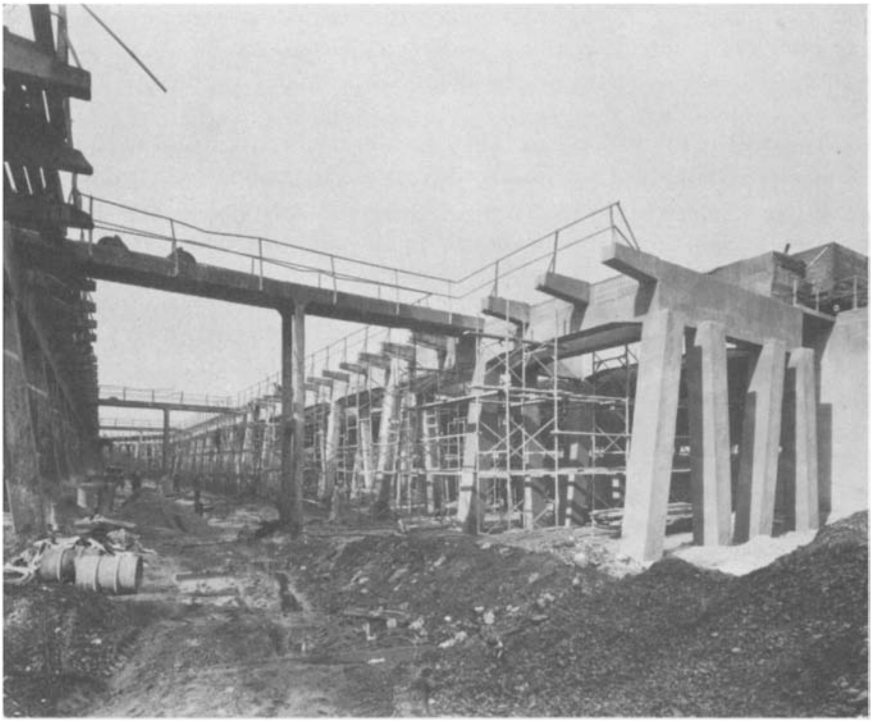


Figure 7.13 Sprayed concrete repairs to gantry in progress and completed

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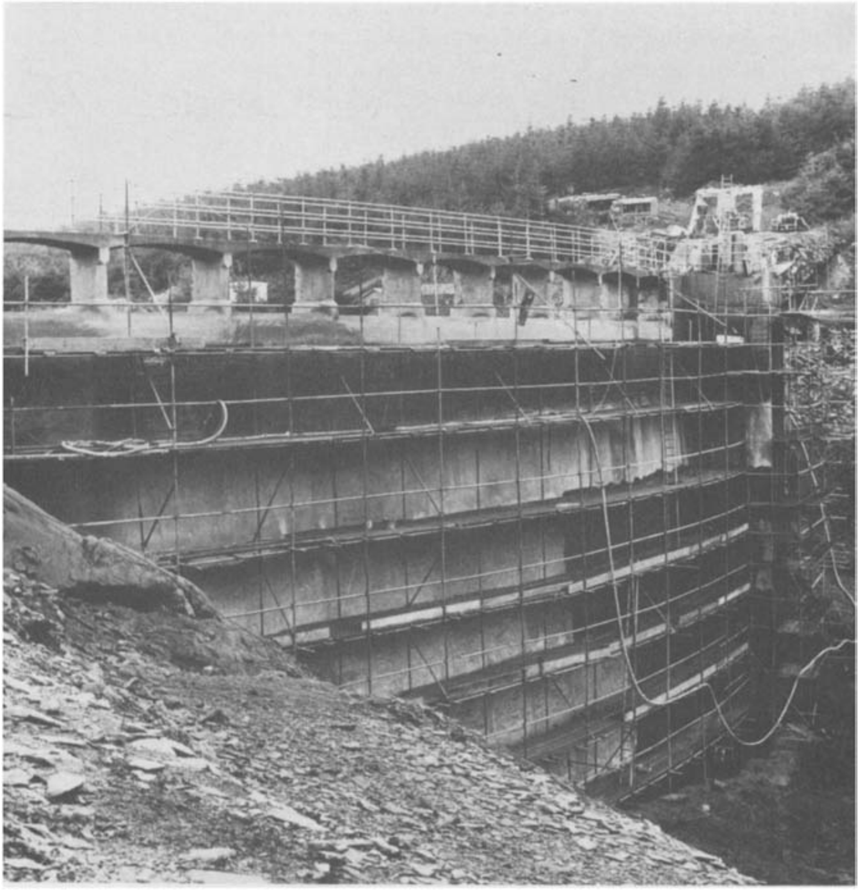

Figure 7.14 Sprayed concrete repair to upstream face of concrete dam

8
Large-volume repairs

R.T.L.ALLEN

8.1
General

When the volume of repair material required is such that hand application or spraying is not appropriate, it is necessary to fix some kind of formwork and fill it with concrete or grout. This often involves working under conditions where compaction of concrete by vibration or tamping would be difficult. The repair material may be concrete that is placed by conventional methods, it may be formed by injecting grout into a mass of aggregate, or it may consist entirely of grout.

8.2
Preparation

Whatever type of repair material is used, the basic requirements for preparation are similar to those for other methods of repair. Defective concrete must be removed so that sound surfaces are exposed, feather edges must be avoided, and reinforcement must be cleaned. The repair material often cannot be placed immediately after preparation has been completed, so it may be necessary to apply a protective coating to the reinforcement in order to prevent corrosion. This may be a corrosion-inhibiting paint, it may be a cement and polymer slurry, or it may be resin-based. Some of these materials reduce the bond between repair material and steel, but that may not be important. If good bond to reinforcement is required, a further coating with a long open time can sometimes be applied, or the initial coating may be blinded with grit in order to provide a mechanical key. It is often necessary to clean the surface of the repair again with compressed air or water immediately before the repair material is placed.

8.3 Formwork

Formwork may be of conventional rigid type that either encloses the member to be repaired or is sealed to it at its edges, or it may consist of a flexible fabric, particularly when grout is to be used. In grouted aggregate work transparent panels are sometimes provided so that the progress of grouting can be watched. When mixed concrete is to be used for the repair, provision must be made in the formwork for placing and compacting it. This may mean that the formwork has to be built up in stages as the work proceeds or it may be possible to provide temporary openings, pouches or ‘letterbox’ slits in the formwork (Figure 8.1) through which access can be obtained. The method to be adopted will depend partly on whether the appearance of the finished work is important: projections of concrete left by pouches can be cut off but the cut areas will be conspicuous unless an overall surface coating is applied. Temporary openings must be sealed carefully if leakage and consequent dark discoloration of the concrete are to be prevented. Formwork must also be shaped in such a way that concrete will fill it completely without trapping pockets of air.

Whatever method is used all joints between sections of formwork, and between formwork and existing concrete, must be sealed so as to prevent leakage and the seal must be maintained while the concrete is being compacted. In this connection it is important to allow for the fact that, when grout or superplasticized concrete is being used, the pressure at the bottom of the formwork will usually be equivalent to the full hydrostatic head because it will not be relieved by partial stiffening or by arching.

In grouted work, the grout is usually introduced at the bottom of the forms and some provision must be made for venting air at the top as the grout rises. With some types of flexible fabric formwork no special provision is necessary because air, but not grout, can escape through the weave of the fabric.

8.4 Mix design

When conventional concrete is used, the mix design will depend partly on the dimensions and location of the repair. For pours in which there is easy access for placing and compacting concrete and with minimum thickness of the order of 100mm or more, a mix containing 20 mm maximum sized aggregate and having normal proportions can be used, but for thinner sections and more difficult access 10mm maximum sized aggregate is often necessary. Superplasticized concrete may be required when compaction would be difficult (1).

For repairs that are to be cast against soffits the mix should be such that settlement after placing is reduced to a minimum. This means that water content must be as low as possible consistent with full compaction and, here again, superplasticizers or water-reducing admixtures can be used to produce concrete

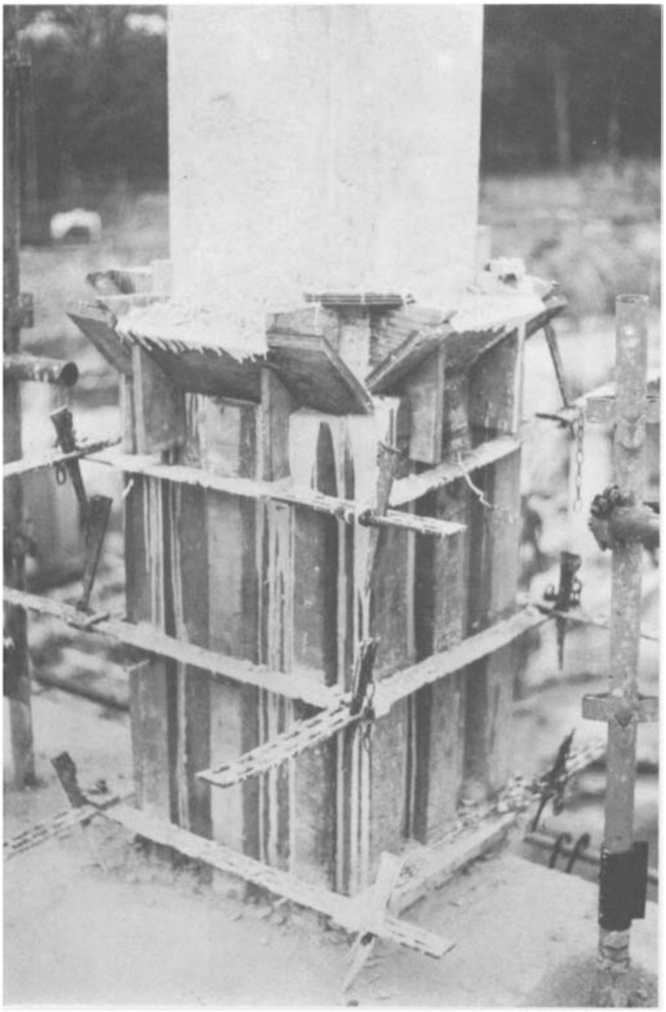

Figure 8.1 'Letterboxes' on formwork to provide access for placing concrete (British Cement Association)

of normal workability but having reduced water content. Settlement will also be reduced if air-entraining agents are used (2). In deep lifts or when settlement cannot be prevented a crack may form between the top of the repair and the soffit of the existing concrete, and this will have to be grouted up, usually with a resin. Grout for repairs may contain intrusion aids and admixtures to reduce water content and to prevent segregation (3). This type of work is usually undertaken by specialists who have developed suitable mixes by experience.

Grouts may consist of cementitious materials, admixtures and water, or they may contain fine sand or condensed silica fume.

8.5
Placing and compacti ng concrete

Methods of placing concrete in large volume repairs are usually similar to those used in new construction, except that quantities may be considerably smaller. Consequently, hand work is likely to be involved rather than mechanization. Particular care may be required to ensure that confined spaces in the formwork are completely filled without trapping air. Compaction is best achieved by internal vibration if there is access for vibrators. In many cases, however, it is not possible to compact the whole of the repair by even small diameter poker vibrators, because their energy is transmitted to the concrete at right angles to the vibrator head and not longitudinally. A limited amount of external vibration can be applied by using a mechanical hammer on the outside of the formwork, and this may be adequate if done in conjunction with internal vibration. Otherwise external vibrators may be clamped on to the formwork, which must then be designed to withstand the vibration without damage or displacement, and particular attention must be paid to the seal between formwork and existing concrete.

8.6
Grouted aggregate construction

In this technique formwork is fixed as for conventional concreting, but it is filled with coarse aggregate. Grout is then pumped in so as to fill the interstices between aggregate particles (4, 5, 7).

The grout should be introduced at the lowest points of the formwork in order to prevent the formation of air pockets. More than one injection point may be required. Injection tubes may be built into the formwork at several levels if complete filling from the bottom would require too great an injection pressure, in which case grout would be introduced at the bottom first and each successive set of injection points would be sealed when the grout had covered the next set above. Alternatively, injection pipes may be inserted from the top, reaching to the bottom of the formwork, before the aggregate is placed. They are gradually withdrawn as the level of grout rises, in much the same way as a tremie pipe in underwater concrete construction. In this case sounding tubes may be provided alongside the injection tubes so that the level of the grout surface can be checked during the progress of the work. This enables the operatives to ensure that the ends of the injection tubes are always immersed in grout, and so to avoid forming air voids. Alternatively, translucent panels may be provided in the formwork so that progress can be observed.

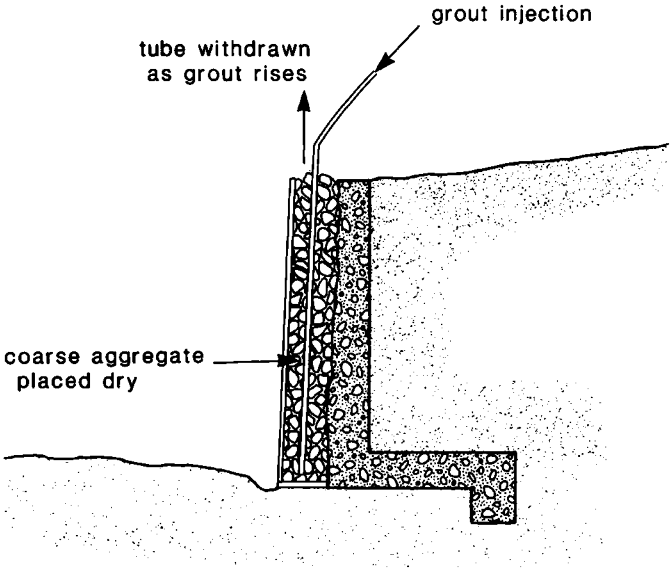

Figure 8.2 Grouted aggregate repair to retaining wall

The formwork, and especially the seals between it and the original concrete, must be designed to withstand the full hydrostatic head of grout because the pressure will not be relieved by arching action as with normal concrete. Vents must be provided at the top and at any other points that may be necessary in order to allow air (or water, in underwater work) to escape as the grout fills the formwork.

Aggregate grading must be such that the grout can flow freely between the particles. This usually means that single-sized stone is used, generally 20 mm or larger.

Grouted aggregate work is usually carried out by specialists who have developed suitable grout mixes for various circumstances. Cement grouts are most frequent but resin grouts are sometimes used. The method is particularly suitable for underwater work and for conditions where access is difficult.

8.7
Curing

Requirements for curing large volume repairs are similar to those for new construction. Although they are less critical in this respect than thin patches, curing is important for a durable result, especially when pozzolanas or Portland blast-furnace slag cement are used. Normal curing methods are usable except that sprayed-on curing membranes are not suitable if a surface coating is to be applied later (6).

Figure 8.3 High-shear mixer for producing cement grout with reduced tendency for sedimentation (see also Figure 8.4)

8.8 Appearance

The surface texture of a formed surface will be determined by the nature of the form face so, if the existing concrete has not become roughened by weathering, a reasonable texture match can be obtained by suitable choice of formwork. Weathered surfaces can be simulated by very light acid etching, followed by thorough rinsing with water, or by very light grit blasting. Finishes such as those left by 'rough-board' formwork can be imitated by a skilled operative using a float on green concrete or on a cement wash. Colour matching is far more difficult to achieve because it is affected by mix proportions and curing conditions, and surface coatings may be the only practical answer.

The appearance of grouted aggregate work will differ from that of conventional concrete because more coarse aggregate particles will be in close contact with the formwork. Consequently they will be visible in the finished surface, especially when 40mm or larger aggregate is used and after weathering.

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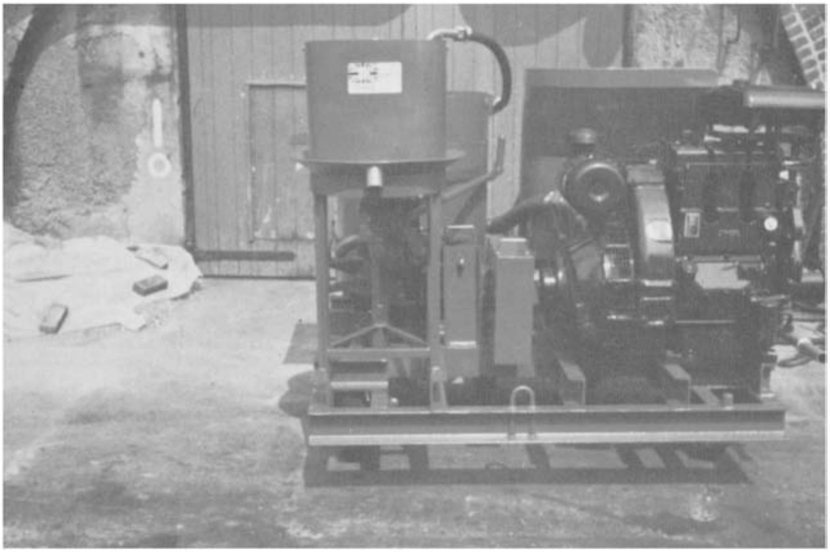

Figure 8.4

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9
Leak sealing
S.C.EDWARDS

9.1
Introduction

Although reinforced concrete is an excellent building material for water-retaining structures, it is hardly, if ever, completely watertight. The limitations of reinforced concrete must therefore be recognized. Monolithic concrete blocks will absorb water to an extent, but will not allow its passage. Concrete structures, though, are hardly monolithic. For practical purposes they comprise many separate pours with various types of joint between them. In some cases the leakage will be unsightly, but causes little inconvenience beyond the possibility of damage to reinforcement. In other instances, small quantities of water might affect electrical installations, or larger volumes will incur expensive pumping costs. The volume of leakage depends essentially on three factors; the availability of water, the water pressure and the sectional area of the leak path.

In many cases the construction joints will allow passage of water. This can be for many reasons, including poor preparation and shrinkage during cure. Sometimes waterbars are designed into the joints to reduce the incidence of leakage; or grout voids are formed which are filled under pressure after post-cure shrinkage has been allowed to take its course (1).

Shrinkage and restraint cracks in other parts of the structure may also form leak paths. These will be of similar proportions to those provided by the construction joints mentioned above. The amounts of water involved vary from damp patches, which tend to evaporate as they are formed, to running leaks which will eventually form pools on undrained surfaces. Damp patches may also be formed when water passes through voids along reinforcing bars. These are normally due to plastic settlement which may in turn be attributable to a number of factors, including insufficient vibration and poor mix design (see Chapter 1, section 1.2). The other common route for small volume leakage is along formwork through-ties of which there may be thousands in some structures. Experience has shown that voidage around these might connect with that around reinforcement, so water appearing from through ties has not necessarily followed the most direct route. There are two routes for larger volumes of leakage.

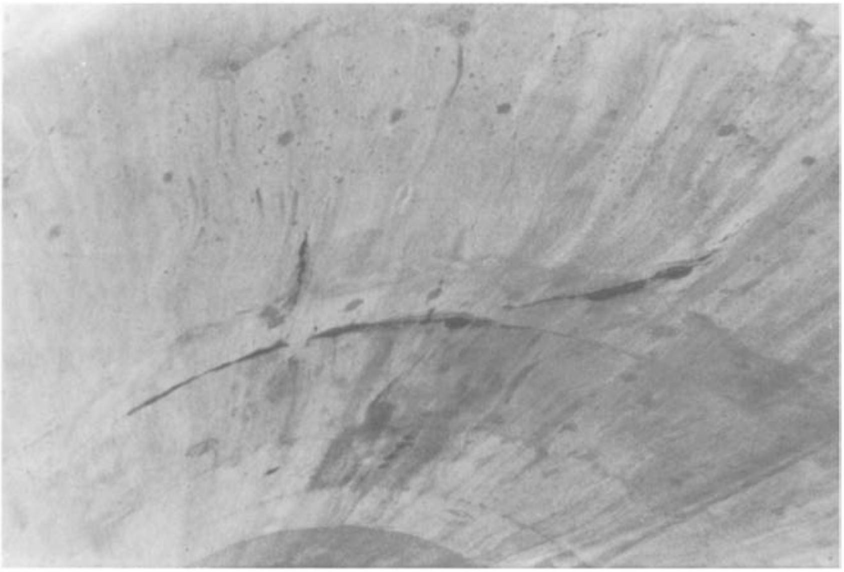


Figure 9.1 Leakage through cracks and construction joints in a concrete shaft

Honeycombed concrete has provided a water path in several cases within the authors' experience. It is preferable in these circumstances to break out the defective concrete, but occasionally leak-sealing alone will be satisfactory, or leak-sealing techniques may be used to assist with the remedial work. More commonly though, water will find its way past water bars in the movement joints designed into structures to take up expansion and contraction.

It is recognized, of course, that engineers take a responsible attitude to all these factors, both in the design stage and during construction. The concern of this chapter is to investigate the alternatives which are available when the precautionary measures fail.

9.2 Site investigation

It is easy to overlook the fact that many tanks and ponds are constructed partially or completely below ground level, and that the points of leakage from these structures may not be immediately apparent. In such cases, the first stage of investigation is that the extent of leakage must be measured by monitoring the loss of liquid from the structure (2). Concrete will absorb water until the surface is saturated, and the extent of this depends on mix design and compaction. In addition, evaporation will occur which must also be taken into account. In response to this, BS 5337 states that the structure can be considered watertight, '…if the total drop in surface level does not exceed 10 mm in seven days…' (3).

Once it has been established that the structure is leaking, the route or routes must be identified. In the case of an unlined concrete structure, it may be drained and allowed to dry. Subsequent inspection will reveal likely sources of leakage, since these points or areas will tend to retain the water for significantly longer than the rest of the surface. Defective construction joints and random cracks will show up clearly. Movement joints however will tend to appear wet whether or not they leak, except in cases where a face seal has been applied.

Movement joints are particularly susceptible to leakage, which is most prevalent in floor slabs and soffits, where the water bar is placed horizontally. Concrete tends to slump away from the lower faces leaving voids which might eventually form a passage for water. Vertical joints are less troublesome in this respect, but still suffer as a result of negligent supervision and accidental damage. Expansion joints may be lagooned to provide an indication of their performance. This may be achieved with sandbags, or more effectively with bricks and mortar. If leakage can be demonstrated in the horizontal section, then it will be necessary to repair the whole joint.

Tiled structures such as swimming pools are more difficult to deal with, because small cracks tend to be hidden and only major defects will be obvious. Some companies advocate the use of fluorescent dyes suspended in the water, which will tend to accumulate in the region of the leak paths.

Once the positions of the defects have been identified, some consideration must be given to their likely cause, and their behaviour once the structure is in service. It should be established, for example, whether the areas in question will be subject to movement. This is quite obviously the case with expansion or contraction joints, but less so in other situations. Take for example, a bridge deck where the leak paths will be subject, not only to varying loads, but also to extreme thermal stresses. These factors should be taken into account when repair materials are selected.

Another significant factor to be considered, is that leak pathways may be more extensive than they appear to be on first sight. This is because the water will confine itself to the easiest route, and might only be apparent over a short length; once this has been sealed though, the water will probably re-appear at either side of the repair. In a more complicated case, a crack through a wall might join with a construction joint in the floor slab. Possibilities of this kind must be recognized, and adequately catered for in repair method statements.

9.3
'Conventional' leak-sealing methods

Some sources of minor leakage may dry up by themselves, and this is often referred to as 'autogenous healing'. It is due to the accumulation of calcium salts along the leak path, which will obstruct the passage of water over a period of time and reduce leakage to negligible proportions (4). New water-retaining structures often exhibit many leaks of this type, and time must be given for them to ‘heal’ before further measures are taken. The deposition of calcium salts may be encouraged by adding lime to the water. This is restricted, though, to situations where the water source is accessible and it is therefore only relevant to structures such as tanks and ponds. Success is further limited to minor leaks which are not subject to further movement and would normally be of little significance.

Leak sealing has been carried out for as long as water-retaining structures have been built; until the mid 1970s, however, techniques had been relatively primitive. Point leakage might be drilled out, for example, and plugged with presoaked hardwood dowels. Lead wool and other proprietary caulking materials can be hammered into joints to stem the flow of water, and in some cases, extensive use is made of ‘flashset’ cements which can be successful in the right application. Very often these methods are still favoured, but more scientific approaches to the problem have become available.

9.4 Surface seals

If there are any rules in leak sealing, the first must be to approach the problem from the water-retaining side of the concrete whenever possible. In many structures, including tanks and retaining walls, the wet side will be readily accessible, particularly if the fault has been found prior to commissioning. Once the trouble spots have been identified, the most straightforward remedial action will involve application of a local or complete surface seal. Normally a coating system will be sufficient to solve the problem (see Chapter 10, section 10.2). It will typically follow the format outlined below:

(i) Surface preparation
(ii) Fill out surface imperfections with resin-based grout
(iii) Apply recommended primer
(iv) Apply two coats of high-build paint.

Although local application of a suitable coating will be sufficient to seal many of the routes mentioned, severe cases will demand quite extensive preparatory work. The areas most commonly requiring attention in this context are construction joints. Bearing in mind that no water flow is present while repairs are being undertaken, injection of suspect joints with a low viscosity resin is both worthwhile and cost effective. The same is true for random shrinkage cracks and formwork through-ties. Following injection, coating systems become optional, but are often included as a first line of defence. Honeycombed concrete, if not considered particularly extensive, may be filled out using a resin-based putty or mortar. In cases where there might be concern about structural integrity, the concrete can, if desired, be repaired by injection with thixotropic epoxy grout, using a suitable formwork arrangement.

In all cases, the affected areas and all those associated with them must be thoroughly prepared prior to treatment. Laitance and surface contaminants may be removed by a variety of means, including grit blasting and power wire brush. This will provide a sound basis for subsequent work (see Chapter 10, section 10.4).

Movement joints are particularly susceptible to leakage, resulting in the passage of relatively large volumes of water. For this reason, most modern designs include a face seal on the water-retaining side of the structure. This may consist of an extruded channel section, or a gun-applied sealant. The latter is normally preferred, on grounds of cost. If the face seal has failed, it should be removed completely, and the expansion joint assessed for its contribution to the observed leakage (Figure 9.2).

Generally, the water will take one or both of two courses:

(i) Through the joint, and past the damaged or misplaced water bar
(ii) Through the joint and into an adjoining crack or construction joint.

In both cases, it will be necessary to introduce a resin into the joint which will cure to form a flexible sealant. First however, the shoulders of the joint have to be thoroughly cleaned and inspected to discover the reason for failure of the original face seal. The material may not have been properly applied, for example, or the shoulder of the joint might have been damaged. Where this is held responsible for failure, the concrete is best repaired by preparing the surface carefully, and then rebuilding flush using an epoxy mortar or something similar. The most common cause for failure, however, is poor adhesion of the face sealant to its substrate, normally because it has not been properly applied. Surface preparation is particularly important. Even top quality sealants will not adhere to dusty, greasy surfaces. The concrete must be thoroughly cleaned prior to their application, and an appropriate bonding coat or primer should be used if recommended.

In some cases excessive movement, outside the capability of the sealant, might cause it to fail. It is unusual to find this type of material lacking adequate flexibility, except in older structures where it might have perished. Instead the problem is very often due to its configuration, as discussed in Chapter 5, section 5.4. In cases where a face seal has failed and the expansion joint is leaking, it is normally insufficient to replace the face seal alone. Some consideration must be given to sealing the water bar. This is normally achieved by introducing a resin capable of forming a flexible seal. The material can be injected into the joint under pressure by setting flexible tubes through the face seal.

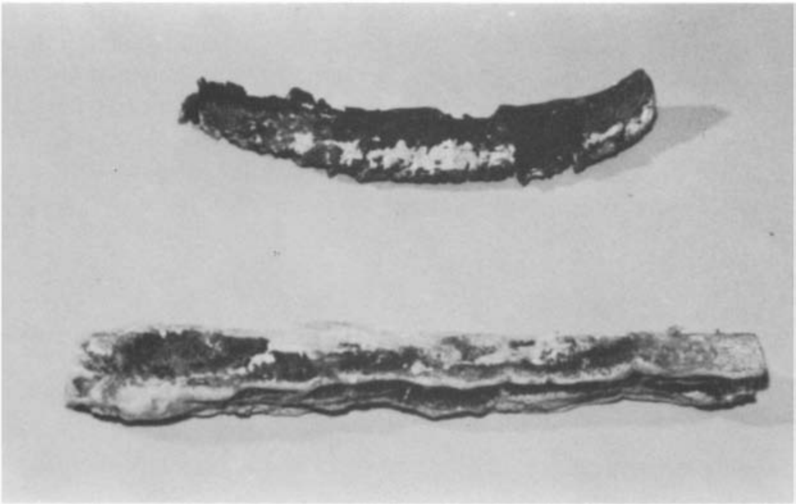


Figure 9.2 Defective lengths of face sealant taken from two sites. (Top) Polysulphide. Badly perished with powdery concrete adhering along its length. (Bottom) Polyurethane. Applied in place of the original seal, with inadequate surface preparation

9.5 Liquid flow and pressure considerations

Sealing leakage from the water-retaining side of the structure is the simplest and most cost effective way of combating the problem. When the wet side is inaccessible, however, the leakage must be tackled from the dry side, which is considerably more difficult. This is achieved by introducing a cold-cured fluid compound into the leak path as will be discussed in section 9.6. Whichever approach is used, faster flowing leaks in general tend to be sealed more easily. This is because the rate of leakage is related to a number of factors including pressure and sectional area. The implications of this are examined below (5).

For the purpose of comparative analysis, laminar flow of water may be considered along a cylindrical leak path of diameter D and length l as shown in Figure 9.3. This is fed from a head of water which exerts pressure P_{i} to deliver a discharge Q at pressure P_{ii}. η denotes the dynamic viscosity of water. From Poiseuille's equation,

$$Q=\frac{(P_{\mathrm{i}}-P_{\mathrm{ii}})\pi D^4}{128\eta l} \qquad (1)$$

which shows that the discharge is directly related to the fourth power of the diameter of the route and to the pressure differential across it. If the equation is rearranged,

$$D^4=\frac{128\eta l Q}{(P_{\mathrm{i}}-P_{\mathrm{ii}})\pi} \qquad (2)$$

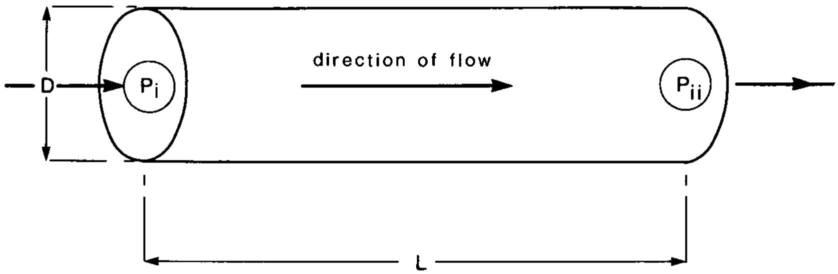


Figure 9.3 Water flow through a cylindrical leak path

The diameter of the route may be determined from known quantities and, for a given discharge, is inversely related to the pressure differential. It follows then, that injection of a sealant directly against the water flow will require less pressure where the sectional area of the leak path is relatively large. Where this is the case, leakage will be easier to seal.

Given the discharge, *Q* and the sectional area, *A* the mean flow velocity *V* through the pathway can be calculated from the following expression:

$$V = \frac{Q}{A} \qquad (3)$$

Successful leak sealing requires injection of grout to fill water passages completely, and it is necessary to attain a relatively high flow velocity to achieve this, because of the limited 'pot life' or working time of typical repair materials. The mean flow velocity is directly affected by viscosity, and since grouts in general have a much higher viscosity than water, relatively high injection pressures are required to achieve the necessary extent of penetration. Further to this, it is important to recognize that viscosity of a liquid is inversely related to its temperature, so ambient conditions and the temperature of the concrete are particularly important when materials are selected for site application.

Example

Consider water from a 10 m head, flowing along a cylindrical leak path of diameter 0.1 mm, and length 1.0 m. An injection point has been fixed and resin of viscosity 0.5 NSm^{-2} (5 poise) will be used for the repair. The expected pot life of the material at this temperature is 2 hours. To calculate the flow of resin required:

$$Q = \frac{\pi D^2}{4} \times \frac{L}{t}$$

where *Q* is the quantity of resin in m^3/h

D is the diameter of the leak path in m

L is the length of the leak path in m

t is the time in seconds.

So

$$Q = \frac{3.142(0.0001)^2}{4} \times \frac{1}{7200}$$

$$= \frac{3.142(1 \times 10^{-8})}{28800} \quad (4)$$

$$Q = 1.09 \times 10^{-12}\, m^3/sec$$

Assuming laminar flow, the Poiseuille equation may be applied*:

$$Q = \frac{(P_i - P_{ii})\pi D^4}{128\eta L}$$

where η represents viscosity in NS/m^2 and $(P_i—P_{ii})$ is pressure differential in N/m^2. Rearranged

$$P_i - P_{ii} = \frac{128\eta LQ}{\pi D^4}$$

By substituting values

$$(P_i - P_{ii}) = \frac{128 \times 0.5 \times 1 \times 1.09 \times 10^{-12}}{3.142 \times (1 \times 10^{-4})^4} \quad (5)$$

$$(P_i - P_{ii}) = 22.2 \times 10^4\, Nm^{-2}$$

In addition to this, the acting hydrostatic pressure must be considered.

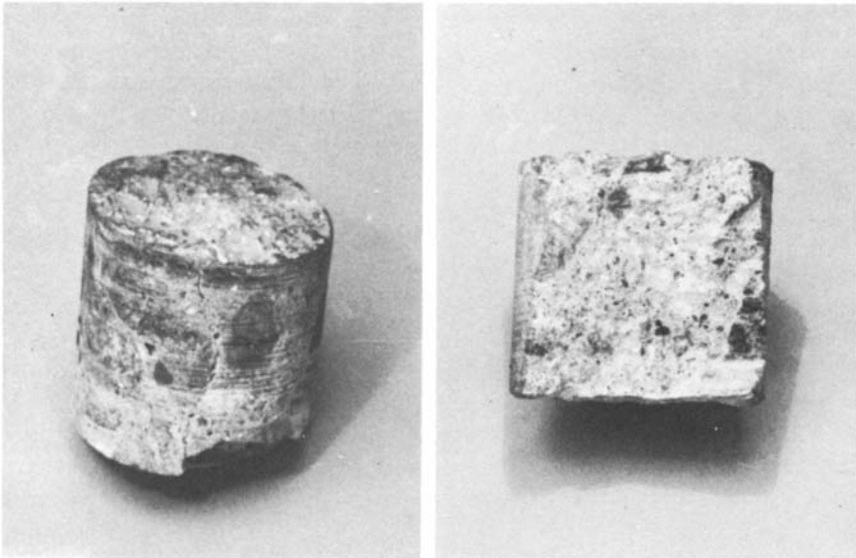


Figure 9.4 (Left) A core cut over a crack through which water was leaking. (Right) The core split to show salt deposited on the inner surfaces of the crack

$$P = h\rho g$$

where P=hydrostatic pressure
h=head of water in m.
ρ=density of water in kg/m^3
By substituting:

$$P = 10 \times 1000 \times 9.81$$

$$\text{So hydrostatic pressure} = 9.81 \times 10^4\ \text{Nm}^{-2} \qquad (6)$$

By adding (5) and (6) the minimum necessary injection pressure may be calculated.

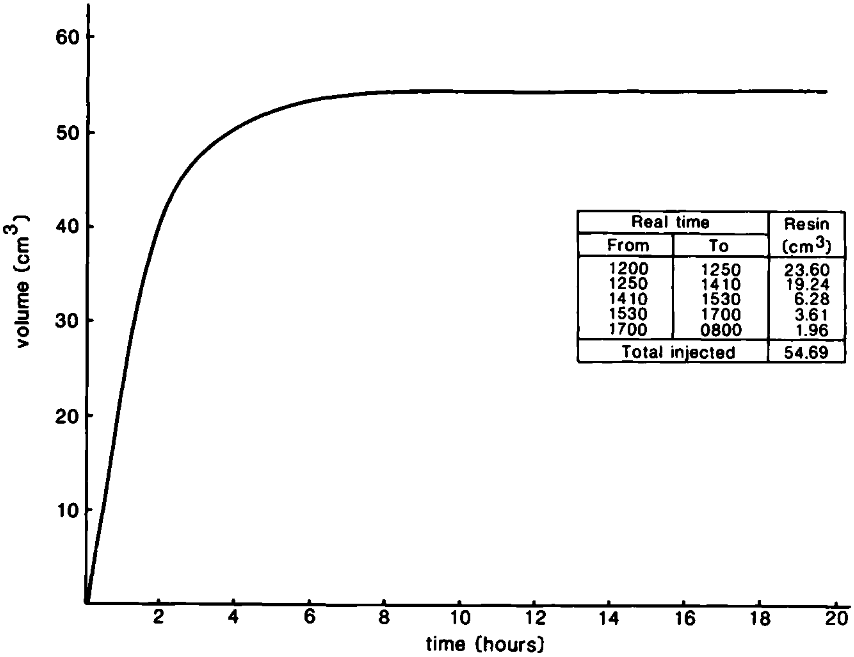
$$\text{Minimum injection pressure} = 320.1\ \text{kN m}^{-2*}$$

$$\text{or} \qquad 3.20\ \text{bar}\ (45.76\ \text{lb/in}^2)$$

In practical situations, leakage is not normally confined to cylindrical routes, so the calculations shown can only be used for guidance. It is true though that water flowing through cracks will tend to follow the path of least resistance. This

* Flow rate Q is not constant in this context; its value falls as the water passage fills with resin (p. 108).

* A leak path of circular cross-section will present the least resistance against flow. In normal cases, however, where the section of the leak path is other than circular, the pressure required to attain the necessary flow rate may be many times higher.



Real time		Resin (cm³)
From	To	
1200	1250	23.60
1250	1410	19.24
1410	1530	6.28
1530	1700	3.61
1700	0800	1.96
Total injected		54.69

Figure 9.5 Direct injection of resin into a leak path plotted from empirical values. Graph shows cumulative volume of resin injected over a 20-hour period

is because cracks are often congested with salts and are rarely parallel-sided for their full lengths.

Experience has shown that the flow of grout into a crack or construction joint decreases with time; this is for two reasons. When pressure is first applied, the majority of liquid being displaced along the leak path is water with a viscosity many times lower than that of the grout. As the water passage is filled with more viscous material, resistance against flow increases. Additionally, the grout slowly cures during the injection period which increases its viscosity. The graph in Figure 9.5 has been plotted from a series of empirical values, and shows the flow of resin into a crack measured over a twenty-hour period.

9.6
Sealing leakage from the downstream side

In most cases where leakage is present, the first principle is to confine the water flow to a tube through which the sealant may be introduced. This is achieved by a variety of methods, the choice of which depends on the original configuration of the leak. Once the flow of water has been controlled, the connection between the tube and the concrete must be made strong enough to withstand the injection pressure. The connection systems may be referred to as anchorages.

9.6.1
Anchorage systems

Anchorages may be divided into two categories. Adhesive systems have been designed where the injection point is held in place with putty or mortar, following suitable surface preparation. These are particularly difficult to use when the substrate is wet, which is normally the case. As such, they are only suitable under specific circumstances:

(i) If they will adhere to a wet surface
(ii) When the water can be completely diverted into the injection tube prior to application of adhesive.

As few materials adhere to wet concrete, the second option is usually preferred. Throughout the industry, there exist many closely-guarded and ingenious methods to persuade water to travel into tubes, thereby allowing the use of adhesive anchorages. It should be pointed out, however, that even the best techniques are not foolproof, and depend very much on the persistent approach of experienced operatives.

Adhesive methods are difficult, and rely heavily on the skilled worker for their success. Mechanical anchorages, although generally less applicable, are much easier to use. The most common example of this is the injection lance with expanding collar, which attains a watertight seal when fitted into a hole of specific internal diameter. Self-sealing lances are frequently used for damp-coursing houses, as well as leak-sealing applications.

The principal advantage of mechanical systems is their ability to withstand higher injection pressures. A typical adhesive anchorage will fail at around 10 bar (143 lb/in2) depending on its configuration. Mechanical anchorages, however, may be designed to withstand pressures up to the limitations of the concrete.

9.6.2
Direct and indirect approaches to injection

The Bernoulli principle has been explained in Chapter 5, section 5.3.3.3, and is significant in leak sealing because stressing of the concrete is possible during injection. It is therefore preferable to maintain lower pressures whenever possible and it will be necessary to compromise in some cases, very often with unsatisfactory results. A typical direct method entails injection of material up the pressure gradient from the downstream side. In a limited number of cases, an alternative, ‘indirect’ approach may be used. Grout can be introduced into the flow of water on the pressure side, so that the pathways are filled under the acting hydrostatic head.

9.6.3
Direct methods of injection

Point leakage is relatively easy to seal either by caulking with a fast curing cement-based compound, or more reliably, by direct injection. Normally however, water flows through cracks or joints as discussed in section 9.1. Injection points are then fixed at intervals, and seepage between them is usually sealed with a band of trowel-applied material referred to as a face seal. (Methods of achieving this are outside the scope of the text.) Apart from diverting the water to injection points, it ultimately prevents the escape of resin or grout pumped into them. Injection normally begins at one end of a joint, and is maintained until resin appears at the next injection point, as described in Chapter 5, section 5.3.3.1.

In cases where water pathways are densely salted as in seawater or earth-retaining structures, resin will either penetrate major leakage routes, or will pass along the back of the face seal. Where there is little or no salting, however, resin will flow more freely and travel down the pressure gradient to relief. In either case the grout must be persuaded to fill the water passageways as completely as possible before it reaches the next injection point. In an ideal case, the pressure gradient must be equivalent between the first injection point, the back of the joint and all subsequent positions to attain the necessary flow characteristics.

The integral complication when using direct injection methods, is that face seals must always be used, and their adhesion to damp concrete is the limiting factor over injection pressure. Surface preparation is very important. The concrete should be abraded to provide a key, and to remove contaminants. It must also be as dry as possible, which depends greatly on the operative's ability to divert water into tubes. Although difficult, these methods are widely used and considerable successes have been achieved. Their main advantage over other approaches is that they are more generally applicable, and operatives build up experience to the level where acceptable rates of progress may be achieved under most conditions.

9.6.4
Indirect approaches to leak sealing

Successful use of direct methods depends largely on the skill and experience of operatives. The indirect approach, however, requires more in terms of planning because the situation can be made worse if the work is not properly carried out. Consider a segmental pipeline joint which is leaking; a contractor might decide to drill, and inject a sealant behind the wall of the segment. If this is incorrectly positioned, or the material is unsuitable, the net result will be further damage to the pipeline. The job will have a much greater chance of success, however, if the work follows a correctly laid down procedure. For this reason it is advisable to employ a specialist firm, experienced in this type of work. Their engineers will have better resources to evaluate site conditions, and access to a range of purpose designed materials and equipment.

Indirect injection methods can now be used in a large number of applications owing to the development of purpose-built equipment and the availability of suitable materials. In addition to controlling large volumes of leakage, for which indirect sealing methods have been used successfully in the past, these techniques can now be used for sealing against low-volume leakage through cracks and joints. Indirect injection methods have considerable advantages. Face seals are not always required and mechanical anchorages can be used in almost all cases. In view of this, higher injection pressures can be used and, as a result, greater penetration of the leak paths can be achieved. Work may then be completed quite quickly in contrast to direct methods and with a greater degree of success.

When these injection techniques are used to seal against the water at source, the water can be prevented from entering the finer passages within the concrete and considerable cost savings can be made. Water leaking through construction joints quite often penetrates systems of fine cracks within the concrete. Water ingress from all positions can therefore be prevented by sealing the water at source. It should also be emphasized that when leaks are sealed in this way, the water is prevented from finding secondary routes through the concrete. As discussed in section 9.3 these are more difficult to fill than the original leak paths, so it is preferable to seal leakage from the source.

9.7 Recent progress with injection techniques

Before 1980, there had been very little development of methods and materials for leak sealing. That which is documented is largely involved with tunnelling where water ingress can cause enormous inconvenience (6).

Modern trends in quality assurance now dictate that laid down methods are proposed for remedial work of any sort. More significantly though, clients are more likely to ask for demonstrations of leak-sealing techniques to prove that they are satisfactory. Companies involved with construction of water-retaining structures are also conducting their own research.

In 1983 a number of companies including concrete repair specialists were consulted with regard to leak sealing. The client asked them to propose reliable and commercially valid techniques for coping with the following problems:

Leaking expansion joints
Leaking construction joints
Seepage through random cracks.

The methods had to be applicable to liquid-storage tanks, where access might be limited, and spillage of the contents undesirable. Escape of the contents would have to be controlled or prevented throughout the operation.

The use of adhesive injection anchorages and face seals was discounted at an early stage because it was considered unreliable. The client favoured indirect techniques using mechanical anchorages in all cases. At this stage a specialist drilling company was consulted on account of the extent of drilling which would be required. A modified coring machine working through a gland was considered the best option, since escaping effluent and cooling water could be collected and recirculated. The drill bit ultimately became the injection anchorage, and materials capable of sealing large volume leakage had to pass through a small annulus between the core and the internal surface of the cutter. This raised particular problems for formulators, because such materials are usually fast curing and fairly viscous.

A further problem raised was that rigid curing materials should not be allowed to enter movement joints. To prevent this, it was recommended that flexible sealant was injected into the joints, prior to sealing adjoining construction joints or cracks.

As a result of these proposals, a number of concrete test pieces were constructed, each weighing around 3.5t, which included the appropriate detail. Each was supplied with a 7 m head of water fed through perspex shutters, which allowed movement of material to be monitored. Leakage had been induced around water bars, and construction joints were opened using rock-splitting techniques. Blocks were also split through to form random cracks. Flow of water through each test piece was measured, and the agreed leak sealing techniques were then demonstrated.

The experiments were generally quite successful; leakage through a construction joint which included a water bar was sealed within ten minutes from the start of injection using a low viscosity epoxy resin. The flow of water through expansion joints, however, was more difficult to seal. One attempt failed on account of the material being of high viscosity and curing too quickly. The second attempt, carried out on a fresh test piece and using a thoroughly modified resin system was more successful.

The work conducted involved quite extensive surgery to the concrete as shown in Figure 9.6 and the client considered that techniques of this type will only be recommended for extreme cases. Following on from this work, direct injection systems which involve less damage to the structure have been developed, and these are more likely to be used in normal circumstances.

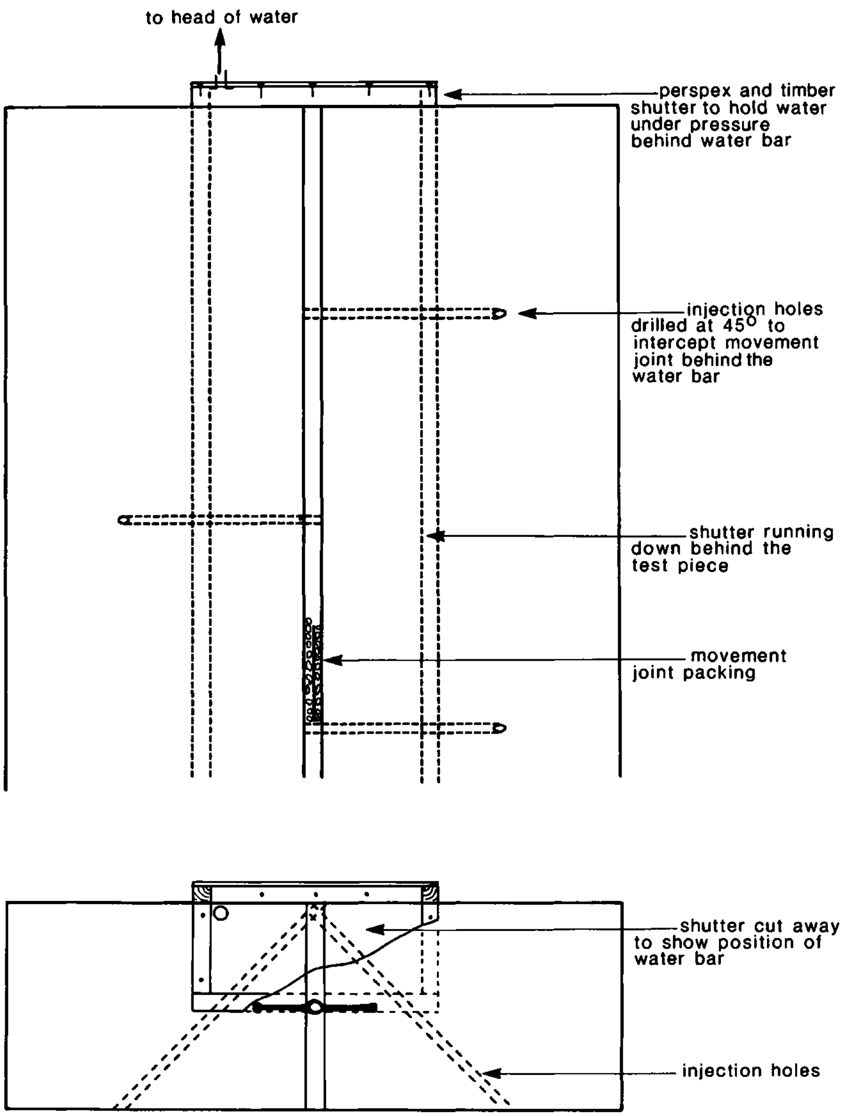


Figure 9.6 An example of an indirect leak sealing method used for repairing an expansion joint in one of the test pieces

9.8
Development of specialized equipment and materials for leak sealing

9.8.1
Equipment developed for leak sealing

Following discussions in section 9.5 it can be concluded that grout injection for

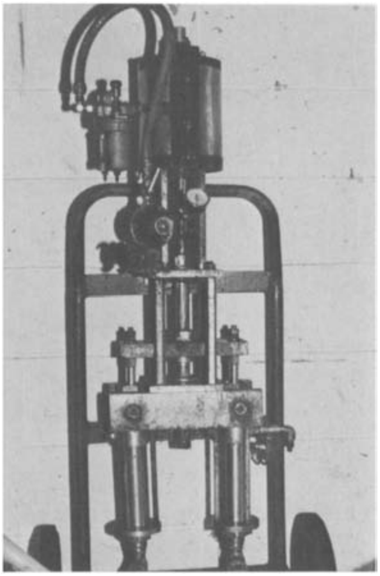


Figure 9.7 Twin piston pump for high pressure injection of two-component resins. (Photograph courtesy of Balvac Whitley Moran)

sealing leaks must be carried out at pressures above the hydrostatic head. The ideal circumstance involves injection of a water passage, at a high enough over pressure to ensure complete penetration before the material cures. The equipment used for this is normally similar to that used for injecting cracks and is described in Chapter 5, section 5.3.3.4. Pressure pots and single piston reciprocating pumps are suitable equipment for situations where the water passage is quite large in cross-section, and relatively unobstructed; in these cases, injection can be completed quite quickly. Fine cracks and leakage along through-ties however will require a longer duration and higher injection pressures to achieve adequate penetration. Twin piston pumps have been developed which deliver the two components of material to the injection lance for mixing immediately before injection. These pumps deliver the material at relatively high pressures and as such are only suitable for use with mechanical anchorages. The material typically has a pot life of only a few minutes and depends upon being injected at high pressures to achieve penetration.

As already emphasized in Chapter 5 high pressures are difficult to maintain for long duration because the pot life of typical sealants is relatively short. This problem has been considered at length by engineers from McAlpine Sea Services, a subsidiary of Sir Robert McAlpine & Sons Ltd, working in conjunction with resin technologists from Colebrand Ltd. A programme of research was undertaken in 1984, and by the end of that year a method of displacement had been developed to inject epoxy resin at 200 lb/in2 over a period of three hours. Additionally, the technique enabled the volume of resin injected to be measured. The method was given further consideration during the following year, when it was successfully used to seal leakage through stressing tendons against a back pressure of 130 lb/in2. The work was carried out by a team comprising personnel from both the companies concerned.

9.8.2
Materials developed for leak sealing

Epoxy resin. This material is suitable for wider cracks, in particular those in walls and soffits. In many circumstances, however, it is not suitable for cracks in slabs. An overall disadvantage of using epoxy resins for sealing against leakage is that they take approximately 3h to become immobile and up to 12 h to gel completely. In certain circumstances this allows time for the water to find a passage through. The main advantage of using epoxy resins is that a structural repair can be produced.

Polyurethane resin. Polyurethane resins are suitable for injection of wet cracks in walls, soffits and slabs, provided that the cracks are in excess of 0.2mm in width. The resin foams on contact with water and produces a tough, flexible seal. Polyurethane resins are available in a range of viscosities and can be used to combat low- and high-volume leakage with equal success.

Water-based acrylic resin. This is suitable for injection of very fine cracks. It is of very low viscosity and as such is able to achieve a high degree of penetration. The resin is suitable for injection of wet cracks in walls, slabs and soffits where the crack widths are less than 0.3mm. The resin blends with any water present in the cracks and includes it in the cured product, which is a flexible gel. The gel time for the resin can be controlled by varying the amounts of catalyst added.

9.9
Sealing leaks in tunnels and pipelines

9.9.1
Leak sealing in tunnels

Underground tunnels and culverts are frequently troubled by water ingress both during and after construction, so leak-sealing methods are often employed. An early example of this was during the construction of the Severn Railway Tunnel which was completed in 1886. The tunnel passes under the Severn estuary, and to the eastern end it is cut through Triassic marls. At one point, water from the River Severn broke into the working through open joints and possibly faults in the marls. These were sealed by depositing clay on the river bed, which was placed in position at low water (7).

Water ingress was also encountered in the same area during 1924 and 1929. Again, clay sealing was attempted but eventually grouting techniques were used over a three-quarter-mile length of the tunnel. Over 80001 of cement grout were injected via holes drilled radially through the brickwork. This served to consolidate the ground and fill voids above and below the tunnel. The existence of voids was indicated by the travel of cement between injection points and was attributed to erosion of the marls since the tunnel's construction. Some grout did in fact escape to the ground surface during injection and also appeared on the river bed in the vicinity of the original leakage. The work successfully reduced water ingress to manageable proportions, and also forestalled the development of further leak paths by reducing possible erosion of the ground.

Cement grouts are commonly used in tunnelling to consolidate concrete sections after they have been placed. Their use in leak sealing is a product of this experience. Material is normally introduced from inside the tunnel through relatively large diameter (typically 50 mm) injection points. The approach can be considered to be indirect since the leak paths are not tackled directly. In contrast to resin injection, cement grout relies upon bulk displacement of water for its leak-sealing properties, rather than the ability to fill water passages. It is advantageous if the extent of voidage around the tunnel is known, and this may be estimated from probe measurements taken at regular intervals along its length. Together with the pressure and availability of groundwater and the local geology, this has considerable influence over the choice of grouting materials. Mix design must be given careful consideration where large quantities are involved, and the setting time should be regulated so the material can travel to the necessary extent, without permitting displacement of significant amounts back into the tunnel. The consistency of grout is also important; the liquid state may have to be cohesive so that water movement will not disperse it. It also has to be able to hold back water while it cures, otherwise leakage will recur. These properties are normally achieved by using a long-chain polymer additive in the mix (8,9).

In contrast to in-situ cast structures, leakage into sectional tunnels is usually quite extensive. Although pressures may be quite high, the water passages are typically large and can be easy to seal by direct injection of resin systems.

Upstream of the Severn Railway Tunnel lies a cable tunnel which runs under the Rivers Severn and Wye. This has undergone remedial work to combat water ingress during annual shutdown periods since it was opened in 1975. Until recently, traditional cold-caulking systems were used which included local applications of flashset cement compounds. This only served to divert the water, and in 1981 a contractor was employed to inject resin against the leakage. The water was emerging from around securing bolts and from positions along the joints between sections. In many cases these were connected, so point leakage could easily be relieved by removing the closest securing bolt. The design of the sections included a central caulking groove, so a method was devised to introduce resin into this, which allowed it to follow the water through the leak

Figure 9.8 Preparing to tackle a leak from the invert of a cable tunnel

paths. The work was quite successful and water ingress was reduced to manageable proportions after three shutdown periods.

9.9.2
Leak sealing in pipelines

Segmental concrete pipelines are often troubled by leakage problems which may be categorized as follows:

Defective pipeline joints
Point leakage through pipe walls
Cracks in the pipes.

Cracked pipes are normally rejected prior to placing, so they are only found underground in rare situations where there has been excessive settlement in the line which has caused segments to crack. The other two problems, though, are quite commonly encountered.

Point leakages may be referred to as 'stars' in the pipe wall, and are due to defective manufacture. These would be quite easily sealed by drilling and grouting, except that they generally occur in unreinforced pipes which tend to be of small cross-section. This obviously imposes restrictions, but specialist teams have successfully sealed leaks of this kind 100 m along a 450 mm diameter pipeline.

Pipeline joints are normally sealed with rubber 'O' rings which may fail for a variety of reasons. Usually though, settlement of the pipe bedding is responsible for spigot and socket openings at the crown or on the invert. If the line is displaced sideways for any reason, the joints will widen at the sides. The methods employed for sealing leakage of this sort are the same as those used for coping with defective expansion joints. The requirements are similar, the joints must be able to cope with further movement. Pipeline joints, however, are easier to seal than leaking joints in cast-in-situ structures. The spigot wall is thin enough to allow indirect techniques to be applied and in most cases, they are successful. Direct injection is less reliable because water ingress tends to be very fast, making the use of adhesive anchorages very difficult. Machinery has been developed over recent years to place a mechanical seal over pipeline joints to allow hydrostatic testing. The same equipment may also be used to inject flexible resin directly into defective joints. Using indirect techniques is less capital intensive though and is more applicable to smaller jobs.

In past years, sealing of pipeline joints has been a frustrating and expensive occupation, and in some cases, a single joint has taken several weeks to repair. More recently though, the situation has improved, and a two-man team with up-to-date materials and techniques can be expected to seal several pipeline joints in a day. The success rate of course much depends on access and other site conditions. The work area must be kept clear of water so that sources of ingress can be accurately pinpointed. After leakage has been sealed, the line must be dried out to allow the affected joints to be cleaned out and face sealed to form a secondary barrier (see section 9.4).

9.10
Conclusion

Sealing leakage of water through structural concrete, and into or out of precast sectional tunnels or concrete pipelines must be considered in perspective. Leak sealing is invariably expensive, so the operation must be necessary and worthwhile. In some cases, proprietary methods such as lead-wool caulking may succeed and avoid the unnecessary expense of calling in subcontractors. The possibility of coating the water-retaining side should be considered as a cost effective option, and should be used if applicable.

Where these measures are not sufficient, outside assistance should be sought, and repair methods discussed in detail to establish the likely extent of work involved. Contractors may not wish to reveal exact methods, but an understanding of their general approach to the situation is essential. In some cases it may be necessary for a test to be conducted to establish whether a proposed method is likely to be successful. If it is not successful, an alternative approach may be proposed and tried. In some cases, particularly when details of the structure are only vaguely known or access is greatly restricted, it will be necessary to admit defeat. These situations often include leaks which persist after all the others have been sealed, and the last few metres of a tunnel which has otherwise been successfully grouted. The remaining option will then be to control the leak and lead it away to a sump.

On a more positive note however, considerable research is now being undertaken involving methods and materials for sealing leaks, and the companies involved are becoming more knowledgeable. A choice of low viscosity resins is now available; some are designed for sealing leaks only, and others of slightly higher viscosity are strong enough when cured to repair structural concrete as well.

The work continues and represents a changing attitude towards leak sealing. Once information is freely available, it might be regarded less as an obscure art, and more in terms of a science. This will certainly please quality assurance engineers, who are understandably disconcerted when confronted by subcontractors with sparsely laid down working methods.

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10
Surface coatings

S.C.EDWARDS

10.1
Introduction

During the last forty years there has been a steadily increasing requirement for coating systems from all sections of industry. Paint manufacturing companies have been able to exploit the growing availability of raw materials from the oil industry to meet this demand, much of which has been from construction companies.

The use of concrete has also grown since World War II, largely on account of its versatility. By its very nature, though, reinforced concrete is susceptible to attack from some chemicals, and in many cases coatings may be used to provide protection. A coating may be described as a material, applied to a substrate, which forms a continuous membrane. Although this definition includes polythene sheeting and other such materials, the following chapter will concern itself with fluid coatings which adhere to the concrete and form films after application.

When concrete cures, approximately 25 percent of the water is retained as water of crystallization and 15 percent as gel. Capillary pores are formed during evaporation of the remaining 60 percent and eventually the 15 percent gel water. Concrete is strongly alkaline, and as such it is susceptible to attack from acidic reagents. The capillary pores allow carbon dioxide and other gases to diffuse into the concrete and dissolve in the pore water to form acidic solutions. Furthermore, the porosity of the concrete encourages absorption of water, which often carries harmful reagents in solution.

The water absorption coefficient A for concrete is approximately 2 $kgm^{-2}\ h^{-0.5}$. Paint, however, absorbs much less water. The figure for some two-pack polyurethane paints, for example, lies between 0.03 and 0.07 $kgm^{-2}\ h^{-0.5}$. More significantly, though, some pitch modified polyurethanes, epoxy and vinyl coatings allow no water penetration at all (1).

Vapour and gas diffusion must also be considered. The amount of water present within a concrete member will vary in relation to the ambient humidity. As the humidity rises, water vapour will travel into the pores, and when it falls vapour will diffuse back out again. When coatings are applied to concrete, diffusion of vapours and gases is affected. The extent of this depends upon μ, the gas diffusion resistance coefficient, of the coating. More commonly this is quoted as μs, the gas diffusion equivalent in static air, which is expressed in metres. The μ_s value for a 250 mm thickness of concrete, for example, is between 6 and 8 metres, depending upon its density. For 0.035 mm (0.0015 in.) of two-pack polyurethane paint, however, μs will be around 1.75 m, and for other less porous coatings the figure will be much higher. It can be concluded then that water absorption and passage of vapour normally allowed by concrete can be significantly controlled by application of suitable coatings. Furthermore, coatings can exhibit better chemical resistance than does concrete, so they may be used as a barrier to protect it against aggressive reagents (2).

It is preferable in most circumstances to use a material which affords the necessary protection while still allowing free passage of water vapour. Generally, this combination becomes more difficult to achieve in aggressive environments, where the paint film needs to be of lower porosity.

The correct choice of coating is therefore important and, at first sight, the range of materials on the market might appear bewildering. This chapter will categorize some of those more commonly encountered, and broadly identify their more suitable applications. It is not prudent, however, to make general statements about coating specification. Many materials have individual characteristics, which might render them suitable for application in circumstances where a different type of material would normally be called for.

Surface preparation and methods of application warrant particular attention, especially with regard to their potential impact on other aspects of site construction and maintenance. Some methods are fast, but may cause considerable inconvenience. Others, however, are slow, and involve considerable downtime. In summary, this chapter presents a broad working profile of coating systems and their application to reinforced concrete. Although the emphasis is upon remedial applications, much of the text is relevant to the use of coatings for the protection of new structures. It is expected that this will be helpful to the engineer, because surface coatings are finding so many new applications in the construction and concrete repair industries.

10.2 The use of protective coatings in concrete repair and maintenance

10.2.1 *Coatings to resist attack from the atmosphere*

10.2.1.1 *Anti-carbonation coatings.* Concrete may be exposed to many environmental conditions against which it requires protection. Among the less aggressive of these is atmospheric carbonation. The process is given more detailed attention in Chapter 2 (section 2.2.2).

Carbonation occurs because carbon dioxide diffuses into the concrete and dissolves in the pore water. This produces carbonic acid which reacts with the free lime to form calcium carbonate. Although this acts as a partial barrier to further carbonation, the process is progressive, except in very dense concrete, and it leads to a gradual fall in pH. Once carbonation reaches the reinforcement, depassivation of the steel results in corrosion and spalling when water and oxygen are present.

Coatings may be applied to concrete to arrest the carbonation process. These are known as anti-carbonation coatings and are normally based on chlorinated rubber, polyurethane resins or acrylic emulsions (3, 4). Although they are principally designed to prevent diffusion of carbon dioxide and oxygen into the concrete, the coatings will also limit or prevent penetration of chlorides in solution.

In most cases, anti-carbonation coatings allow free passage of water vapour. This is so that vapour pressure does not build up behind the paint film and cause it to blister. It has been argued, though, that this is unnecessary and that adequate surface preparation will allow a relatively impervious film to be applied without subsequent loss of adhesion (5). Although this is correct, and there are numerous examples of such coatings which have been successfully applied to concrete, it is not necessary to use impervious materials as anti-carbonation coatings. It should also be emphasized that adequate surface preparation is required prior to the application of all coatings where a long and effective service life is expected.

Anti-carbonation coatings may be effectively used to resist carbonation and general atmospheric deterioration of the concrete. In cases where carbonation has occurred but has not reached the reinforcing steel, application of a coating system will limit the ingress of oxygen, carbon dioxide and moisture and will reduce the rate of deterioration of the concrete. It should be emphasized that concrete should be coated only after a suitable pore filler or levelling coat has been applied (section 10.4.1).

Where corrosion and spalling are widespread, anti-carbonation coatings are used as the final part of the repair specification. They are applied after the patch repairs have been carried out, in order to prevent further carbonation of the original concrete (Chapters 6 and 8).

10.2.1.2 *Coatings to resist the effects of acid environments.* In addition to the constant ingress of gases which lead to a lower pH within the concrete matrix, concrete structures are occasionally subject to abnormally acidic environments. This is most often due to combustion of fossil fuels, or of elemental sulphur which occurs at chemical plants. This releases sulphur dioxide into the atmosphere which readily dissolves in rainwater and forms sulphurous acid. Limited amounts of sulphur trioxide are also present in flue gases, so some sulphuric acid may be produced as well.

At power stations and steelworks where tall chimneys are used, most of the sulphur dioxide is carried away in air currents, and damage occurring on the plant is limited to etching around the top section of the chimney. On chemical plants where gas may be lost accidentally and released through ventilators, it is more likely to cause local damage to the plant. The effects of acidic rain tend to accumulate over a number of years and result in direct etching of the concrete, leaving an exposed aggregate finish on vertical surfaces. Where the concrete is in prolonged contact with the water due to poor drainage, the effects will be more severe, and partial or complete disintegration is not uncommon.

In the situations described above, the coatings needed to arrest the process of acid attack may be different from those normally specified as anti-carbonation coatings. They have to withstand more aggressive conditions, and in some cases a fairly high degree of chemical resistance (refer to Table 10.1, pages 133–134) may be necessary to afford protection to the substrate. Under most circumstances, two-part polyurethane coatings will cope well with the relatively dilute acids and still allow passage of water vapour through the film. There are situations, though, where the surface will have become quite badly etched and there will be difficulty achieving a continuous film. This is particularly relevant to the materials described above, because they are normally applied in relatively thin coats. In these circumstances it may be preferable to use a high-build epoxy paint to achieve the necessary protection, or to apply a suitable levelling coat prior to applying the specified coating.

10.2.2
Bridge deck coatings

During the winter months, many tonnes of de-icing salts are spread on the roads, producing large volumes of concentrated chloride solution. Some of this will percolate through to concrete bridge decks, entering construction joints and fine cracks in the surface and promoting the corrosion of the reinforcing steel. Modern bridge designs incorporate waterproof membranes which are applied to the decks in order to protect them against chloride attack. Some older bridges, though, are not provided with this protection, and spray application of a suitable membrane is one of the alternatives which may be specified when the deck is stripped for maintenance.

The existing standard for the protection of bridge decks, Technical Memorandum BE 27 (6), has become outdated on account of the increased number of types of membrane which are now available. As well as this, problems have been experienced with certain types of material. The Department of Transport therefore commissioned an extensive study of bridge membrane systems. A suitable bridge deck membrane has to withstand construction traffic before the asphalt is laid. It is also subject to heat from the asphalt and compaction forces during rolling. Thereafter, it must contend with traffic loading and other factors including the thermal stresses of the environment.

In order to investigate the suitability of materials, samples of spray-applied and preformed membranes were laid and each provided with protection over identifiable areas. The slab was divided lengthways, and hot-rolled asphalt with stone aggregate was laid on one side and an asphalt sand carpet on the other. In both cases, normal road laying machinery was used, so the membranes were subject to authentic site conditions. The outcome of these tests was reported in 1990 (7). A list of performance tests required for bridge deck coatings has been specified by the Department of Transport and product approvals are being handled by the British Board of Agrément.

10.2.3
Coatings to protect cracked concrete

10.2.3.1 *Conventional coatings.* Despite the efforts of design engineers, concrete is inherently prone to cracking. Cracks may occur in roof slabs, and so these are protected by membranes of many descriptions. In time, though, flat concrete roofs may need maintenance, and local repair is rarely satisfactory. The best approach is to strip and replace the original membrane. As with bridge decks, the application of liquid coatings is only one of the available alternatives. A significant difference between roof coatings and those for bridge decks which may not be immediately obvious is that the former are exposed to sunlight. Ultraviolet light can be very damaging to coatings, and this limits the choice of paint systems which are suitable.

Coatings are quite often applied locally over cracks to prevent ingress of water and carbon dioxide. Cracks which are protected in this way are normally very fine and not considered to have any structural significance. Repair of such cracks by resin injection tends not to be recommended in structures where movement is anticipated, because new cracks are likely to form. It is therefore necessary for coatings used in this type of repair to have flexibility as well as the ability to bridge cracks. High-build polyurethane and epoxy-polyurethane formulations have both been successfully used in this application. The method has been deployed to cover cracks in some offshore structures which would otherwise have been subjected to chloride attack. Coatings have also been successfully used to protect concrete affected by alkali silica reaction. The main requirement of such a coating is that it should be able to bridge cracks and also be flexible enough to accommodate further movement.

10.2.3.2 *Surface impregnants.* Silicone products have been used as masonry water repellents for more than thirty years. Originally, protection was confined to ceramic, non-alkaline building materials, but the late 1970s and 1980s have seen the development of materials suitable for most substrates including concrete. Strictly speaking, surface impregnants are not coatings, but they have been used quite extensively in related applications in recent years. A significant advantage offered by some of these materials is that they seal the surface without altering its appearance.

10.2.3.3 *Silanes.* Silanes are silicon-based products of low molecular weight which are recommended for use as hydrophobic impregnants for new concrete. They impregnate the pores of the concrete and, in the presence of moisture, chemically bond with silicon-based molecules on the inner surfaces. The active part of the molecule is the hydrophobic residue which lines the inner surfaces of the pores after application. The surface of the concrete then becomes resistant against impregnation by water at low pressure and subsequent attack from dissolved gases such as carbon and sulphur dioxides.

Silanes have been used extensively on the Continent and more recently in the UK, to protect underdeck beams of highway structures, which would otherwise be subject to chloride attack from dissolved de-icing salts (8). They have been successfully deployed to prevent water ingress to fine cracks in a number of structures, and they have been tested for the protection of reinforced concrete bridge decks (9). It should be emphasized that silanes are not suitable to act as a barrier against water penetration under pressure and, as such, cannot be used in place of coatings in such situations (10).

10.2.3.4 *Siloxanes.* Siloxanes are silicon-based impregnants with a higher molecular weight than silanes. Consequently, they cannot achieve the same extent of penetration. Their use is recommended on older concrete structures where surface laitances are weathered and offer less resistance against impregnation. Siloxanes are also significantly cheaper than silanes and offer a similar degree of protection when used under the correct circumstances.

10.2.3.5 *Overcoating of impregnants.* Although the water repellent properties of silanes and siloxanes are advantageous, their use leads to increased diffusion of carbon dioxide and other gases into the concrete. This is because the water content of the surface pores becomes significantly lower, and consequently less resistance is offered against diffusion. It is for this reason that these materials are occasionally overcoated with anti-carbonation coatings (11). This has the dual advantage of increasing gas diffusion resistance and promoting adhesion between the coating and the concrete. There is some argument regarding the necessity for overcoating impregnants. If the level of moisture within the pores becomes significantly lower, then potentially harmful gases will not dissolve as readily and will have less effect on the structure. In this context, overcoating will provide double protection which might be considered unnecessary.

10.2.4 *Coating concrete pipes and culverts*

Concrete pipes have been used extensively as aqueducts in upland water catchment areas. As well as being exposed to aggressive weather conditions, the pipes are subject internally to relatively acidic water. Moorland water contains dissolved organic acids (referred to as humic acids) and limited amounts of sulphuric and sulphurous acids which originate from sulphate deposits in the

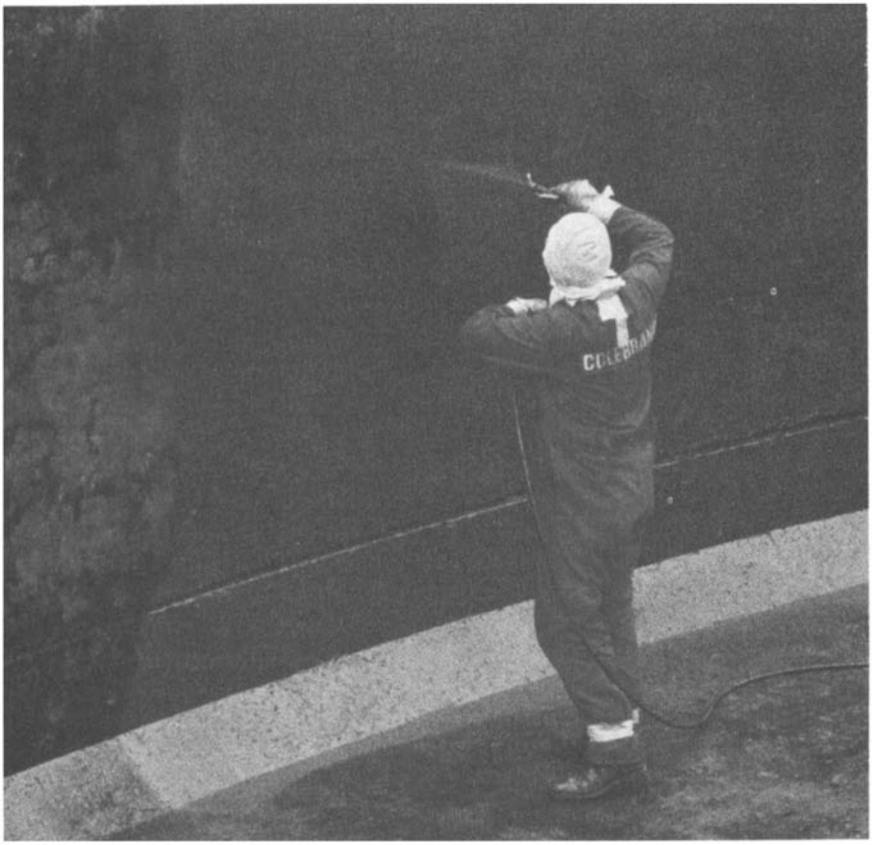

Figure 10.1 Application of waterproof coating to reinforced concrete culvert crossing over motorway

ground (11). These, together with carbon dioxide in solution, are products of bacterial activity.

The fact that water is flowing in the pipes is significant; the supply of acid is constantly replenished, and the salts produced by the reaction are washed away. The latter process is assisted by constant abrasion from the stones and gravel which are carried through the invert. Production of pipe segments results in particularly dense concrete, which is in accordance with BS 5911 (12).

This has good chemical and abrasion resistance, and is therefore better able to withstand the conditions described above than *in-situ* cast concrete. It is not uncommon, however, to find reinforcement exposed in the inverts of pipe segments when they are used for this purpose. High-build pitch epoxy coatings are among those which may be used to remedy the situation, which demands robustness and good water resistance. Coating systems are normally applied to the bottom third of the aqueduct which is where most of the damage occurs.

10.2.5
Remedial applications in sewers and effluent treatment plant

Concrete sewer pipes may be subject to attack from factory effluents which tend to be discharged at night when the dilution factor will be at its lowest. This is a more significant problem in countries where the disposal of liquid waste is not so carefully controlled as it is in Britain. The pH of sewage normally fluctuates around 7, which presents no hazard to concrete. The majority of significant damage occurs not in the invert of the sewer, but at the waterline and over the crown of the pipe, which in time will lead to sewer collapse. The attack is due to the production of hydrogen sulphide gas by sulphate-reducing bacteria. This takes place under anaerobic conditions existing in the slime layer which adheres to the invert of the sewer. The upper slime layer is aerobic, and some of the gas produced will be oxidized to thiosulphate as it diffuses through it, while the remainder will dissolve in the stream. The concentration of hydrogen sulphide in sewage builds up as the stream progresses, so it eventually begins to diffuse into the atmosphere. In dry conditions, crystals of elemental sulphur will be formed, but the gas normally becomes dissolved in surface condensation where it is oxidized to sulphuric acid by a species of bacteria named *Thiobacillus concretivorus*. The acid reacts with free lime in the concrete to form calcium sulphate (13). This in turn will combine with alumina present in the concrete to form the double salt calcium aluminium sulphate, which crystallizes with thirty molecules of water. This requires much more space, created by cracking the concrete. The final stage of the process is that calcium aluminium sulphate, which is unstable, reacts in the presence of water. This produces a pasty material, consisting of aluminium hydroxide, gypsum and residual aggregate from the concrete. The presence of this layer slows the diffusion of hydrogen sulphide into the concrete. In the band between high and low water, however, the slime is washed away intermittently; so sulphuric acid migrating down the walls, and hydrogen sulphide gas, are allowed unobstructed access to the concrete. It is for this reason that damage is most significant at the water line.

The process described above relies upon anaerobic slime below the water level and the presence of oxygen above it. The level of sulphuric acid attack is therefore specific to the flow rate and other prevailing conditions which are outside the scope of this chapter. It is necessary, though, to determine the likely level of attack before a protective coating can be specified. Some thiobacilli can withstand concentrations of sulphuric acid up to 7 percent, which is around pH 0. 2. Application of a coating to prevent the acid reacting with the concrete will allow higher concentrations to develop, which may subsequently damage the coating.

Materials are available which will withstand acid conditions. Vinyl coatings are resistant to the most severe conditions while amine-cured epoxies can be used in less aggressive circumstances. Two-pack polyurethane paints can also withstand milder conditions, but difficulties may be encountered during application if the system is at all sensitive to surface moisture. Whichever coating system is specified, it must be applied at a relatively high film thickness. This is because surface preparation has to be very thorough to remove all traces of disintegrating concrete, and this leaves an uneven surface upon which it is difficult to apply a continuous coating as a thin film. In these situations, vinyl and polyurethane coatings have to be applied in several coats to attain the necessary film thickness. Coating application is further hampered by practical difficulties peculiar to sewer renovation. The worst affected sewers are invariably those which can only be shut down for limited periods, owing to the number of connections running into them.

Concrete inlet channels to sewage treatment works may be subject to a limited amount of leaching due to dissolved acids which have accumulated in the effluent. The acidity of sewage at this stage sometimes reaches pH 6 or lower during fine weather when rainwater dilution is low. Where affected, the channels may be lined with pitch epoxy or a coating with similar protective properties. Normally, though, the low pH values are anticipated and catered for prior to construction.

Many effluent treatment plants include the anaerobic digestion process for breaking down sludge. This yields methane as a byproduct, which is stored and used as fuel for plant and vehicles. The conditions inside the digester are anaerobic, so small amounts of hydrogen sulphide may be produced, a little of which reaches the atmosphere above the sludge. Oxygen is present in limited quantities so sulphuric acid can be formed by the same process as takes place in the sewers. This results in gradual deterioration of the gas dome and losses of methane to the atmosphere. The positions of leakage may be determined by brushing soapy water over the dome while it is in service. This will cause bubbles to form at the points where gas is escaping.

In the circumstances described above, an internal lining can be applied to prevent the gas escaping and to protect the dome against further damage. pH values in digesters tend to be higher than those normally encountered in sewers, so the choice of lining material is not as limited. It is advantageous if the coating has a degree of flexibility, because the plant usually operates at temperatures above the ambient levels normally encountered during paint application.

Application of linings to concrete gas domes is often hampered by the extent of damage which has occurred. The surface tends to be quite soft, and grit blasting will result in an exposed aggregate finish. In extreme cases this will require extensive filling prior to the coating being applied. It may also be advisable to inject construction joints and obvious cracks with a suitable resin. If it is considered necessary, the injection work should be undertaken after the coating has been applied and allowed to cure.

10.2.6
Tank linings

Concrete tanks and other liquid-retaining structures may be lined for a variety of reasons. Internal linings may be specified to prevent structures from leaking, in which case the coating has to be capable of bridging cracks and be compatible with the material inside the tank. In other cases, linings may be used to prevent spoiling of the contents as a result of reaction with the concrete. Most commonly, though, tank linings are specified to prevent potential reagents from damaging the structure.

Demineralization plants use strong acids and alkalis to regenerate ion exchange resins. These areas are subject to splashes and short periods of standing contact with strong reagents. Where various structures such as bund walls are built from concrete, coatings may be used for their protection. The exposure conditions of these areas are known and easily controlled, so a suitable coating will have a long service life. Effluent trenches and buffer tanks, however, are subject to a greater variation in pH, and are therefore more likely to require remedial coatings. In less severe conditions, suitable materials include vinyl, polyurethane and pitch epoxy, but in some circumstances reinforced bisphenol polyesters may be more reliable because they remain resistant over a wider range of pH.

Experience has shown that the internal surfaces of these tanks can become quite badly damaged, as deterioration of the original lining tends to go unnoticed. In these situations, extensive preparatory work is necessary to provide a sound substrate for the new coating. This may necessitate the use of a trowel-applied material to build the surface back to its original profile before the protective lining can be applied.

Water towers are often protected externally against the weather, but it is not normal practice to apply linings. In soft-water areas, towers and supply reservoirs may be subject to acidic water, but the potential effects of this are normally catered for in the original mix design.

Coatings are most often used to line drinking-water tanks when they are cracked and leaking. The materials recommended for this purpose must be tested and approved by the Water Research Council which lays down standards (14) for the following:*

(i) Organoleptic and physical deterioration of the water
(ii) The release of any toxic metals into the water
(iii) The release of any cytotoxic compounds into the water
(iv) The ability of the material to support the growth of microorganisms either in the water in contact with the material, or on the surface of the material.

The list of approved coatings is included in the *Water Fittings and Materials Directory* (15).

10.3
Types of coating available

10.3.1
Constituent raw materials

Coatings comprise a blend of ingredients which cure to form a cohesive film. The behaviour of the paint as a liquid, and of the cured coating, depend largely upon the relative quantities and types of raw materials used. These include

Table 10.1 Binders commonly used in coating for concrete

Binders	*Curing reaction*	*Classification of coating*	*Typical dry film thick-ness depending on formulation*	*Examples of normal applications*
Two-part epoxy resin system	By reaction with hardener component	Solvent-based	0.020–0.250 mm	Abrasion-resistant paints, floor coatings, tank linings suitable for drinking water and chemical resistant finishes
		Solvent-free	Up to 15.0 mm	Structural pipe linings and trowellable surfaces
		Water-borne	0.040–0.120 mm	Medium viscosity coatings without solvent hazards, floor coatings
Two-part polyurethane resin system	By reaction with hardener component	Solvent-based	0.025–0.075 mm	Anti-carbonation coatings, high gloss decontaminable and chemical-resistant finishes with good solvent resistance anti-

*Items (i)-(iv) are verbatim quotations from the UK water fitting and by-laws scheme (Information and Guidance Note No. 5–01–02, 1985).

Binders	*Curing reaction*	*Classification of coating*	*Typical dry film thick-ness depending on formulation*	*Examples of normal applications*
				graffiti coatings
		Solvent-free	0.500–2.00 mm	Heavy-duty floor coatings
Single pack polyure-thane	By reaction with atmospheric moisture	Solvent-based	0.125–0.150 mm	Floor coatings and anti-skid dressings
Epoxy polyurethane	By reaction with common hardener component	Solvent-based	0.100–0.250 mm	High-build anti-carbonation coatings and coatings with good flexibility capable of bridging cracks
Vinyl	By solvent evaporation	Solvent-based	0.025–0.70 mm	Chemical-resistant coatings for aggressive conditions but with poor solvent resistance
Chlorinated rubber	By solvent evaporation	Solvent-based	0.100–0.300 mm	Anti-carbonation coatings which may be applied in cold conditions suitable for tank linings in some situations, particularly where ease of cleaning is necessary
Acrylic/latex emulsion	By water evaporation	Water-borne	0.100–0.700 mm depending on formulation and application	Anti-carbonation coatings with excellent colour stability and roof

				coatings with good resistance against ultravoilet light, crack-bridging coatings
Polyester resin solution in styrene	Polymerizes following the addition of peroxide catalyst	100% solids but styrene is volatile and some evaporates during cure	Up to 1.5 mm depending on weight of glass	With glass fibre and other materials for reinforced linings to tanks, manholes and pipes. Also have very good chemical resistance

binders, diluents, fillers, pigments and solvents, some or all of which may be used as the main constituents of a coating.

10.3.1.1 *Binders.* The active ingredient of coatings is the binder, which integrates the components into a cohesive film. These include various types of liquid organic resins or solid resins in solution. Whichever sort is involved, the paint solidifies when the binder cures. Table 10.1 includes some of the main types of binder available and illustrates their use in coatings for the construction industry.

The reactive constituents are among the most expensive parts of a coating, and used alone they have very limited application. Diluents, solvents and fillers are therefore used to attain more suitable properties, with the added advantage in most cases of reducing raw material costs.

10.3.1.2 *Diluents.* In general terms, diluents are liquid extenders which increase the fluid content of the system and usually reduce its viscosity. Some diluents are reactive, in which case they are polymerized into the system. Normally, though, they are non-reactive and act as plasticizers which lend flexibility to the cured system at the expense of chemical resistance. The inclusion of either type of diluent into a coating will allow a greater proportion of fillers to be added.

10.3.1.3 *Solvents.* Solvents are volatile organic liquids in which the constituent resins and diluents of a coating are soluble. They are normally non-reactive and form no part of the cured paint system. Solvents are included primarily to thin or lower the viscosity of coatings to facilitate their application, particularly in cases where the material is based on viscous or solid resins. In addition, their inclusion is particularly helpful to paint formulators, who are able to determine finish, texture and other characteristics by deploying different types and quantities of solvent.

10.3.1.4 *Fillers and pigments.* The inclusion of solvents and diluents in paint formulations will allow a greater proportion of fillers and pigments to be added. Fillers are normally inert, graded powders which are used in coatings for a variety of reasons. A particular blend of fillers will give thixotropy to the coating and allow it to be applied at relatively high film thicknesses on vertical surfaces. Other fillers will confer abrasion resistance. In addition, individual fillers are recommended for use with particular types of binder, or for specific environmental conditions once the coating is in service.

In contrast to fillers, which tend to be opalescent, pigments are very finely ground, opaque powders. Pigments are used to colour coatings for cosmetic purposes, or to tint base and hardener components of two-part products in contrasting shades, to ensure thorough mixing by applicators.

10.3.2
Solvent-based coatings

Solvent-based coatings are perhaps the most commonly used in the construction industry due to their versatility, and the wide range available. From a practical point of view, they are easily applied and where large areas are involved, airless spray or roller is the most commonly used method (see section 10.5). However, solvent-based paints are not without their drawbacks. Although these coatings can be tailored for most available methods of application, paint film thicknesses must not be so high that solvents cannot escape. This is particularly relevant to epoxy paints which are especially prone to solvent retention. Careful control of wet film thickness is therefore necessary during application, otherwise the cured film is likely to blister, particularly if the structure is subject to immersion. Solvent retention is more likely to occur if ventilation is insufficient. In these cases, mechanical ventilation must be provided to ensure that all of the solvent evaporates before the film cures.

The construction industry is becoming more affected by controls on emissions of organic solvents, and considerable precautions must be taken to satisfy health and safety regulations. In 1988 the COSHH regulations came into force within the industry, and companies not doing so already were obliged to ensure that the necessary safe handling information about the materials was provided to the personnel engaged in using them. It was also required that the material was ‘assessed’ and if it was found to be potentially damaging to the user or anybody else in the area, then another, less hazardous material should be used in its place, or appropriate measures taken to protect personnel likely to be affected. Although this was incumbent upon the employer before the COSHH regulations came into force, the regulations required the process to be formalized and the materials assessment put in writing together with any precautionary measures which would have to be taken (16).

Most solvents used in coatings for concrete are highly flammable, and potentially explosive above specific concentrations in air. This level is referred to

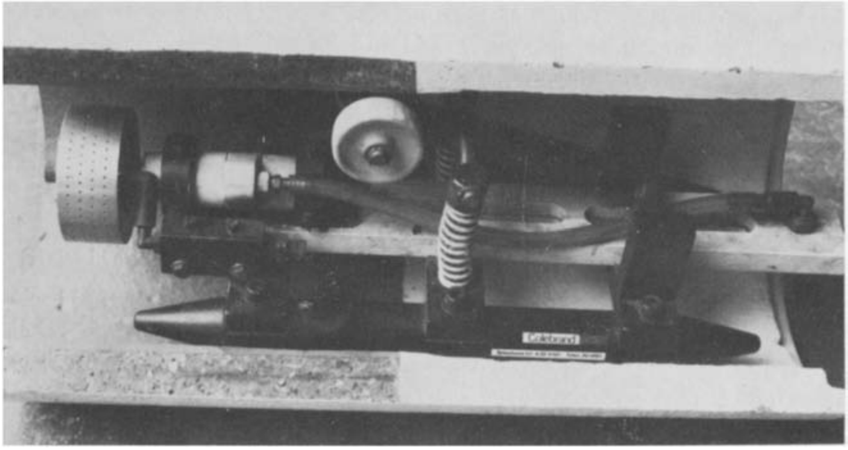

Figure 10.2 Paint spinner designed to apply high-build thixotropic materials for structural lining of concrete pipes (photograph courtesy Colebrand Ltd)

as the Lower Explosive Limit (LEL) (17). During paint application in enclosed spaces where this limit is likely to be exceeded, mechanical ventilation should be provided, capable of maintaining the solvent vapour level below 25% of the LEL. In addition, scaffolding and all spray equipment should be earthed to eliminate the risk of static build up and subsequent sparking.

Those solvents which are not flammable, 1, 1, 1-trichloroethane for example, may be particularly harmful. In fact the majority of solvents fall into both categories, to a greater or lesser extent. Threshold Limit Values (TLVs) refer to the time-weighted average concentration of airborne vapours for a normal 8-hour working day, or 40-hour working week, to which nearly all workers may be repeatedly exposed, day after day without adverse effect (18). Enclosed spaces should therefore be thoroughly ventilated during paint application, and if this is inadequate to keep the vapour below TLV then positive pressure air-fed breathing apparatus should be used by applicators.

10.3.3
Solvent-free coatings

To overcome some of the difficulties encountered with solvents, a significant number of solvent-free coatings are on the market. These are distinct from solventless coatings which contain a very small proportion of solvent. Solvent-free coatings can be divided into conventional liquid coatings and surfacers that may be trowelled. The latter are often used as the first coat on uneven surfaces, or to fill blowholes following surface preparation. There are, however, specific examples of solvent-free materials designed to achieve a very high-build film in one application. Figure 10.2 shows a paint spinner designed to apply this type of material to the internal surfaces of damaged concrete sewer pipes to effect a

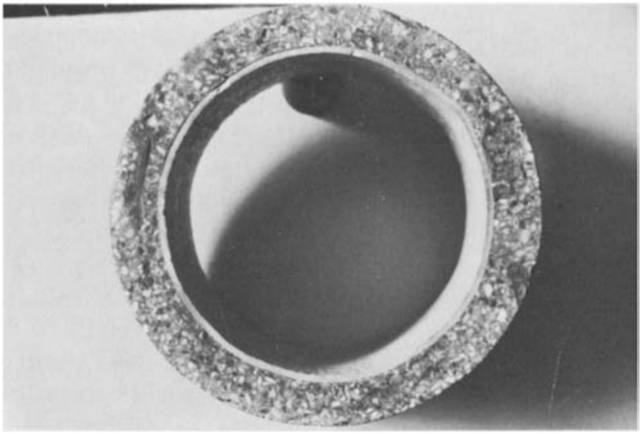

Figure 10.3 Section of concrete pipe to which a high-build structural lining has been spinapplied (photograph courtesy Colebrand Ltd)

structural repair. Figure 10.3, showing a section of pipe which has been coated, demonstrates the film thickness which can be achieved.

Liquid solvent-free coatings can be applied in place of solvent-based materials in many cases. As with the pipe coating described above, greater film thicknesses can be expected from a single application than could normally be achieved with conventional systems, with the added advantage that there is no risk of solvent entrapment. Some high-build coatings can suffer from exotherm problems though, resulting in delamination from the concrete. In these cases there is a limit to the film thickness which can be applied in a single application.

Solvent-free coatings are most often specified because of the reduced risk of toxicity and fire hazard during application. Their favoured application in this respect is to large areas of flooring where adequate ventilation of solvent-based materials would be uneconomic. Other reasons for using these coatings on floors include their high build, and the relative ease of achieving self-levelling properties. Their major disadvantage is that they are relatively difficult to apply in comparison to their solvent-based counterparts; this is primarily due to their higher viscosity. They are very often applied using rollers, but in some cases it may be preferable to use squeegees.

10.3.4
Water-borne coatings

Another approach to the problems associated with solvents and their removal from coating formulations is to suspend or emulsify the uncured material in water. The water acts not as a solvent but simply as a vehicle for the paint system. The most obvious example of this is household emulsion paint which comprises pigments dispersed in acrylic resin emulsified with water. This system is in fact the basis for some reflective roof coatings which are used quite extensively by the construction industry. Furthermore, water-based acrylics are among the best anti-carbonation coatings (19).

Chemical-resistant and high-build materials are more difficult to formulate using these resins, because there are fewer raw materials which are suitable for water-borne coatings. Demand has grown in recent years, however, particularly since the advent of the COSHH regulations. As a result of this, there is a wider range of water-borne coatings now available. Epoxy resins form the basis of many industrial paint systems and, using these, the range of water-based paints has been significantly improved. Some earlier systems suffered from short pot lives and exceptionally long cure times in thin film. These formulations have now been superseded by technically superior products which are capable in some cases of better performance than solvent-based epoxies. A good balance of chemical-resistant and physical properties has encouraged their application in food-processing factories and hospitals as floor and wall coatings where their solvent-based counterparts might not have been acceptable.

In many respects, water-borne coatings compete with solvent-based materials whose principal advantage over solvent-free coatings is reduced viscosity. Water-borne coatings, too, are easily applied using conventional methods, whereas some solvent-free materials have a tendency to be sticky and unmanageable. The major disadvantage of water-borne coatings is that they will not cure properly in humid conditions which do not allow sufficient water evaporation. In such cases mechanical ventilation is necessary, as with solvent-based systems, but the health and safety requirements regarding harmful vapours and potential explosion are not applicable. Water-borne coatings do not cure at all well in cold conditions because the water will not evaporate quickly enough. It should also be pointed out that these materials need to be protected against freezing both during application and storage.

10.3.5
Reinforced coatings

These are typically solvent-free materials reinforced by the addition of flakes or fibres which may be made from several materials, e.g. glass, rayon or polycarbonate. A certain anomaly does exist here, however, because the majority of reinforced coatings likely to be encountered, including conventional glass reinforced polyester, are in fact styrene-based. Styrene is a volatile material, which in this case is used both as a solvent and as a reactive diluent. The system applied, however, is 100% reactive and consequently there is no possibility of solvent entrapment.

Less commonly, epoxide resins are used in fibre-reinforced systems, but tend to be more expensive and are only competitive where polyester will not fulfil the requirements of specification. Another system which is rarely encountered is fibre-reinforced and solvent-based. Epoxy systems are unsuitable for this because they have a tendency to trap solvent, and the presence of fibres associated with a high film thickness will exacerbate the problem. Some polyurethane systems may be more suitable in this respect because they exhibit fewer problems with solvent entrapment. Such materials are rarely used in place of polyesters, however, because the film thickness attainable is not comparable. Their use is confined to applications where the material must be reinforced to endure site conditions, e.g. floor and bridge deck coatings which might be subject to heavy traffic at an early stage of cure. Where solvent-based materials are used in high-build linings with fibre reinforcement, it is best to ensure that as low a proportion of solvents as possible is present.

The fibre-reinforced systems normally encountered tend to be used for repairing liquid-retaining structures which are badly cracked. The reinforcement allows the coating to bridge cracks, and the typically high film thicknesses (3–5 mm) ensure that under normal circumstances there can be no passage of liquid. The high-tensile strength of the material makes it well able to resist cracking if the structure is subject to thermal movement. Conventional coatings do not exhibit comparable strength and would tend to crack.

It is often assumed that the condition of the surface prior to application of fibre-reinforced coatings does not need to be of the same standard as for other types of coating. Heavily blasted concrete, for example, does not provide a good basis because air tends to become trapped behind the laminate. A smooth surface profile is therefore essential, but extensive filling of minor blowholes is unnecessary because the coating will be able to bridge all such imperfections.

Application of reinforced coatings is generally very difficult in comparison with conventional coatings. Low-viscosity glass flake coatings may be applied by brush and roller, and some higher-viscosity grades by spatter gun. More usually, though, they have to be trowel-applied. Fibre-reinforced systems are even more difficult to apply because of their tendency to suffer from air entrapment. They are normally applied in layers by hand-rolling the fibre into the resin with a ribbed roller. The process can be accelerated by using a spraying machine, but the laminate must still be thoroughly rolled to wet out the fibres.

10.4 Surface preparation

10.4.1 *Introduction*

Concrete is a fairly good substrate for coatings on account of its porosity, which provides an excellent mechanical key, but surface preparation of some kind is always necessary to ensure the adhesion of paint to the concrete. This involves the removal of any material which the coating will not adhere to, or which may become disbonded from the surface following application, leading to failure of the paint film.

A further aspect of surface preparation is to ensure that continuity of the paint film is not interrupted by surface imperfections. Sharp edges such as shutter marks should be ground smooth, and blowholes, which are more prevalent on vertical surfaces, should be filled with a suitable filler. Two kinds of filler are available and either may be used, dependent of course on the manufacturer's specification. Polymer-modified cement-based grout is normally preferred on the basis of cost and ease of application. Resin-based grouts are more expensive, but are often specified as part of a complete system.

10.4.2
Preparation of sound concrete surfaces

In many cases it is necessary to apply coatings to concrete which is not in particularly bad condition. This would include the application of anti-carbonation coatings, for example, and tank linings to prevent the escape of the contents. In these circumstances, adhesion of the coating becomes a function of the extent of surface preparation.

The numerical values in Table 10.2 are meant only as a guideline because they are affected by many parameters, including the strength of the concrete and the types of coating involved. In many cases paint systems include primers which may be used before the finishing coat is applied. These promote the adhesion of the coating system, but should not be considered as an alternative to conventional techniques of surface preparation.

In this context the necessary extent of preparation depends upon the purpose for which the coating has been specified and the adhesive values required. Surface preparation should be sufficient to allow the coating to achieve its purpose without involving unnecessary costs. Decorative paints, for example, require a basic standard of preparation which will guarantee good adhesion for a number of years. These materials tend to be renewed quite regularly because they are cosmetic. Most areas are easily accessible and the work involves inconsiderable downtime.

At the other end of the scale, protective linings for effluent tanks cannot be regularly maintained. Access and downtime are both expensive, so it is

Table 10.2 Standards of surface preparation

Standard	*Description*	*Methods*	*Expected tensile adhesion*
Third	Dry and free from grease, free from dust flakes and salts	Application of emulsified degreaser, (where necessary) washing clean with water, scraping and	0.5–1.0 Nmm^2

Standard	*Description*	*Methods*	*Expected tensile adhesion*
		hand wire brushing to remove loose matter and brushing clean	
Second	Dry and free from grease, free from dust, flakes, salts and superficial laitance	Application of emulsified degreaser (where necessary) and washing clean with water scraping off any loose matter, power wire brushing and vacuum cleaning to remove dust	1.5–2.0 Nmm^2
First	Dry and free from grease, free from dust, flakes, salts and laitance, with a sharp even finish	Application of emulsified degreaser (where necessary) and washing clean with water, grit blasting, high-pressure water jetting and acid etching	2.5–3.0 Nmm^2

necessary to ensure that surface preparation is thorough and suitable for the coating concerned.

10.4.3
Preparation of unsound concrete surfaces

Coatings must in many cases be applied to badly damaged concrete or surfaces which have become impregnated with contaminants. In these circumstances, the standard of surface preparation is fairly uniform because the surface must always be abraded back to a sound substrate. The variable factor is the method of preparation needed to achieve this.

Acid-damaged surfaces must be scabbled back to sound concrete, and care must be taken to clean all salts from the surface. Water-soluble salts will cause more permeable coatings such as polyurethanes to blister in immersed conditions or humid atmospheres such as sewers. If necessary, the surface should be water jetted to ensure their removal.

Less severely damaged surfaces such as the insides of aqueducts should be grit blasted to remove all friable matter from the inverts of the pipes. Special attention should be paid to the areas around the waterline because they are quite susceptible to carbonation. They can be tested by tapping with a light hammer to detect areas where the cover may be spalling. Any defective areas found should be cut back and repaired with a resin-based mortar prior to coating.

In cases where surface contamination with grease or oil is suspected, a representative area should be treated with diluted hydrochloric acid. If the solution bubbles, it indicates that the pores of the concrete are sufficiently clean to allow normal methods of surface preparation to be used. If not, a

suitable cleaning method should be found by testing as follows.

Stage 1. Apply emulsified degreaser to an area and scrub in thoroughly. Rinse with water and treat with acid. If the solution reacts with the concrete then the cleaning method will be suitable.

Stage 2. If Stage 1 is unsuccessful, scrub a defined area with a solvent such as trichloroethane. Remove the solvent with detergent and rinse with water. Pour acid over the surface; if it effervesces, the cleaning method will be acceptable.

Stage 3. Remove about 3 mm of the surface using a hand scabbler or needle gun. Treat the area with acid as before; if it reacts the method is suitable. If not, then further concrete should be removed.

In all cases, after the acid has been applied, the area should be thoroughly rinsed with water to prevent the formation of salts.

Leakage of water through concrete is also detrimental to the adhesion of coatings—this is particularly prevalent in basements. The concrete should be thoroughly inspected in order to find damp patches which indicate point leakage. If none are found but the passage of water is still considered likely, polythene can be sealed over a chosen area for a 24-hour period. Water or water vapour travelling through the concrete will then condense on the underside, demonstrating the extent of the problem. See Chapter 9 for further information regarding leakage into structures.

Where new or old concrete is concerned, the tests and observations referred to above can only indicate the likely condition of the surface to be coated. In cases where adhesion is particularly critical, tests may be carried out using an instrument such as the 'Elcometer' adhesion tester, which evaluates the tensile adhesion of a coating to its substrate.

10.4.4
Methods of surface preparation

Methods of surface preparation have so far been given only a little attention and the following paragraphs will consider them in more detail.

10.4.4.1. *Acid etching.* Acid etching is a particularly efficient method of surface preparation, resulting in a sharp even finish ideal for paint application. Although sulphamic acid is recommended where stainless steel is cast into the concrete, a 10% solution of hydrochloric acid is more generally used. The acid reacts readily with the alkaline constituents of the concrete. This exposes particles of fine aggregate within the mortar layer which form a first-class key (20). The acid should be sluiced off with fresh water as soon as the reaction finishes, to prevent the formation of salts which might subsequently cause blistering of the paint film. Several applications are normally necessary to achieve a suitable finish, particularly if the surface laitance is relatively intact.

Where large areas are involved, there may be problems with disposal of the spent acid solution, which is a potentially harmful substance. Care should also be taken when handling the acid, because fumes are given off, and splashes will cause burns. Appropriate protection and proper ventilation is therefore essential when using acid etch techniques.

Etching is especially suitable for areas demanding clean conditions because no dust is produced. Unfortunately, its most effective use is restricted to floors, owing to practical difficulties with other surfaces. Apart from this and the precautions outlined above, it is an excellent and cost-effective method which sets a standard for the surface preparation of concrete.

10.4.4.2 *Power wire brush.* The power wire brush is quite often used to prepare concrete prior to coating. It is undoubtedly more labour-intensive than acid etching, but still comparatively inexpensive with regard to plant charges. Power wire brushing concrete results in a regular and relatively blowhole-free surface, although the profile is not as sharp as is attained with acid etch. Dust is an obvious problem, but it can be controlled by mechanical extraction. Power wire brushing is not recommended where large areas are involved. It is a fairly slow method of surface preparation, and limited to smaller jobs where low overhead costs are particularly important.

10.4.4.3 *Abrasive blasting.* Abrasive blasting is the principal means of surface preparation for concrete and most other substrates. It is plant-intensive and can cause considerable inconvenience on account of noise and dust if these factors are not responsibly controlled. It is, however, a fast and effective means of surface preparation.

The most widely used abrasive is copper slag grit, which is preferred to sand on account of its low silica content. The grit is propelled against the concrete surface using large volumes (typically 300–400 cubic feet per minute) of compressed air at 100 psi (7 bar). The grit is contained in a blast pot, a pressurized steel hopper which feeds a predetermined amount of grit into the high-velocity air stream.

Abrasive blasting, although fast, is not without its drawbacks. The grit, once blasted into the structure, has to be bagged out again and the aggressive abrasion results in numerous blowholes, all of which have to be filled prior to coating. However, the method can be regulated; the faster the blast nozzle is moved by the operator, the lighter will be the abrasion, and less grit is also used, which reduces the time spent refilling the blast pot and clearing spent abrasive afterwards. The more troublesome aspects of grit blasting can be eliminated where large floor areas are involved. Mobile machines can be used which blast the surface with re-usable steel shot. This process is very clean because the dust produced during blasting is collected when the shot is recycled. Furthermore, the work can be conducted very quickly with no requirement for loading grit or clearing it away after the blasting has been completed (see section 12.5.1).

10.4.4.4 *High-pressure water jetting.* High-pressure water may also be used to clean and abrade concrete. This is normally used where the concrete is already wet, for example in splash zones or under water, where special underwater paint will be specified. Where high-pressure water is used alone, the finish obtained is clean and smooth, so quite often sand is added to the water jet as it leaves the lance. This adds profile to the surface, which is a prerequisite for underwater application of organic coatings. Water jetting is a preferred method of surface preparation prior to concrete repair but is not recommended prior to application of coatings.

10.4.4.5 *Scabbling.* Scabblers and needle guns are generally not preferred for preparation prior to coating, but they may be used to break back concrete for several millimetres where there has been excessive penetration of contaminants, or because the surface is unsound. Following this, walls may be smoothed with a trowel-applied coating prior to application of the paint system. Floors can be similarly treated with a screed or a high-build self-levelling compound. Flailing is a light-scabbling technique which may be specified for surface preparation of bridge decks prior to application of coatings.

10.5
Methods of paint application

10.5.1
Spray techniques

Bearing in mind that relatively large unbroken areas are normally involved when coating concrete, airless spray is the most commonly recommended method of application for medium-viscosity paint systems. This is because minimal labour is involved and large areas of paint can be applied very quickly with little wastage. Airless spray depends upon paint being pumped through a very small orifice, typically of 0.5 mm diameter, at very high hydrostatic pressures, typically in the region of 1800–3000 psi (126–210 bar), which results in atomization. The spray pressure is maintained by a reciprocating pump which is normally driven by compressed air.

The pressure and distance from the tip at which the paint becomes fully atomized places some limitations on the use of this method. The quantity of material pumped through the spray tip is relatively large and it requires that the gun is passed steadily and quite rapidly over the surface. Good access is therefore essential, so airless spray is not recommended in cases where access is difficult.

Conventional air-assisted spray, which is commonly used for applying paint to cars, can also be used to apply protective coatings to concrete. It is slower than airless spray application, but has the advantage of being more controllable. This allows its use for application of coatings in cramped conditions where control of film thickness would otherwise be difficult.

The physical properties of the paint are particularly relevant to its method of application. Airless spray is most suitable for medium-viscosity thixotropic materials which are relatively easy to pump. Where more viscous materials are specified, atomization may be achieved at higher spray pressures or after warming the paint to lower its viscosity. This is particularly relevant to site application of coatings, where the material might have been stored at low temperatures. Quite often, difficulties encountered with spraying can be alleviated by installing suitable heaters in the paint store. Paints must not, however, be thinned by adding solvent without advice from the manufacturer.

Materials which are difficult to atomize under any circumstances, such as those based on high-molecular-weight resins, can sometimes be applied more easily by air-assisted airless spray techniques, particularly if the paint is preheated. In this method paint is discharged at high pressure into an airstream which breaks it into a manageable spray.

Spray methods of paint application are relatively expensive on small jobs because of plant costs. Furthermore, atomization of solvent-based paint produces high levels of vapour quite rapidly, so good ventilation is essential. In many cases, it will also be necessary to provide positive-pressure air-fed breathing equipment for applicators, particularly when work is carried out in enclosed conditions. In cases where spray techniques are not cost effective or are unsuitable for the material specified, alternative methods have to be considered.

10.5.2
Roller application

Paint rollers are widely used for applying decorative finishes and are also suitable for many other kinds of coating. They may be used to achieve fine finishes with solvent-free paints, some of which are otherwise very difficult to apply. A further advantage is speed, particularly over accessible areas such as walls and floors. A feature of roller application is that relatively thin films are applied, which may not seem advantageous in cases where a minimum dry film thickness is specified. Thin films are preferable though, and the number of coats may be increased proportionally to compensate. This is also beneficial to materials which suffer from pin-holing because it is less prevalent in thin films. Roller application is therefore a particularly viable option with few disadvantages and as such is used extensively to coat concrete surfaces.

10.5.3
Brush application

Brush application has the obvious drawback of being slow and labour-intensive. It is used alone only occasionally, where the surface areas involved are small, for example, strip coats over cracks and construction joints. More often, though, it is used in conjunction with roller application, where inaccessible areas such as corners must be brush-coated first.

10.5.4
Trowel application

Thixotropic solvent-free coatings designed for high build can rarely be applied by airless spray or roller at the ambient temperatures experienced in Northern Europe. The normal method is to apply them with a trowel in the same way as a conventional rendering material. Finishing methods vary in relation to conventional materials. They can be polished smooth, whereas resin-based surfacers are normally finished with squeegees. Squeegees are also used for spreading self-levelling coatings over floor areas.

This section has considered those methods of paint application most often used within the industry. Additional techniques are certainly available, as are numerous variations of those described above. It is the contractor's responsibility to select a method of paint application which is not only suitable for the material, but is also cost effective and practicable in the individual site situation (21).

10.6
Selection of protective coatings for concrete

10.6.1
Suitability of protective coatings for concrete

When coatings are incorporated into proposals for concrete repair, they must be capable of fulfilling a number of requirements.

A suitable material has to form a barrier against the physical and chemical factors which are damaging the concrete. Equally, there may be other reagents or physical conditions involved, which although not damaging to the concrete, might cause deterioration of the coating. It is therefore necessary to know as much as possible about the chemical and physical conditions to which the coating will be exposed.

Other factors outside the service conditions have also to be considered. Where coatings are applied for remedial purposes the concrete is quite often in poor condition, and surface preparation will result in an uneven finish. This may not be satisfactory for some coatings which cannot be applied in thick films. The problem may be alleviated by filling out major surface imperfections and blowholes by using a suitable filler, but more often a high-build paint system is still preferred to ensure effective protection of the substrate.

10.6.2
Multi-coat systems

It is unusual for concrete to be coated in a single application. Even when a high-build material is used, a primer is normally applied first to seal the surface. This is typically an unfilled resin dissolved in solvent. Its low viscosity allows it to penetrate the concrete and provide a good mechanical key for subsequent coats.

It is very often advantageous to use multi-coat paint systems for concrete protection. There are two main reasons for this. In the first instance, a greater film thickness will be applied, which affords better overall protection. More significantly, though, the coats may be in different shades, so sparsely-coated areas can be seen more easily.

Some multi-coat systems include a number of high-build layers before the finishing coat. This is to ensure that continuity of the final coat is not broken by sharp peaks in the substrate.

It is not mandatory for primers and intermediate layers to have the same chemical resistance as the final coat, but it is an obvious advantage if they have. They must, however, all be compatible with each other, and subsequent coats have to be applied within the overcoating interval to ensure good intercoat adhesion.

10.6.3
Environmental parameters

Surface temperature and relative humidity should always be taken into account when coating materials are selected. Atmospheric humidity is defined as the mass of water present per unit volume of air. The relative humidity is the ratio between the amount present and that which would be present if the air was saturated at that temperature. The level of relative humidity is significantly for two reasons. Firstly, a number of coatings are directly affected by it during application. For example, some moisture-cured polyurethane paints tend to blister if the level of relative humidity is too high. Water-based coatings will not cure properly in these conditions, because sufficient water evaporation cannot take place.

Dew point is the second factor concerned. At the air temperature concerned and the prevailing level of relative humidity, the dew point is the surface temperature at which water vapour in the air will start to condense. Coatings should not be applied to concrete whose surfaces are below the dew point. The moisture on or just below the surface will interfere with adhesion. The problem is not so significant when the surface temperature is high; the worst case is when hot and humid air comes into contact with surfaces which are cold. In this situation, it is not practicable to warm the concrete because of its high heat capacity. The cost-effective solution is to ventilate the work area with dry air, thereby keeping the surface above the dewpoint.

For the same reasons as discussed above, it is important to take surface temperatures into account when specifying coatings. The surfaces cannot be warmed, and many paint systems, particularly those based on epoxy resins, will cure only very slowly at low surface temperatures, and hardly at all below 5°C. Polyurethane and vinyl coatings are among those which are not so sensitive and may be used at lower temperatures.

10.6.4 *Conclusion*

When a coating is considered for a particular application, its properties should be carefully evaluated in relation to the expected service conditions, and those which will be encountered during application. Experience of the coating in a similar application should also be taken into account. In the event, the final responsibility lies with the manufacturer, who must provide satisfactory evidence that the coating will fulfil the requirements of the specification.

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11
Underwater repair

R.D.BROWNE, A.McLEISH and P.C.ROBERY

Many of the methods and techniques available for above-water repair can be used underwater with only minor modifications. The materials specified for use in air, however, are often completely unsuitable for underwater use.

The major effects that underwater working has on repair operations are summarized as follows:

(a) The cost and difficulty of underwater working requires that operations to be carried out at the repair site be minimized and made as simple as possible. The method of repair must be tailored to suit the available methods of access (Figure 11.1).
(b) Preparation of the damaged area requires specially adapted techniques. Care must be taken to ensure that the area is not contaminated prior to application of the repair material.
(c) The material selected for the repair must be compatible with underwater use both during placing and curing. Many resin-based repair materials are not suitable for use underwater; cementitious systems however are in an ideal medium.
(d) Placement methods and formwork must be adopted that minimize mixing between repair material and water.
(e) Checking during the repair operation and regular inspection on completion is difficult and costly to achieve underwater.

The cost of carrying out repairs underwater is far greater than for similar repairs carried out in the dry. For offshore applications rigs costing in the order of £ 10000/day may be required to support the repair operation. The cost of failed repairs is therefore high. It is even more important that laboratory trials on both repair methods and materials be used to identify possible problem areas and ensure smooth site operations.

Care is needed to evaluate the structural state of the damaged area, particularly in relation to repair where a replacement material may lack the mechanical properties of the parent material and where it is difficult to restress the repair to the original state.

11.1
Preparation of the damaged area

Prior to carrying out a repair operation it is often necessary to clean the damaged area to allow a detailed inspection. Only when the extent of the damage has been assessed, using divers or remote operated vehicles to photograph the area, can a repair programme be prepared. The first stage in the repair will be to remove all crushed or badly cracked concrete. In some cases it may also be necessary to cut away badly distorted reinforcement. Figure 11.2 shows the form of damage that may result from localized impact.

The removal of concrete and cutting of steel underwater present a considerable number of problems, with the combination of hydrostatic pressure and an electrically conductive medium (seawater), necessitating complete modification of well-tried surface cutting equipment.

The choice of the cutting technique will be governed by the nature of the work; the thermic lance for example will cut through steel and concrete simultaneously, while high pressure water jetting can be used to remove the concrete alone, enabling existing reinforcement to be utilized in the repair.

The following sections outline the various techniques available for preparing damaged reinforced concrete prior to underwater repair.

11.1.1
Surface cleaning

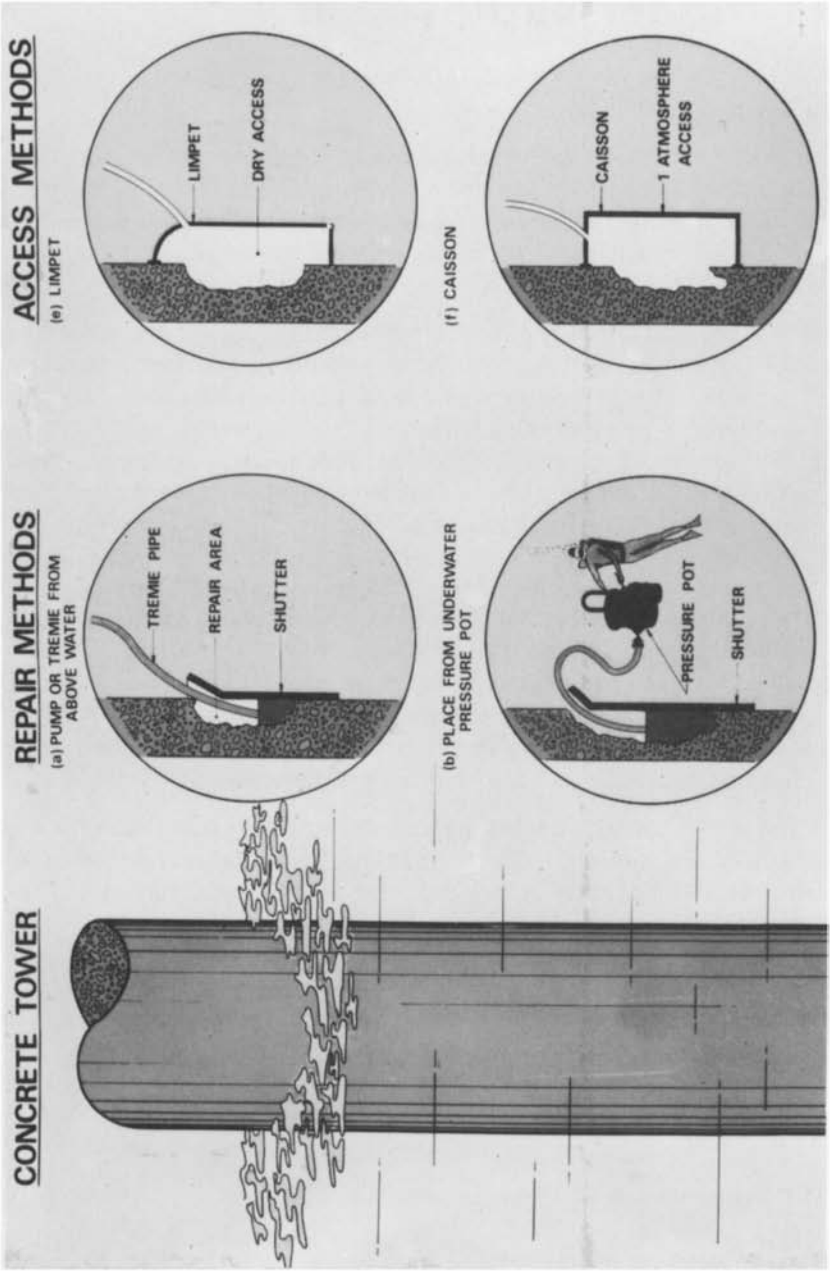
Depending upon the depth of the damaged area and age of the structure, various levels of marine encrustation may exist. It is necessary to remove any surface layer both to be able to define the extent of damage and also to ensure a good bond between existing and repair materials.

Small areas may be adequately prepared using hand-held or mechanical wire brushes, needle guns or scabbling tools. For larger areas, however, a high pressure jet (see below) will provide a more effective solution. Depending on the strength of the encrustation or contamination, an abrasive slurry or detergent may be added to the jet to give better cutting or to assist in removal of oil contamination respectively.

Once the area has been cleaned, the extent of cracked and spalling concrete can be more clearly defined and the damaged areas cut out. Guidance on inspection and testing techniques can be obtained from numerous statutory and guidance documents developing from the offshore oil exploration industry.

11.1.2
Removal of damaged concrete

Where repair to damaged reinforced or prestressed concrete is required, a method of cutting out concrete must be selected which causes the least disruption to the



existing reinforcing steel. The following techniques may be used to remove concrete, although in some cases the reinforcement must be cut out separately using specialized techniques.

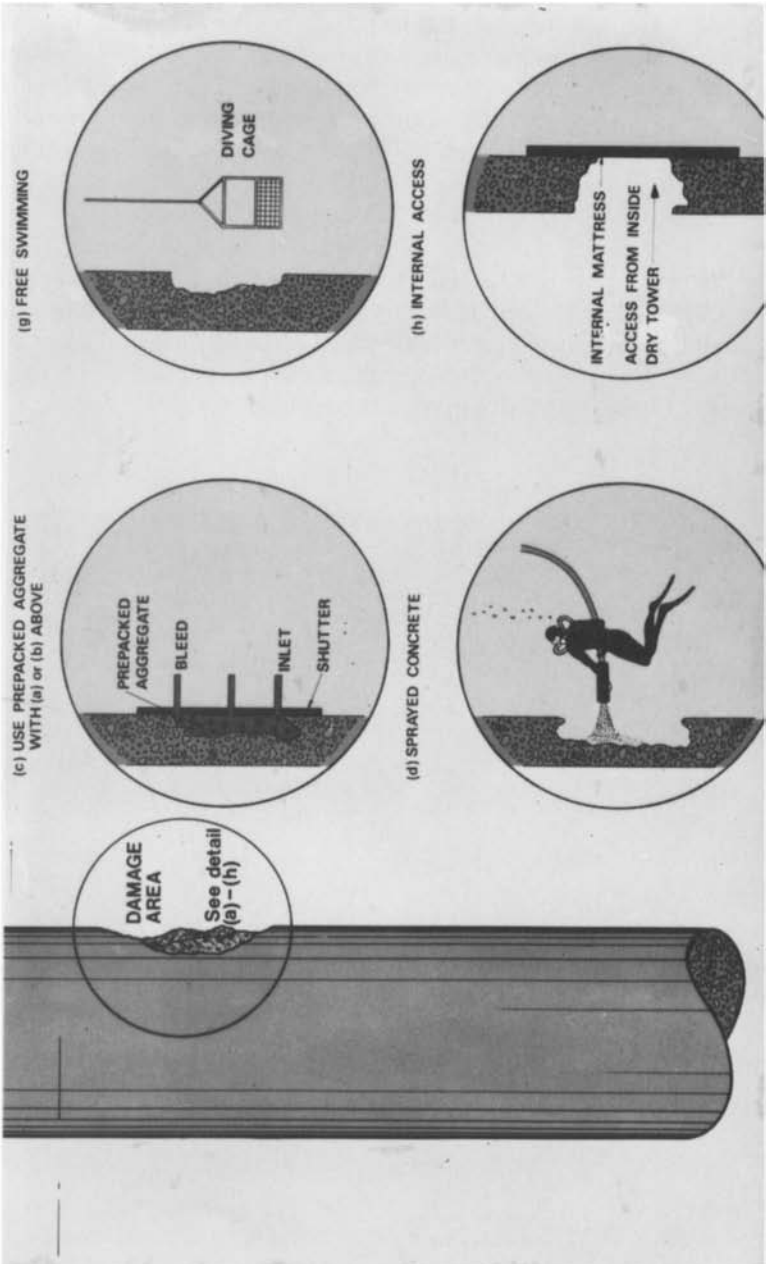


Figure 11.1 Repair and access methods

High-pressure water jetting. This method of cutting is one of the most commonly used systems for underwater work. The system involves the removal

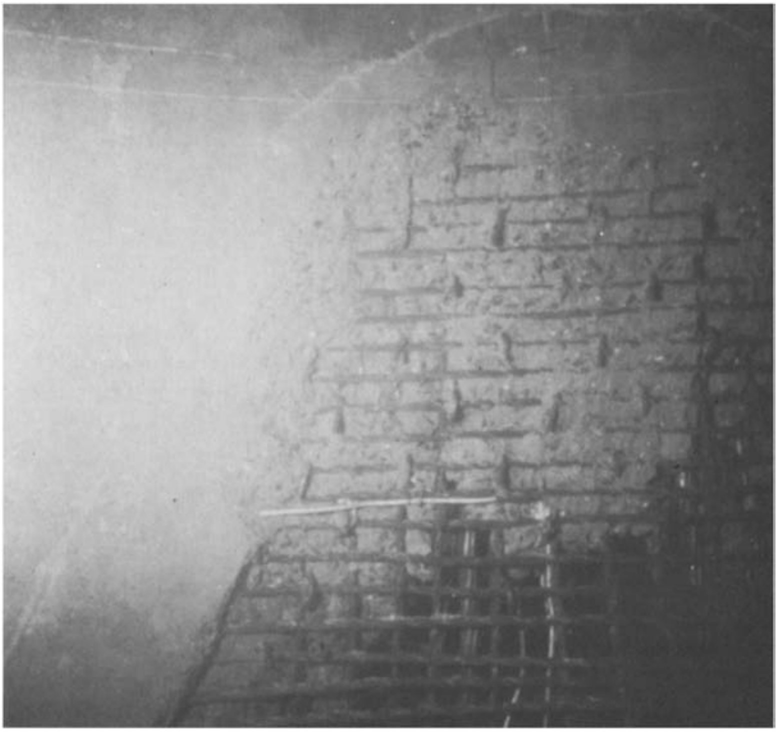


Figure 11.2 Damage caused by impact

of concrete by the use of water delivered at very high pressure (typically between 200 and 1000 atmospheres) (1). A thin, high-pressure jet of water is directed onto the concrete surface, removing the hardened cement paste mortar from between the aggregate.

When used underwater, the action of the jet of water accelerates the surrounding seawater, effectively enlarging the cutting jet. As a result, cutting rates are faster underwater than for equivalent surface cutting. However, the reaction of the jet upon the surrounding water acts as a propulsion system, therefore the cutting jet has to be balanced by an equal and opposite dummy jet.

Figure 11.3 shows a high-pressure water jet being used to remove cracked concrete from around reinforcement. The reinforcement itself is cleaned but not cut by the water jet. If the reinforcement is also to be cut then an abrasive slurry is injected into the cutting jet.

Splitting techniques. Traditionally hydraulic or pneumatic expansive devices have been used to split concrete (2). Hydraulic expanding cylinders are inserted into pre-drilled holes and pressurized until splitting occurs. The spacing of holes is calculated on the basis of the percentage of reinforcement and level of prestress.

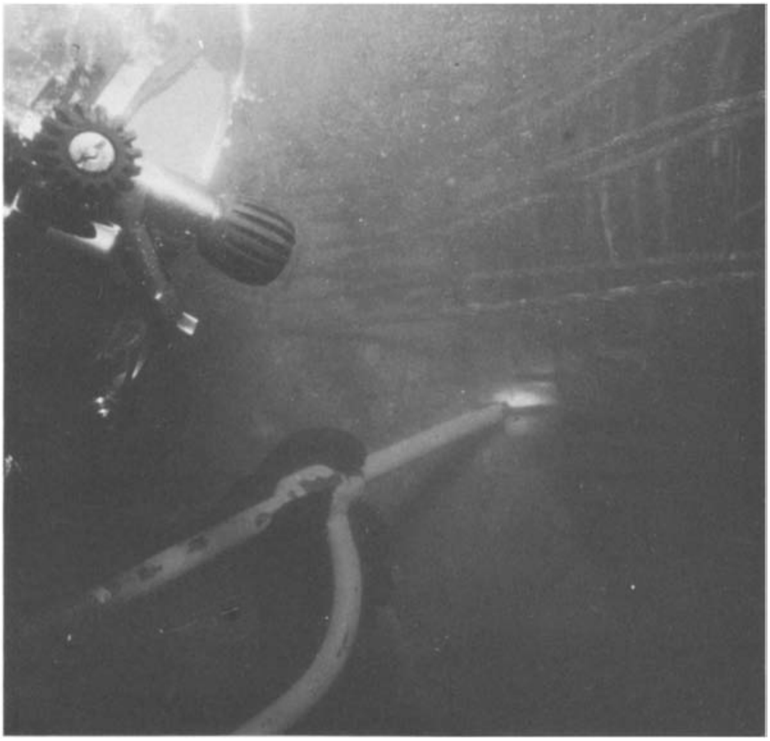


Figure 11.3 Concrete removal using high-pressure water jet

More recent developments have shown that expansive cements can be cheaper and equally as effective as the hydraulic system. The cement is mixed to a paste with water and poured into plastic bags. Divers transport the bags to pre-drilled holes in the structure. Over the next 12- to 24-hour period the cement expands and generates stresses of approximately 30 MPa which is easily sufficient to split concrete.

Mechanical cutting. Underwater cutting using hydraulically powered diamond tipped saws and drills has been used extensively for minor work (e.g. coring) for many years. The only problem to the diver is the provision of a reaction force onto the drill. This can be easily overcome by a strap or strut arrangement bolted to the structure on which the diver can bear.

This type of cutting is relatively slow and can only be used to cut to a limited depth, governed by the saw blade diameter. Therefore it is only of use for relatively small-scale demolition and preparatory work. However, it will cut both concrete and steel simultaneously if required.

Conventional pneumatic breakers and saws can be used underwater to only a limited depth (6.0–9.0 m). However, recent developments in breakers using a closed hydraulic system have proven to be successful. Future developments of this system should enable cutting out by breaker at considerably greater depths.

The Cardox system. This system is in between the splitting technique and explosive demolition. Again holes are drilled at pre-determined intervals. Into these, cartridges of pressurized carbon dioxide are placed and caulked-in firmly (Figure 11.4). The pressure is then released by electrically detonating a small initiating charge in each cartridge, producing a comparatively gentle explosion which bursts the concrete apart. Cracks in the concrete run between the prepared holes, enabling a controlled cut to be made. The 'soft' explosion produces no shockwave and therefore makes the process suitable for work in close proximity to other structures (2). After splitting, the cartridges are recovered and re-pressurized with carbon dioxide, enabling repeated use of the 'hardware'.

After splitting, reinforcement may need to be cut away using bolt croppers or an oxy-fuel torch. However, judicious placing of the charges can shear up to 15mm diameter reinforcing bars.

Thermic lance. Traditionally, the most commonly used method for cutting concrete on land is by use of a thermic lance. The lance can take several forms, but basically comprises a long steel tube packed with steel rods. Oxygen is passed down the centre of the tube and the lance ignited by an external heat source. The exothermic reaction that results generates temperatures up to 3500 °C, enabling the tip of the lance to quickly melt through concrete or steel.

However, when cutting underwater, the pressure required to force the oxygen out of the nozzle of the lance rises sharply with depth. In addition, the steel rods of the lance burn at a much faster rate, due to the hydrostatic pressure. Therefore, cutting by thermic lance could only be carried out at relatively shallow depths (60m maximum). The risk of a severe steam explosion is also a prohibitive factor and as a result, most diving firms consider this method to be too dangerous to use.

Explosive cutting. Explosives have been used for many years in underwater applications, using contact demolition charges. The size and placing of the charge has been largely a matter of experience. The resulting cut or tear in the structure is typically very irregular with the risk of damage to adjoining structures (3).

For demolition work where a precise cut is required, the shaped charge has been developed. The basic charge consists of a specially selected explosive sheathed in a soft metal, such as aluminium, copper or lead (3). The sheath has a conical section which collapses upon detonation of the explosive, forming a high velocity jet of metallic particles with an associated high energy shockwave. As a consequence of this, the energy from the detonation is concentrated onto a relatively small target area, enabling straight line cuts in plate, hole cutting or complete severance of structures to be made. Currently, shaped charges have been developed that will cut through 1.2 m diameter concrete piles sheathed in a 38 mm steel casing.

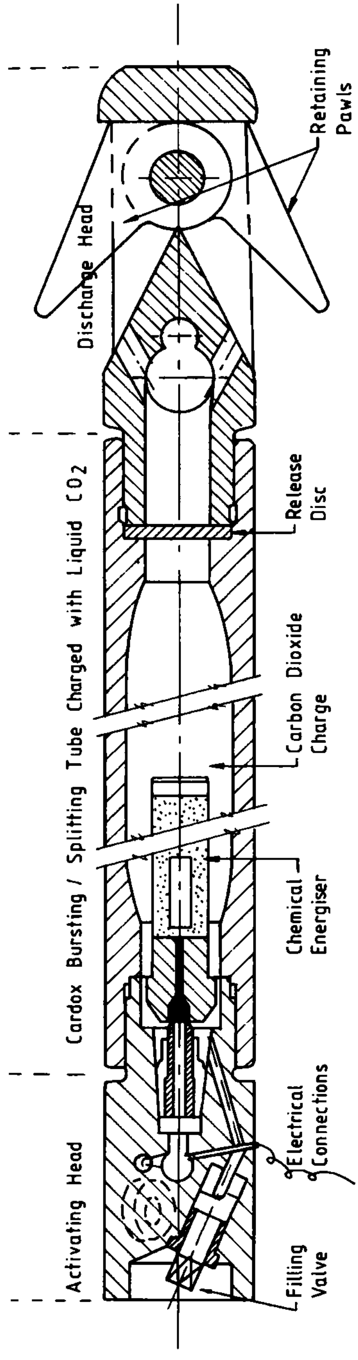


Figure 11.4 The Cardox system

11.1.3
Cutting of reinforcement

All broken or severely distorted reinforcement will have to be removed and replaced prior to reinstating the cover. Severely distorted reinforcement should not be bent straight as it will be strain-hardened by the bending and may cause structural failure at a later date.

Three methods are in common use for cutting steel underwater, namely oxyfuel, oxy-arc and mechanical cutting.

Oxy-fuel gas cutting. The oldest established underwater cutting technique is to use an oxygen-fuel gas torch for steel cutting. This technique relies upon the inter-action of the gas flame and the carbon steel to be cut, oxidizing the metal by a process known as 'burning'.

The process is termed 'oxy-fuel' cutting because at depths greater than approximately 10 m, the conventional oxy-acetylence cutting torch cannot be used; the acetylene gas becomes unstable with risk of explosion. To overcome this difficulty, hydrogen is used as the fuel gas, but because the oxyhydrogen flame is not as hot as the oxy-acetylene flame, cutting by burning or melting is a much slower process.

Oxy-arc cutting. This system relies upon the same burning reaction as the oxyfuel system, except that an electric arc not a flame is the primary heat source for the operation. The main difference between surface and underwater arc cutters is that the electrode for the latter is usually hollow, through which oxygen is passed. The jet of oxygen both oxidizes the metal and blows away the oxidized products to keep the working area clean.

When used for removal of damaged reinforcement cages, the oxy-arc system has been found to provide a very fast means of cutting steel (Figure 11.5).

The oxy-arc system can be modified by using a high pressure water jet (6 bars above depth pressure) in conjunction with the arc. This removes oxidized products from the working surface, to leave a clean scour ready for welding.

Mechanical cutting. When only a limited number of small diameter bars have to be cut, it will be often more convenient to use a mechanical type of cutter. Such machines are usually hydraulically driven diamond-tipped saws, although purely mechanical tools such as bolt croppers may also be used.

11.1.4
Final preparation

Once all damaged concrete and embedded steel have been cut away the repair can be undertaken.

The first stage will be to replace reinforcing bars with new lengths either joined by couplers or lapped with the existing bars. Broken prestressing tendons must be extended to enable the section to be re-stressed after the concrete has been reinstated. Techniques for reinforcement and prestressing repair have been

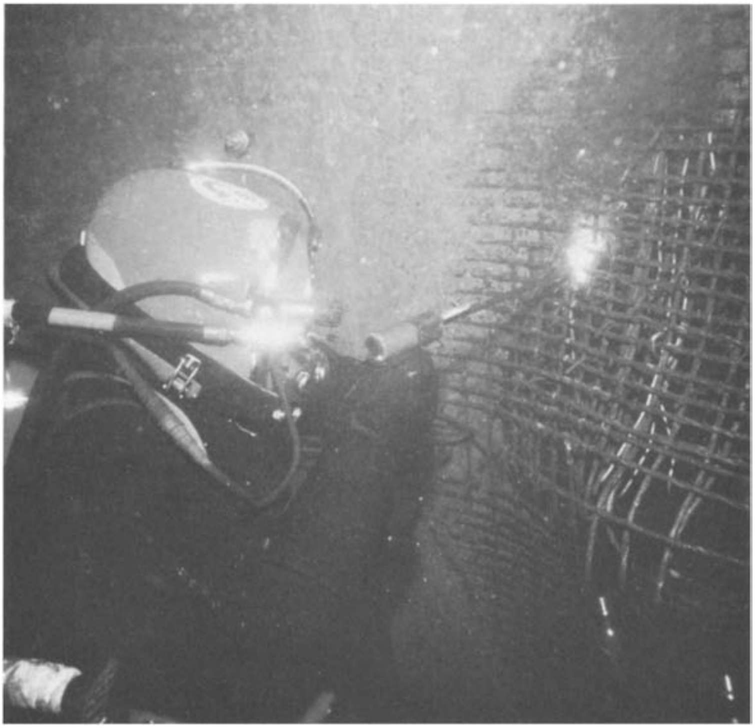


Figure 11.5 Oxy-arc burning of reinforcement

developed and assessed by Taylor Woodrow (4) with particular emphasis on restoration of in-service stress.

Immediately prior to reinstating the damaged concrete the surface must be flushed with clean water to remove any bacterial or microbiological growth. This may develop over a period of only a few hours and may significantly reduce the bond between the repair material and the structure, which may result in failure of the repair.

11.2
Patch repair

Minor damage, such as that caused by scouring, dropped objects or gentle ship impact, will not normally result in exposure of reinforcing bars. For cosmetic reasons, or to prevent future deterioration, it is often desirable to fill such defects. This can be achieved by the use of special cementitious or resin-based materials which are suited to application in small volumes.

The following sections describe these two types of underwater patch repair material.

11.2.1
Cementitious mortars

When conventional cementitious mortars are immersed in water rapid washout of the top surface will occur, as the cement is dispersed by water movement. However, good bond to submerged concrete can be achieved, as long as the interface is thoroughly prepared and free from marine growth (see section 11.1.4). To prevent weakening of the exposed layer, which may reduce the bond to any subsequent layers which may be applied, admixtures have been developed which resist washout of cement from the mortars and grouts (5). Proprietary grouts are also available, based on special cements and sands, with thixotropic and adhesive additives, which resist washout.

As with all cementitious repair mixes, forced-action mixers are essential for high performance mortars. Once mixed above water, the mortar can be poured by free-fall through water to fill formwork. The mixes are normally formulated to be self-levelling to ensure good compaction and avoid the need for vibro-compaction. They can normally be used in thicknesses of 20 mm up to 150 mm.

Stiff, trowel-grade mortars can also be produced which are suitable for application to vertical surfaces. However, the mix will be prone to damage due to wave action or other causes until it has set. Hence it is more usual to repair defects in vertical surfaces using either formwork and a free-flowing grout, or a hard epoxy putty (see section 11.2.2).

11.2.2
Resin mortars

Normal epoxy or polyester resin mortars are totally unsuited to use underwater. Not only do they fail to bond to immersed concrete, but the water itself reacts with the curing agent to reduce severely the performance of the mortar.

By careful formulation of the base resin and curing agent, special epoxy and polyester resin mortars have been developed which can be used underwater.

The base resins must have a low viscosity, as they cannot contain volatile solvents when used underwater. Also, the base resin usually contains heavy aggregates such as barytes to increase the water-displacing characteristics of the mortar when poured into formwork.

There are a few products available which are suitable for underwater application, perhaps the earliest of which was produced by Sika Ltd. Most formulations are free-flowing, and so can either be poured through water directly into formwork, or for larger volumes can be poured or pumped into a preplaced coarse aggregate (see section 11.4.6). For vertical work, formwork will normally be required, although special types of underwater-grade epoxy putty have been developed for this purpose. The putty is pre-mixed in the dry and then knifed into place by the diver. Care is required when applying the putty as its adhesion to the concrete will be low until it has cured.

11.3 Injection into cracks

Having identified the extent of cracks by inspection, the general procedure for injection underwater is the same as for dry workings. As described in Chapter 5, the first stage in the repair is to pre-drill 50 mm deep injection points along the line of the crack, using a spacing of between 100mm and 300 mm depending upon the crack width. The line of the crack must then be thoroughly cleaned by high-pressure water jetting to remove contaminants. Using an epoxy putty (see section 11.2.2), the line of the crack is sealed. Injection pipes are sealed into the injection points to ensure a grout-tight joint (Figure 11.6).

Depending upon the width of the crack, either cementitious grout or epoxy resin can be used to fill it. Cementitious grouts will normally be suitable for cracks of width greater than 3 mm. However, owing to the risk of washout of the cement, epoxy injection resins are normally preferred. Epoxy resins must be low viscosity solvent-free underwater grades in order that the water in the crack is replaced by a structural material; as discussed in section 11.2.2, conventional epoxy resins are prone to inter-reaction with water, which severely weakens their strength.

Injection is most easily achieved by use of a pressure pot, which is filled with pre-mixed epoxy resin and then lowered by crane to the injection points (Figure 11.7). Alternatively, lines for base resin and hardener can be run to the injection point, where a special inter-mixing nozzle blends the two components prior to injections. The latter system is suited to deep repairs, where the time delay between filling the pressure pot and injecting the resin may exceed the pot life of the material.

For small repairs the use of hand-held cartridge injection guns is a satisfactory method.

Injection begins at the lowest injection point. Pumping continues until a uniform water-free stream of resins flows out of the next highest injection point. Only then is the lower injection point locked off and injection transferred to the next point. Once injection is complete and the resin has fully cured, the projecting injection points may be ground off as required, using hydraulically-powered grinders.

11.4 Large-scale placement

Where large volumes of material are required, for example to reinstate damage or renew ballast for pipelines, consideration must be given to bulk placement underwater. Precast, high density concrete mats for renewing ballast can be obtained in various sizes and offer many advantages over wet-cast systems (Figure 11.8). However, where wet casting is required, the following sections give various alternative methods for repair.

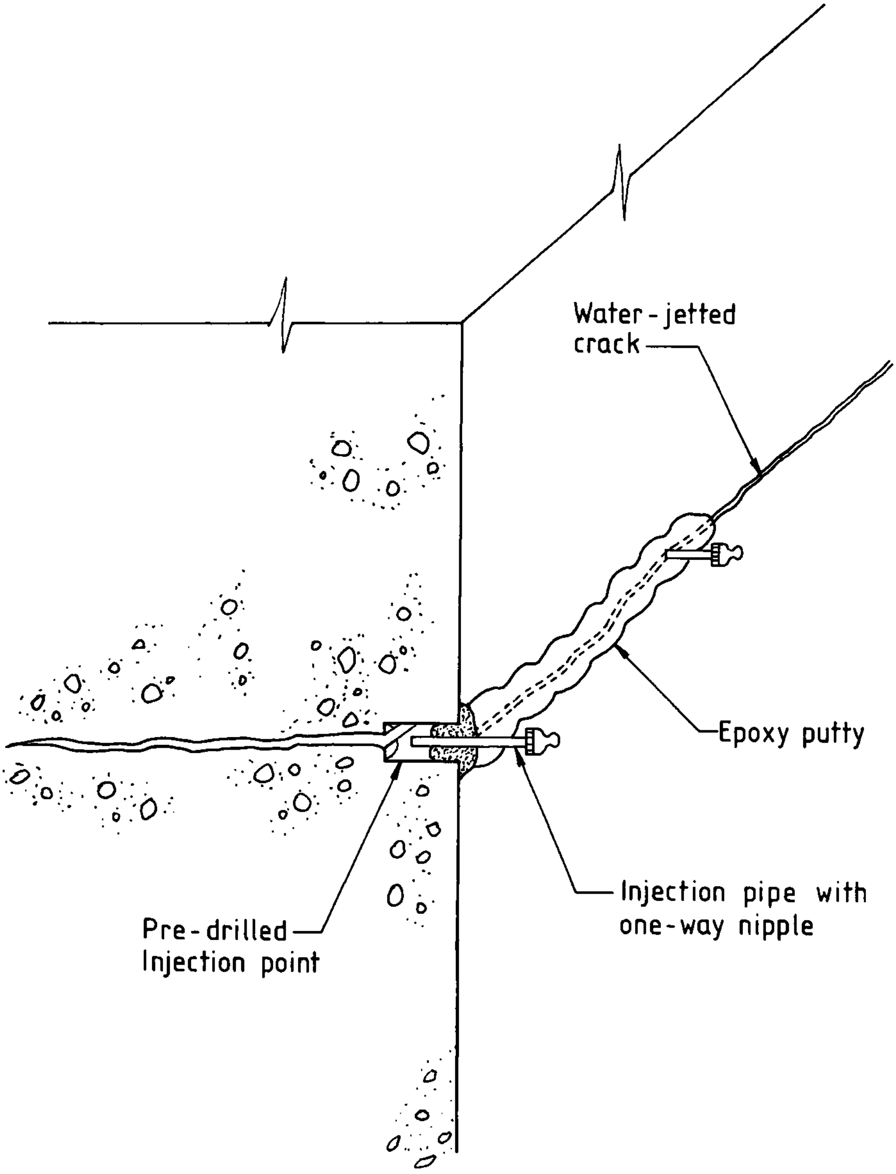


Figure 11.6 Example of a crack injection operation

11.4.1
Formwork

The requirements for underwater formwork differ from conventional land-based work in a number of key respects. Perhaps the most important of these is care necessary at the design and fabrication stages, to ensure that the formwork can be

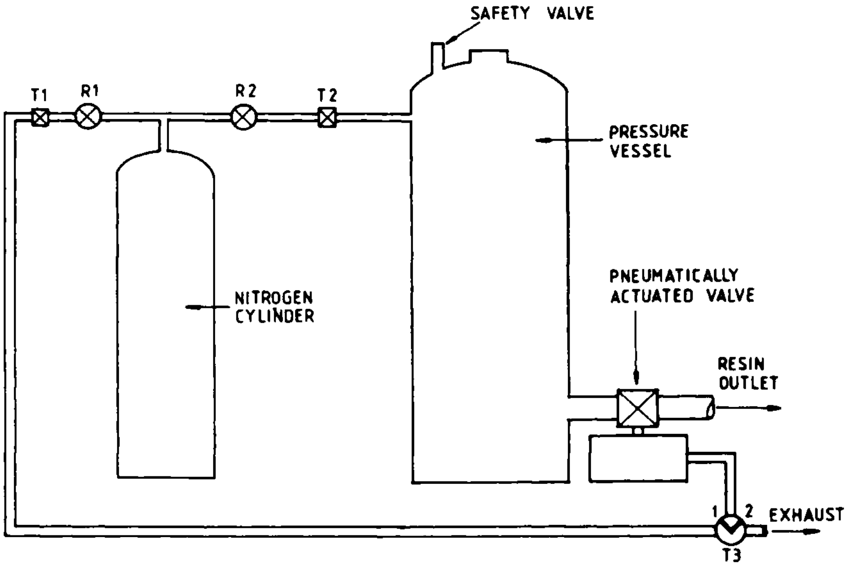


Figure 11.7 Taylor Woodrow pressure pot for resin injection

simply erected underwater and be tolerant of variations in the existing structures. From experience gained from a large number of surveys, it is rarely the case that plans for below-water construction correspond exactly with what has been built. Figure 11.9 shows steel formwork fabricated to fit the damaged surface being lowered into place. Flexible seals ensure a leak-tight fit. To minimize underwater operations the formwork is complete with inlet pipes and external vibrators.

For repairs to members above the sea-bed, all types of conventional formwork material can be used. However, as in most cases there will be no need to strike the form, design can be simplified. Attaching the form to the structure and achieving a grout-tight seal to possibly irregular or unexpectedly different surfaces will be a difficult operation. For most vertical work, positive attachment is preferred, using steel straps or rock bolts drilled into the concrete to secure the form, with a thick layer of compressible gasket such as neoprene rubber to form the final seal (Figure 11.10). Although the net pressure on formwork due to the concrete will be substantially less than for above-water work, this should not be used as a reason to skimp on design, as the cost of failure can be very high.

For work on the sea-bed, gravity-based forms such as precast concrete blocks or driven steel sheet piling are the most common means for containing the pour. Increasingly, flexible fabric forms are being used, consisting of supported or unsupported woven textile which contains the concrete but permits trapped water to escape.

As with other stages of underwater repair works, trial assembly on land with input from the divers who will have to carry out the work will be an essential step in the design process.

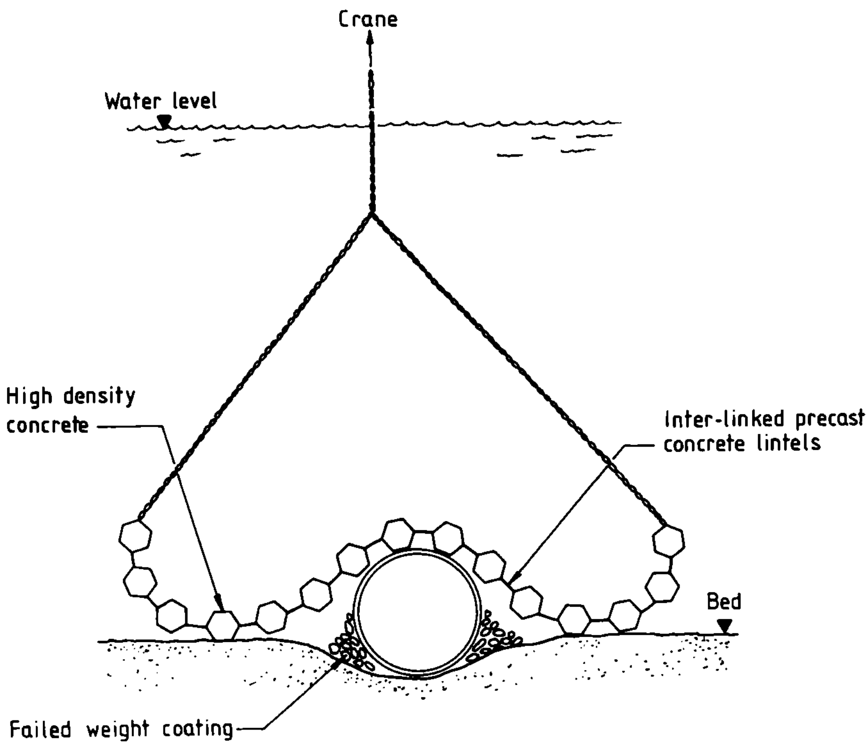


Figure 11.8 Precast concrete pipe ballast

The final stage will be to seal gaps due to unexpected variations in line or level. For this, flexible fabric, plastic sheeting and sand or cement bags all have uses.

Once the formwork has been completed, a final inspection will be required to check for foreign matter in the form such as marine growth. Only then can instructions be given for pouring the repair mix.

11.4.2
Design of concrete mixes

The mix design for underwater repair is normally carried out in the same way as it would be for dry workings. However, depending on the nature of the repair works, certain modifications may be required as summarized below (6).

Cements. Ordinary Portland cement is normally used for both marine and freshwater concreting, although special cements may need to be specified for certain environmental conditions. The fineness and setting time of the cement may be governed by other factors such as the need to prevent bleeding and the delay between mixing and placing respectively, as discussed in other sections of this chapter.

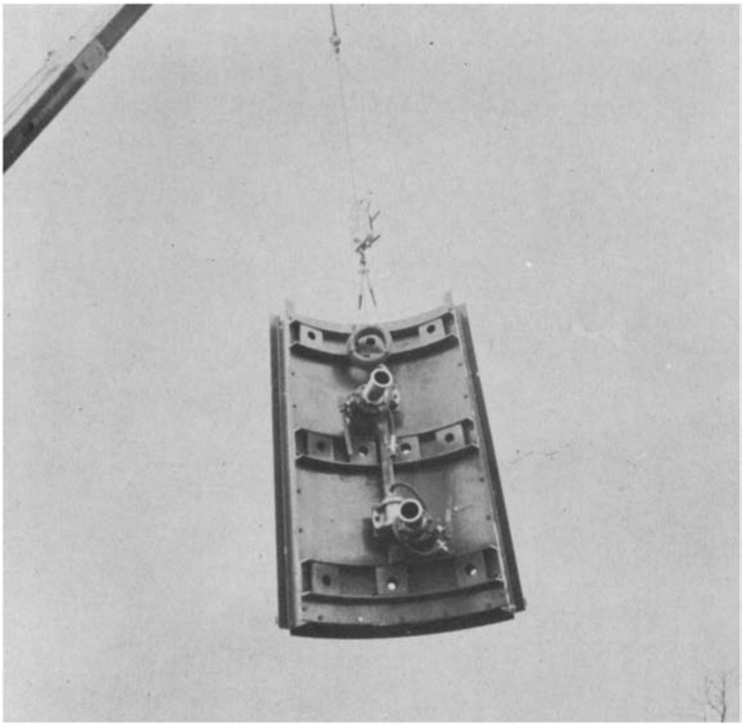


Figure 11.9 Prefabricated steel formwork

Aggregates. The normal approach to repair, which is to use similar sizes, gradings and proportions of aggregate as was used for the original structure, is still considered good practice. However, in some cases the size of the repair may require selection of a smaller maximum aggregate size. Because high workability mixes are required for the more common tremie and pump placing methods, rounded coarse aggregates and a well-graded overall distribution will be essential. Well-washed marine dredged aggregates and round river gravels will be most suitable. For mass concrete work, unwashed marine gravel can be used as long as it is free from marine growth or other inclusions.

Water for mixing. Fresh, potable water must be used for all but mass concrete work. Where sea or river water is used, it must be verified that it is free from contaminants which may adversely affect the setting or other properties of the concrete. Seawater or water taken from the tidal area of rivers should only be used for mass concrete where there is no embedded steel.

Admixtures. For repair to small, heavily reinforced areas, superplasticizing (high range water reducing) admixtures will be essential to give the necessary flow characteristics. This may require modifications to the mix proportions in order to maintain the stability of the concrete mix. However, for most large pours, conventional admixtures may not be necessary (see also section 11.1.4).

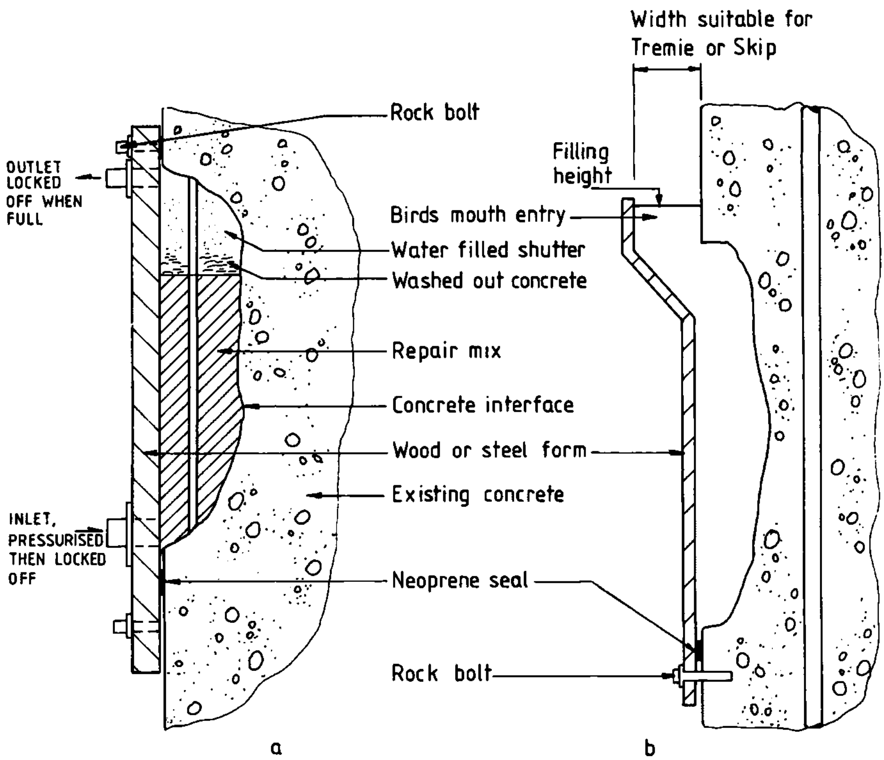


Figure 11.10 Typical formwork detail for underwater repair: *(a),* pumping shutter; *(b),* bird's mouth shutter

Where substantial delays are expected between mixing and placing the concrete, it may be necessary to use retarding admixtures to delay the set of the mix. However, this is often unnecessary as the low water temperature will itself normally be sufficient to delay setting times of the concrete mix.

Mix proportions. For mass concrete or large reinforced concrete repairs, where concrete is to be placed by bottom opening skip or toggle bag, mixes are not normally designed. Using existing data, concrete mix proportions are selected to give the required strength, using a slightly oversanded mix. The cement content is then raised by approximately 25%. These adjustments increase the cohesiveness and mobility of the mix while combating loss of strength due to both the absence of compaction and loss of cement by washout (6).

Lean mixes of less than 330 kg/m^3 are not likely to be suitable due to washout of the cement. However, for general application there is no advantage to be gained in specifying high strength mixes unless more controlled placing methods are used, such as pump or tremie (see 11.4.3).

Bleed. As with repair to concrete in the dry, repair mixes which have to be cast under and against existing concrete will form a void at the interface unless the mix is proportioned to prevent bleeding (7). Rounded aggregates, well-graded fine sands and fine cements should be used. Cohesive superplasticizers such as those based on modified lignosulphonates or sulphonated naphthalene formaldehyde condensates, will also be required to reduce the water content of the mix. Because of this, the mix will need to be proportioned for pumping (see below) and contain a higher proportion of sand than is normally used.

Prior to commencing the works, the bleed of the mix will need to be checked using an appropriate bleed test, such as ASTM C232 (8).

Pump/tremie mixes. To avoid blockages in the line under a pressure gradient, particularly at bends and tapers, care must be taken in the selection of mix proportions. Various techniques are available for the design of pumpable mixes. These are based on both reducing the permeability of the mortar, by choice of suitable gradings to prevent grout loss, and keeping the volume of paste sufficiently high to lubricate the mix (9).

11.4.3
Methods for placing concrete

When conventional concrete is placed underwater there is a danger that some of the cement will be washed out from that part of the mix in contact with the water. This can lead to a reduction in strength of the surface concrete and may create leakage paths through the concrete to the reinforcement. The placement method used for underwater repairs must be chosen to minimize the area of contact between concrete and water and to prevent turbulence. Where non-dispersable concretes (5) are used for the repair (section 11.4.4) then normal surface placement methods may be adopted.

The main methods for placement of concrete underwater are outlined below (6).

Bottom-opening skip. Where mass concrete is required to stabilize a structure's foundations, or seal-in anchor blocks of pipes for example, the simplest method is to pour the mix into a bottom-opening skip and lower it slowly through the water until it is above the repair area. The trap is then opened and the mix free-falls under gravity. In order to minimize washout of cement the skip must be fitted with flaps at the top to protect the concrete during placing. Skirts fitted at the bottom will also be beneficial in confining the concrete while it is being deposited (Figure 11.11).

The main disadvantages with skips are the small volumes of concrete they contain and the long turnround time between each placement; the latter being a result of the slow rate of movement of the full skip to prevent washout of the concrete. As a result of this, if large volumes of concrete are required there may be poor homogeneity because of considerable washout both during placing and while waiting for the next batch of concrete. For this type of work, tremie or pump placement is preferred. Also, difficulty may be experienced in accurately directing the concrete, particularly where small letterbox type openings have

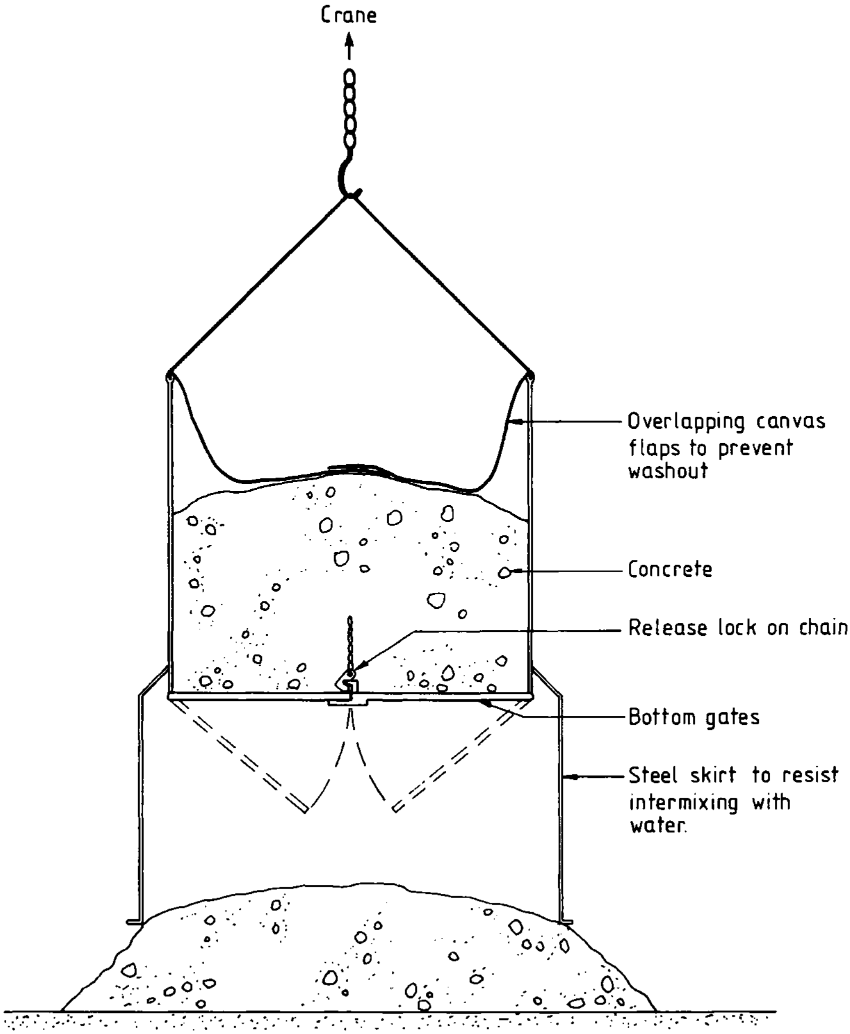


Figure 11.11 Typical arrangement for a bottom-opening skip

been provided. However, the method is ideally suited to intermittent work, where small volumes of concrete are needed at different locations.

Tremie pipe. To overcome 'washout' by water, the tremie system was developed. This enables concrete to be placed from the surface, usually via 150 mm diameter flexible pipes, to the exact placing location (Figure 11.12). For easy flow and good compaction, the mix is normally designed to be very workable (see section 11.4.2).

Care must be taken during assembly of the tremie to ensure all joints are strong and watertight. The tremie pipe is then rested on the bottom of the form or on the bed and then carefully filled with the concrete mix. To prevent intermixing with water, a plug of foamed rubber is normally used as a barrier between water in the pipe and the concrete being charged into the top. Once the plug reaches the bottom of the line, it should float back to the surface once placing commences.

The rate of placing is controlled by raising the tremie outlet. However, at all times the outlet must be continuously immersed in the concrete to prevent uncontrolled outflow and the inclusion of water pockets in the mix. It is normally impossible to see the end of the pipe owing to clouds of washed-out cement, hence the rate of outflow of the concrete is the only guide as to the position of the tremie pipe in the placed concrete. If the end of the pipe does emerge from the top of the concrete, the sudden rush of concrete will signal the need to stop concreting and inspect the placed concrete. It may be necessary to remove some or all of the concrete before restarting the tremie work.

Washout of the exposed surfaces of the mix will still occur, although placing concrete into closed formwork will reduce this problem. By passing a poker vibrator down the inside of the tremie pipe and giving short bursts of vibro-compaction, the mix can be placed and compacted simultaneously without trapping excessive amounts of water in the mix. However, this will need an increased size of tremie pipe and may rule out the placing technique because of access problems, e.g. through the reinforcement cage.

The tremie is ideally suited to placing large volumes of high workability concrete or where congestion prevents the use of bottom-opening skips. Properly executed tremie concrete should be more homogeneous than concrete from a bottom-opening skip, but for the highest quality pumped-placing is preferable.

Pumping. This is one of the most suitable means for placing concrete to restore structural capability. The concrete can be pumped in at the bottom of the formwork, displacing water through a vent opening at the top. As an additional means of quality control, the pumping can be continued to forcibly flush out the top layer of concrete, which may be weakened by intermixing with water (Figure 11.5). By locking off inlet and outlet valves a pressure can be maintained within the formwork to counteract the effects of bleeding of the mix (see section 11.4.2).

If concrete is to be pumped vertically downwards for any distance, there will be great danger of the mix free-falling down the pump line at a faster rate than it can be pumped. Because the line will be full of water this will result in severe washout and weakening of the mix. To prevent this, a sponge plug is forced into the top of the line before pumping begins. This supports the mix and prevents free-fall between strokes of the pump. Once the line has been filled and the plug expelled, the line can be connected to the formwork for filling.

For very deep pours, this precaution may be insufficient and pairs of 90° bends may be required periodically to break the fall of the concrete down the pipe (Figure 11.13).

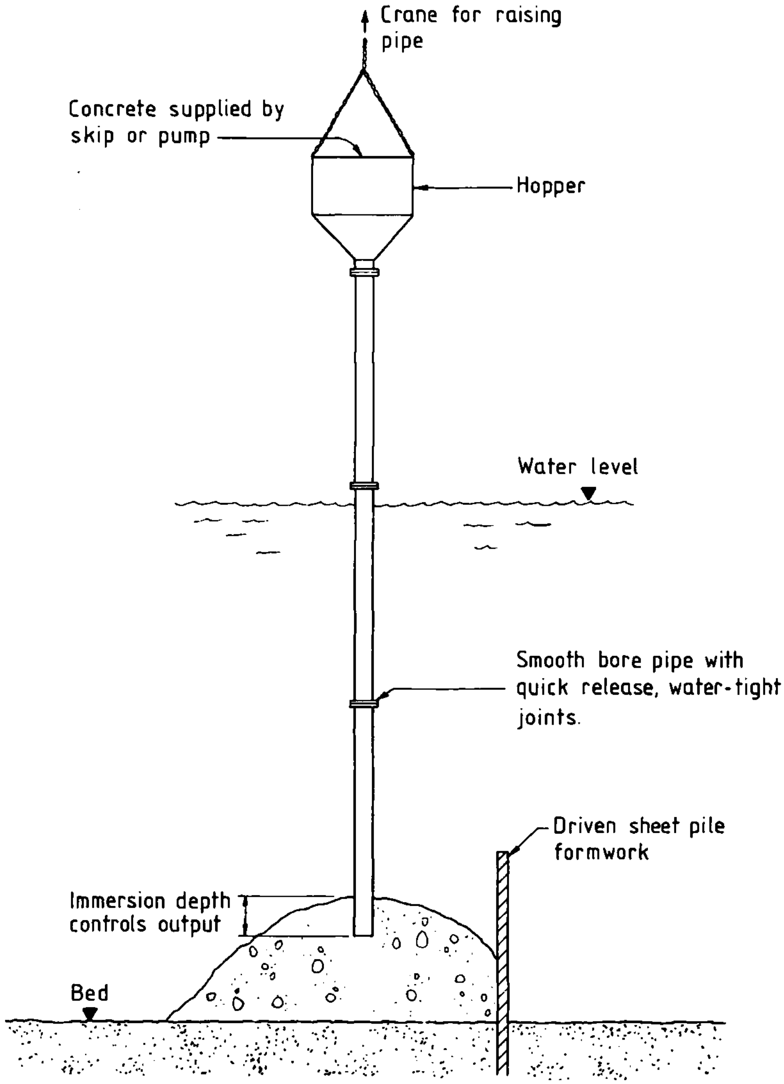


Figure 11.12 Typical arrangement for a tremie pipe

To enable the mix to flow into all the spaces in the reinforcement cage and the form, the mix will have to be very workable and self-levelling (see section 11.4.2). This is especially true as it is very difficult to vibrate the formwork underwater without mixing water into the concrete (for this reason pokers must not be used).

Toggle bags. These are reusable canvas bags which can be used for placing small quantities of concrete. They are sealed at the top and have an opening at the bottom which is released when the bag has been located above the formwork.

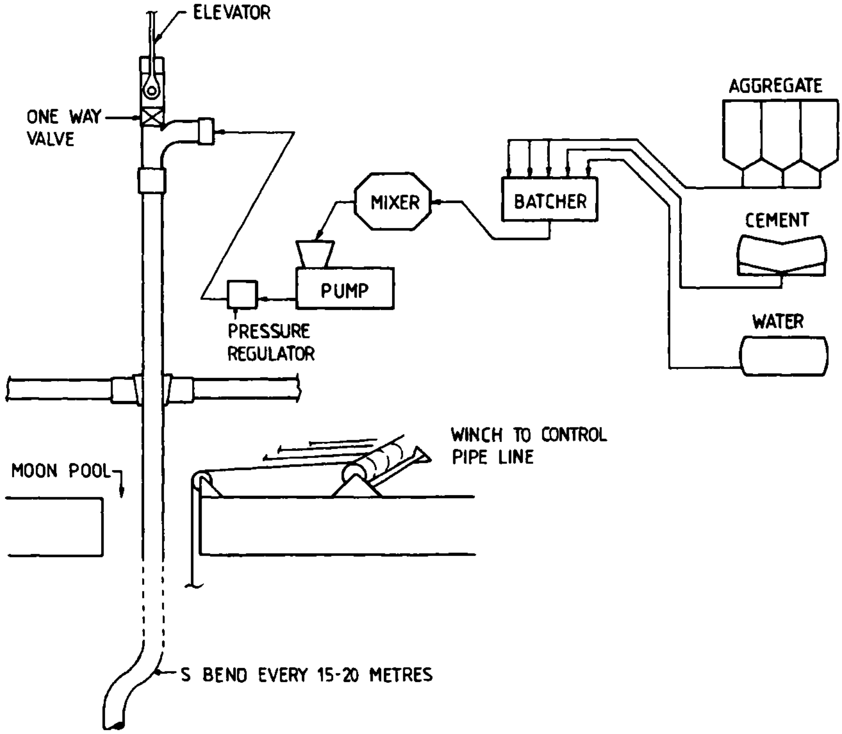


Figure 11.13 Example of pump line configuration for underwater placing

Similar problems exist as with bottom-opening skips with regard to washout of the cement.

Bagged concrete. Hessian bags half-filled with concrete are laid interlocking in brick bond fashion. Cement paste seeping between the weave of the hessian provides a bond between the individual bags. The method is normally used for scour repair, ballast renewal, or as a temporary protective measure.

11.4.4
Non-dispersible concrete

Non-dispersible concrete is highly cohesive and water repellent and can even be allowed to freefall through water with little risk of segregation or washout of the cement (10). Unlike conventional concrete placed underwater there is no requirement to prevent mixing of the concrete with the surrounding water. This flexibility increases the rate at which the concrete can be placed and reduces the need for detailed underwater control of the repair operation.

The good erosion resistance of the non-dispersible concrete when in a plastic state prevents deterioration of the concrete surface (10). Hence this type of mix is ideally suited to placing by bottom opening skip. There is also added protection against plant breakdown, as a second lift may be poured onto an existing set concrete with only minimal preparation. This type of concrete can also be placed by pump into prepared formwork, or be pumped into letter-box type openings, allowing the concrete to free-fall into the form to displace water and then coalesce into a dense mass. It should be noted that the extra cohesiveness of this type of mix may make it unsuitable for placing by tremie, owing to the greater adhesion to the walls of the pipe.

The non-dispersible properties are achieved by the addition of a number of admixtures to conventional concrete. Proprietary admixtures designed to achieve non-dispersible properties, and prebagged non-dispersible cements and concretes are now commonly available although details of their formulations are not published. The mixes are designed to be self-compacting and self-levelling, flowing around reinforcement or other inclusions to produce a homogeneous mass (10).

From early tests carried out on these materials by Taylor Woodrow, the properties of non-dispersible concretes appear to be similar to those of a conventional, high cement content concrete.

Although there is little published information on the proprietary additives the material has been in use for more than 10 years and there is no reason to believe that its long-term behaviour will differ from that of conventional underwater concrete.

11.4.5
Preplaced aggregate concrete

This method of concrete placement is ideally suited to underwater or tidal work, especially where access conditions are limited or fast flowing water could wash away conventional concrete.

In this process a large, single-sized coarse aggregate, typically not less than 40 mm, is placed into prepared formwork (11). A high flow cement/sand grout is then introduced into the bottom of the form, which displaces water from the interstices in the coarse aggregate. Pumping then continues until a washout-free stream of grout emerges from the top vent in the formwork. To prevent washout of the grout, formwork usually completely encloses the aggregate, tapering upwards towards the vent point. However, for massive pours washout of the upper layer is not as important and this detail is often neglected.

The finished concrete has a high aggregate/cement ratio, with point contact between the aggregate. This produces a low restrained shrinkage, typically 50–70% that of conventional concrete, with few voids in the mix to reduce strength (12).

Care is required in the selection and proportioning of materials for preplaced aggregate concrete. The size for the coarse aggregate is governed by the need to provide channels through which the grout can easily pass. If the coarse aggregate

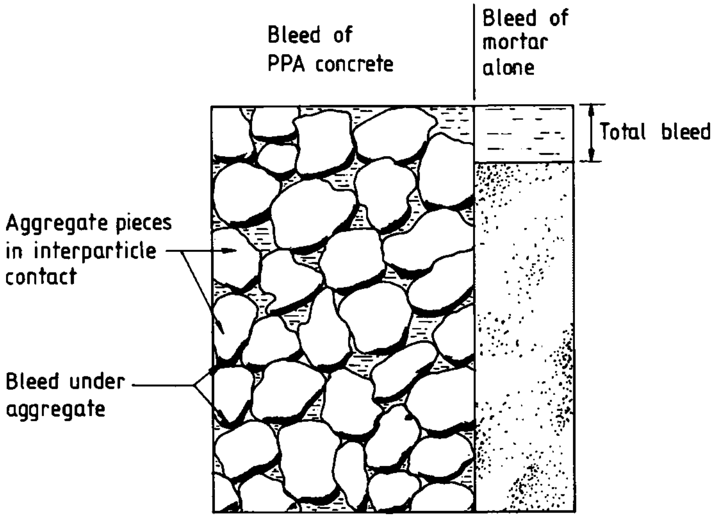


Figure 11.14 Schematic representation of bleed under aggregate

is less than approximately 20 mm in size, the sand/cement grout will tend to bridge between the interstices and prevent injection. For such small aggregates, a sand-free grout must be used, although this can cause other undesirable problems such as severe bleed lens formation under the aggregate (7), as shown in Figure 11.14.

Normal injection grouts consist of ordinary Portland cement, and well-graded zone M sands, with plasticizing admixtures added to improve the flow of the grout. Often, pulverized fuel ash (or fly ash) is added as part of the cement and/or sand to improve the flow of the grout.

For successful injection of the grout, the formwork must be designed to be watertight to prevent leakage. It must also be adequately vented to enable air and water to escape and permit 'purging' with some of the grout to remove any water contamination of the grout/water interface during filling. For small-scale repairs injection can be carried out through an inlet pipe at the bottom of the formwork. For much larger areas of concrete, such as replacing mass concrete pipe anchors for example, it is common practice to use vertical grout pipes (12). These are usually 20 mm diameter and spaced at 1.5 m centres; the exact size and spacing depending upon the size of the form and the aggregate characteristics. Grout is then pumped into the bottom of the form via these injection pipes, which are raised gradually as filling proceeds.

Injection should proceed slowly at a uniform rate without interruption until the form is filled. Vibration of the formwork at the level of the injected 'grout front' is beneficial as it enables trapped air or water to escape and gives a better bond and surface finish, although this is seldom necessary for underwater repair work.

11.4.6
Epoxy resin concretes

Preplaced aggregate concrete can also be made using underwater grades of epoxy resin in place of the cementitious grout discussed in section 11.4.5. Although the epoxy resin will be several times the price of cementitious grout, it possesses several unique properties: the particle size is very small (typically less than 100 µm); the viscosity is generally low although it may increase significantly at low temperatures; the formulation can be varied to give a long or short pot life. As a result, epoxy resin grouts are more versatile and can be used with a much smaller coarse aggregate size than for cementitious preplaced aggregate concretes.

As a result of the low epoxy binder content used in preplaced aggregate mixes, the cost of repair using a thin layer of epoxy resin concrete can be comparable with using a proprietary non-dispersible cement mortar.

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12
Repair of concrete floors

E.MOLD

12.1
General

Concrete floors can be repaired and upgraded to increase their life in domestic, office and industrial buildings*. In many instances where there is no change in use of a building, upgrading may only mean changing the colour of the floor or removing oil and increasing skid or slip resistance. For instance, in farm buildings it is often necessary to remove animal fats and detritus and to follow this by roughening the surface to reduce the danger of animals' slipping.

Where loaded vehicles are involved on a floor surface, such as fork lift trucks, the concrete is more prone to damage, especially at joints. If this damage is not repaired, the floor may become unsuitable or even dangerous.

In the lifetime of many industrial buildings there is often a change in use. In many instances the floor has to be upgraded to conform to its new role. This may vary from a complete structural upgrading requiring changes in surface levels, to the repair of visual damage only and provision of a thin surface topping. Services may be required below the floor surface, and the floor surface replaced. Additional thermal insulation may be required.

12.2
Preliminary work

The repair of concrete floors should not be attempted before a thorough survey has been carried out. From this survey it may be necessary to analyse the causes of defects so that a specification for the repairs can be drawn up bearing in mind the future duties of the floor.

In industrial premises it is sometimes necessary to thoroughly clean off all the dirt before surveying, otherwise defects may be hidden. It is best to set up a grid system of 1 to 3 m (depending on the accuracy required and size of the floor) and record existing levels to a known datum. Condition of floor, necessary repairs and any other testing requirements can be tied in with the grid. Existing services in the floor should be plotted to avoid future damage and they should be tested to ensure that their present condition is satisfactory. In many repairs it may be decided to provide some form of bonded coating or topping over the whole floor area, but before this is carried out damaged areas and joints should be reinstated, cracks investigated and an appropriate repair carried out, otherwise these defects will ultimately reflect up through the new topping.

12.3 Definitions

The following terminology will be used when discussing repairs to floor slabs.

Ground floor slabs. Concrete floors that are cast directly on top of a sub-base which is in turn supported by the soil beneath it are called ‘ground floor slabs’ (Figure 12.1). These floors are normally reinforced with steel mesh reinforcement to control cracking which may occur between control joints. The strength of the floor and the loading it can carry will depend upon:

(i) The strength or load-carrying capacity of the soil or subgrade (this may be the original soil but is often fill material)
(ii) The thickness of the concrete slab
(iii) The strength of the concrete in the slab.

These floors are often used in both light and heavy industrial conditions where the surface of the concrete slab is the wearing surface i.e. no topping or flooring material is added. They are sometimes required to be laid to close surface tolerances especially in high racking systems where fork lift trucks operate. The concrete in the floor will be finished by either power trowels or by surface grinding and should be of high quality. The concrete mix should contain 330kg of cement per m^3 of concrete with a water/cement ratio not exceeding 0.50, and the concrete when placed should be thoroughly compacted.

Suspended floors. Concrete floors which are suspended either on piles and ground beams or on columns and beams in multi-storey buildings are called suspended floors. There is a wide variety of suspended floors and they will be designed for load-carrying in such a way that the steel reinforcement carries the tensile stresses and the concrete the compressive stresses. Care should be taken on suspended floors if heavy equipment or the use of tools with high dynamic loadings is envisaged. Professional advice should be taken and also a structural check should be made on the final dead load of the repaired floors.

Toppings. Many suspended floors are constructed using precast concrete units and will be finished with a topping, where the surface of the topping is the wearing surface.

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*Repair materials suppliers are listed on p. 196.

Screeds. Cement/sand screeds are used where a flooring material such as carpet, tiles or rubber is to be the finished surface. They are often used in offices, hospitals and domestic buildings.

Figure 12.2 'Razorback' beam being used for compacting concrete in an unreinforced concrete floor slab (British Cement Association)

Toppings and cement/sand screeds are used on both ground floors and suspended floors (Figure 12.3).

12.4
Causes of defects

The causes of defects in concrete floors slabs are many and varied and some of these are listed below:

Aggressive chemicals and acid spillages

Wear from small-wheeled machines

Unsuitable mix proportions

Inadequate curing procedures at the time of casting

Insufficient preparation given to the slab surface before application of surface coatings, toppings or screeds.

Cracks may have been caused by:

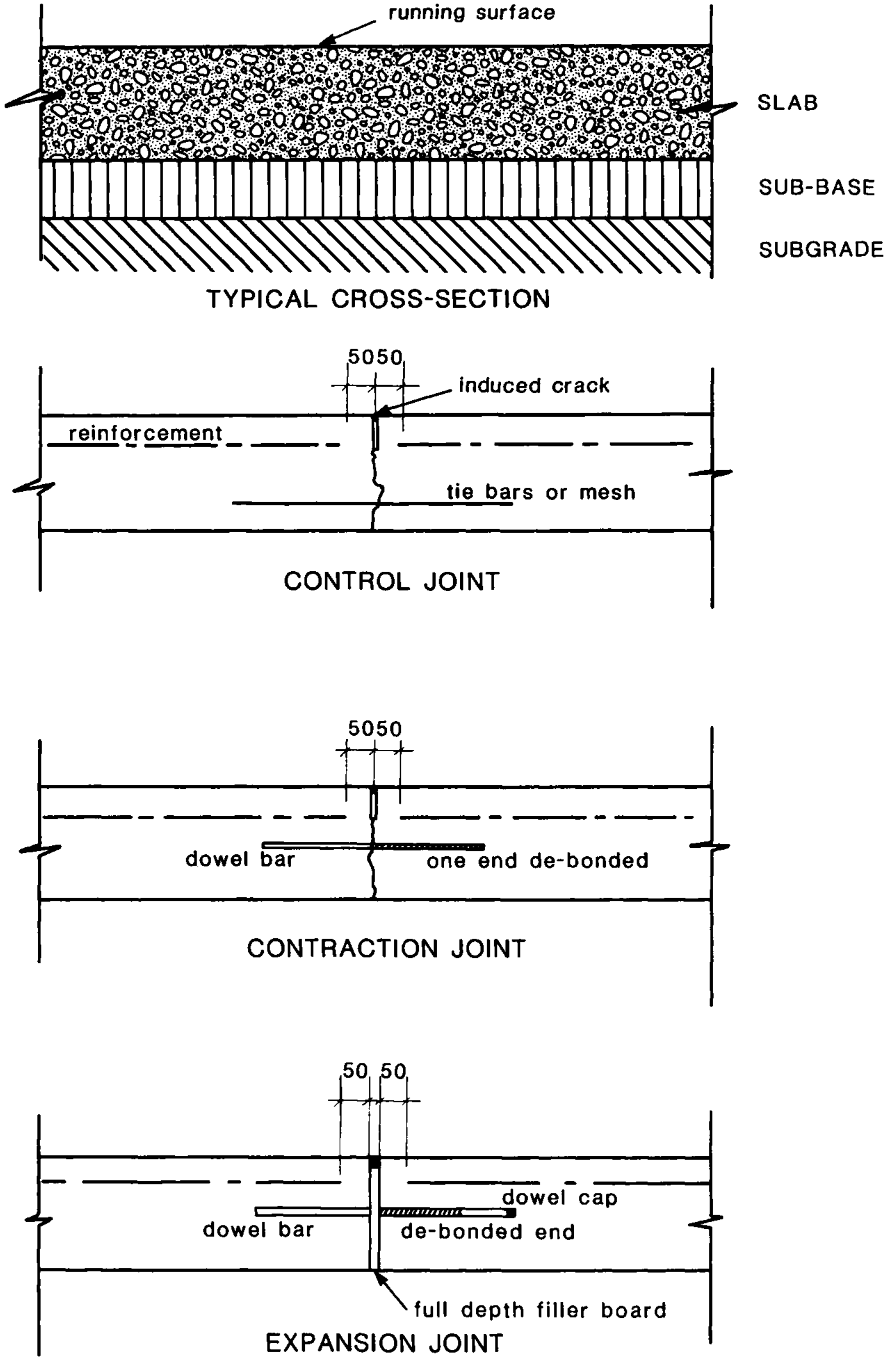

Figure 12.1 Expansion joint

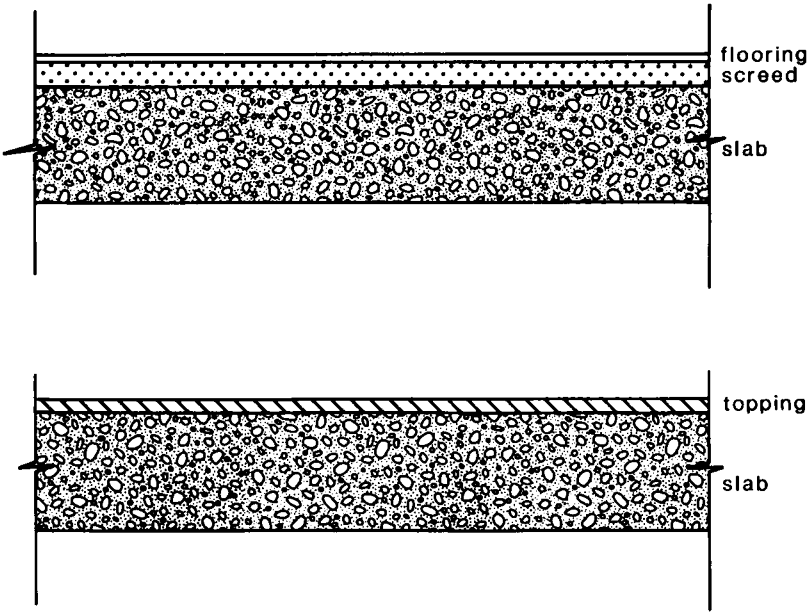

Figure 12.3 Cross-sections of floors with screeds and toppings

Heavy loadings, especially heavy point loadings, for which the slab was not designed

Loss of support to ground floor slabs due to some settlement of the subgrade Movement joints which are inadequate through design or workmanship faults.

12.5 Repairs to floor slabs*

12.5.1 *Preparation*

The success of repairs depends upon surface preparation. One of the most efficient and economical methods of achieving a clean, dry, and chemically free surface is by using portable steel shot-blasting equipment where the dust and contaminants are collected into a container by a powerful vacuum so that air pollution is eliminated (Figure 12.4). Depending on the depth of texture required or the surface hardness of the concrete the applicable size of shot will be used, and the speed with which the operator moves the machine over the floor will also

*Some repair materials suppliers are listed on p. 196.

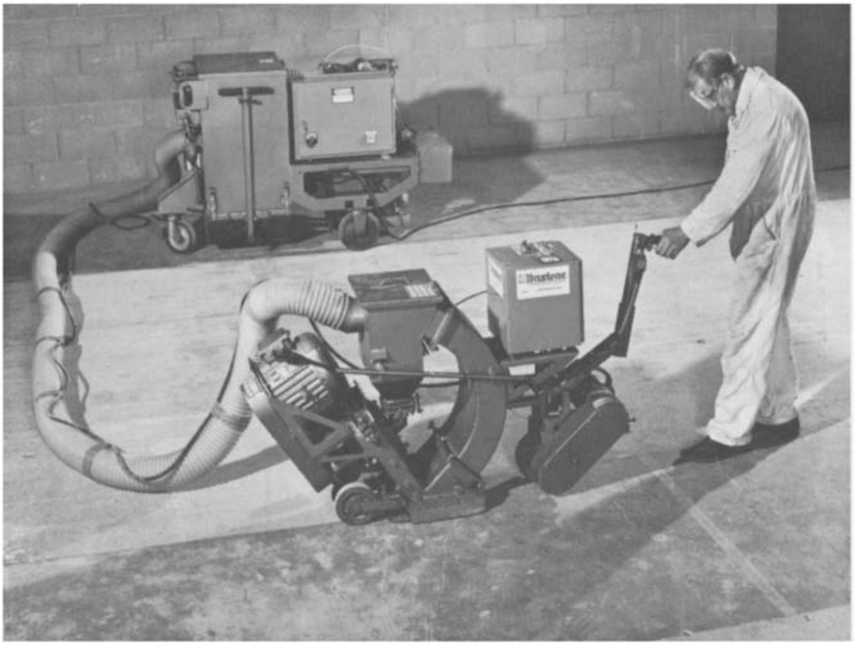

Figure 12.4 The 1–10D Blastrac shot blasting equipment, with a vacuum dust collector unit, on an industrial floor (British Cement Association)

affect the depth of surface texture. More than one pass of the machine may be necessary, especially if previous floor finishes such as paint or resin have to be removed (Figure 12.5).

Concrete planing machines are an alternative but are usually slower and are often used on smaller areas; extension flails can be fitted to some makes of machine so that they can work close up to walls and columns. As illustrated (Figures 12.6, 12.7) they can be coupled up to a vacuum container in pollution sensitive areas.

For areas where a deep rugous texture is required and air pollution is not a problem, Errut/McDonald scabbling machines (Figure 12.8) are often used and are operated by compressed air. These are made in various sizes of one up to eleven heads depending on the size of the area to be scabbled.

Where water can be applied and drained off and where a light texture is required, 10% hydrochloric acid solution can be used (Figure 12.9). This is brushed onto the floor surface and washed off thoroughly with a pressure hose.

Operatives should wear protective clothing, including gloves, boots and goggles.

In some instances a floor may have to be degreased before the surface can be prepared by one of the above methods. Scrubbing in a degreasing powder with a stiff broom and washing off with a pressure hose will remove most animal fats (Figure 12.10).

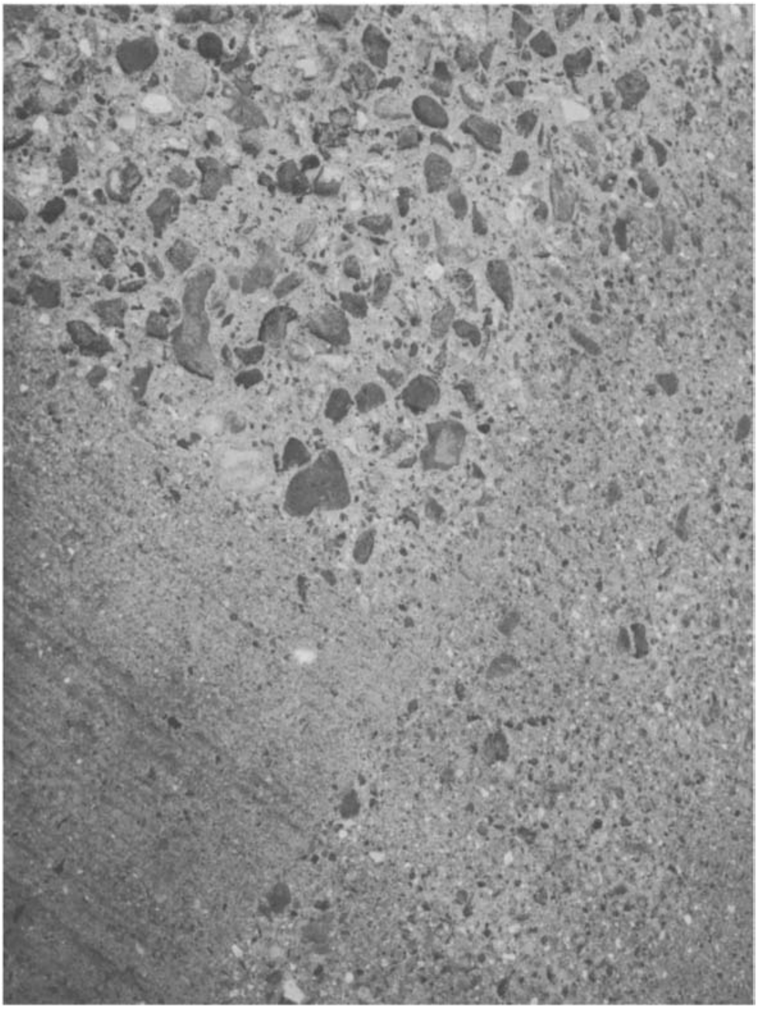

Figure 12.5 Untreated floor surface (bottom left) and two depths of shot blasting on the floor surface (right and top) (British Cement Association)

12.5.2
Thin bonded toppings

Where there are localized depressions caused by wear, which may be either at the middle of a slab or at a joint, these can be repaired by marking out perimeter lines at least 100 millimetres outside the worn area as shown in Figure 12.11.

The lines are then cut into the surface using a concrete saw. A single headed scabbling machine can then be used to remove the concrete from the area to below the level of the wear or damage. It is important that the arris formed by the sawcut is not damaged by the scabbling process. The repair area is then thoroughly

Figure 12.6 Errut planer with vacuum cleaner attachment (British Cement Association)

wetted and kept wet (for 24 hours if possible). All surplus water must be removed from the area before attempting to place the filling material. All dust must be carefully removed after scabbling. Air compressors used for removal of dust and water should be fitted with oil traps to prevent oil contamination of the freshly scabbled surface.

If the repair area is at a joint, a former is required to reform the joint edges. A piece of wood tapered in section, wrapped in polythene, longer and deeper than the repaired section is suggested. The cementitious filling materials for the repair can be either carefully weigh-batched on site using three parts of medium graded concreting sand to BS 882 and one part of ordinary Portland cement to BS12, mixed in a forced action mixer (Figure 12.12) with sufficient water to give a mix which will compact together when firmly pressed in the hand, or they can be purchased ready batched from a proprietary manufacturer. Names and addresses of these can be found at the end of the chapter. The quantities required for repair are small and it is not possible on many sites to accurately batch and mix small quantities of separate materials. The proprietary materials are carefully batched and quality controlled and will contain admixtures. A measured quantity of water is used in mixing which will give a low water cement ratio with a high workability. When placed, a small portion of the mix is scrubbed into the concrete to be repaired and the repair is completed by immediately placing the rest of the mortar. With proprietary materials, because of their higher workability,

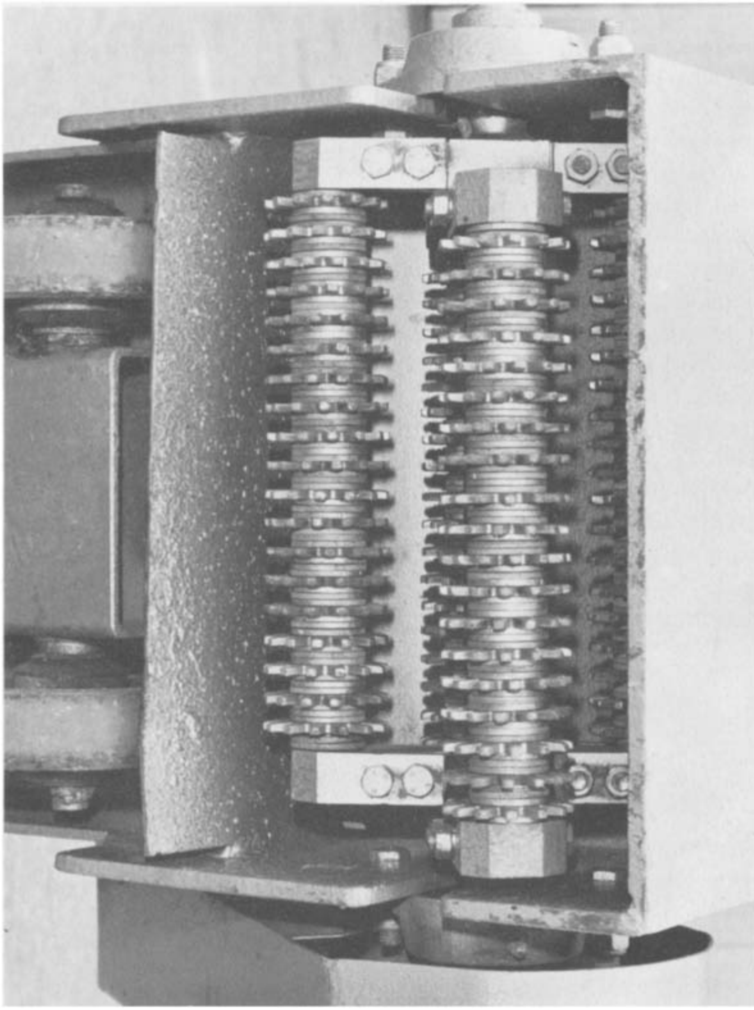

Figure 12.7 Errut planer showing the flail heads (British Cement Association)

hand tamping only is required. With a cement/sand mix a high compactive effort is required. Vibrating hammers with a square plate on the foot are often used, but on large areas a short beam can be fitted with a form vibrator and used in an up-and-down motion to press the material into the repair area. The repair is finished off with a hand trowel, trowelling the material into the edges. It is then covered with polythene held down at the edges with sand, and kept covered for seven days.

If the floor has to be put back into use earlier than this and high early strengths are required, some manufacturers supply a two-part pack, one containing the dry cementitious mortar materials and the other a polymer, normally styrene

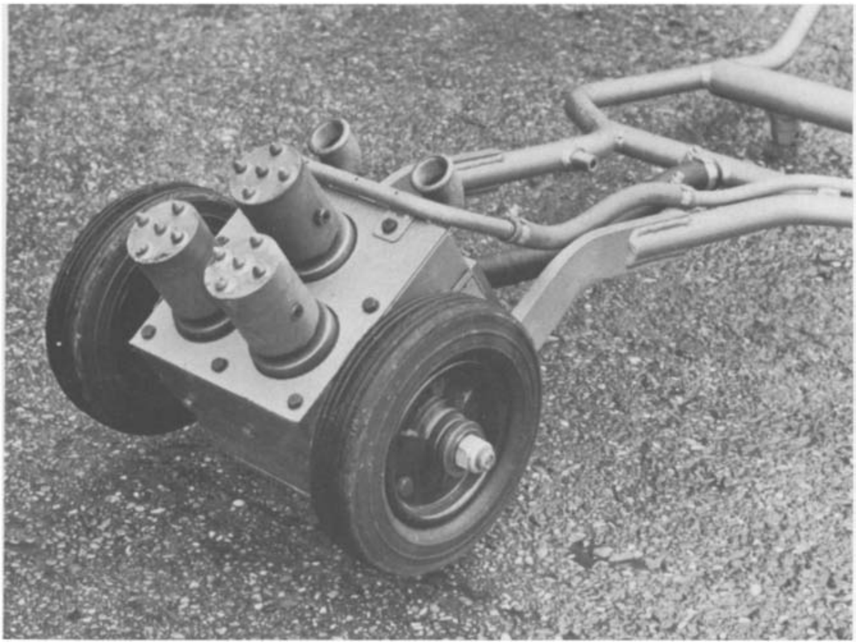

Figure 12.8 Triple-headed scabbler showing tungsten-carbide-tipped hammer heads (British Cement Association)

butadiene rubber latex (SBR). The SBR is used in lieu of water to the manufacturer's instructions. High quality local repairs can be carried out easily and quickly using these methods.

12.5.3
Reinstating joint sealants

Worn areas and fretting at joint edges cause deterioration of the joint sealant materials and it becomes necessary to take out the old sealant and renew it. This is best done with hand levers or crow bars, getting the lever under the old sealant and pulling up as long a length as possible. Finally, the joint cleaning can be finished off with a mechanical wire brush, removing any old sealant which is still adhering to the concrete.

All the worn areas or wide frets can be repaired with thin bonded toppings as previously described, but by increasing the joint width of the new sealant it will be possible to encompass small frets up to 10 mm deep within the new width. The joint can be widened with a concrete saw, sawing a new line parallel to the joint edge.

When applying a new joint sealant material it is important to follow the instructions given by the manufacturer of the materials.

Figure 12.9 Hydrochloric acid solution being applied and pressure-washed off (British Cement Association)

Generally it is recommended that a cold applied sealant should be used. The sealant materials are normally two-part packs which must be carefully mixed together. It is often recommended that a primer be used on the concrete edges before applying the sealant. A masking tape should be placed along the edges of the joint so that after placing the sealant with a gun, it can be trowelled level with the concrete edges and any surplus jointing material can be removed on the masking tape.

12.5.4
Repairs to cracks

Cracks occur for many reasons but the main cause is shrinkage, often occurring during the concrete hardening period.

Shrinkage cracks often occur at columns and at manholes and it is often good practice to accommodate these if possible in a control joint to line up with the expansion joint material on the column or manhole surround, so that the crack will occur in the joint. Except for their unsightly appearance, shrinkage cracks can be left without treatment but they will reflect up through toppings and coatings if these are applied to the floor surface (Figure 12.13).

They can be repaired by either resin injection or by opening the cracks, so that a filling material can be applied.

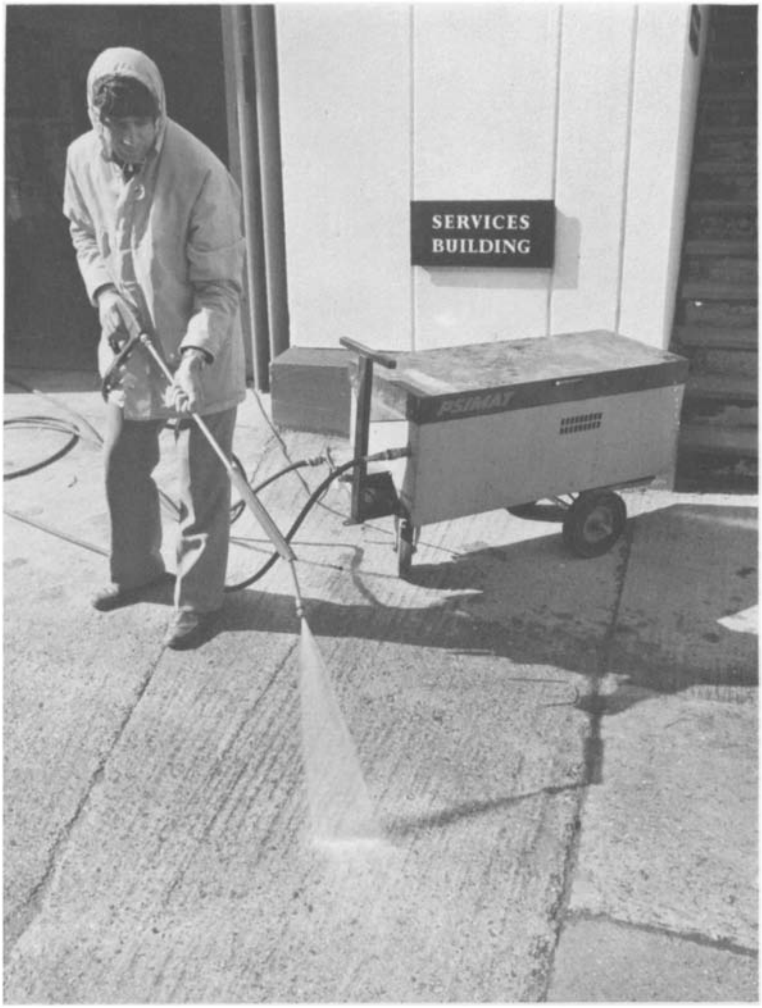

Figure 12.10 Cleaning dirty concrete with high-pressure water (British Cement Association)

Resin injection should be carried out when the crack has recently occurred and has not had time to get filled with dust or water. Injection nipples are grouted into the surface of the crack at intervals of approximately 0.5m and the surface of the crack is sealed between the nipples with a rapid curing resin. When the resin has hardened a gun containing a resin is applied to each nipple in turn. After filling the nipples they are removed and the holes that contained them made good.

If it is decided to open a crack, an Errut/McDonald crack cutter is used to chase out along the line of the crack (Figure 12.14). The opened crack is

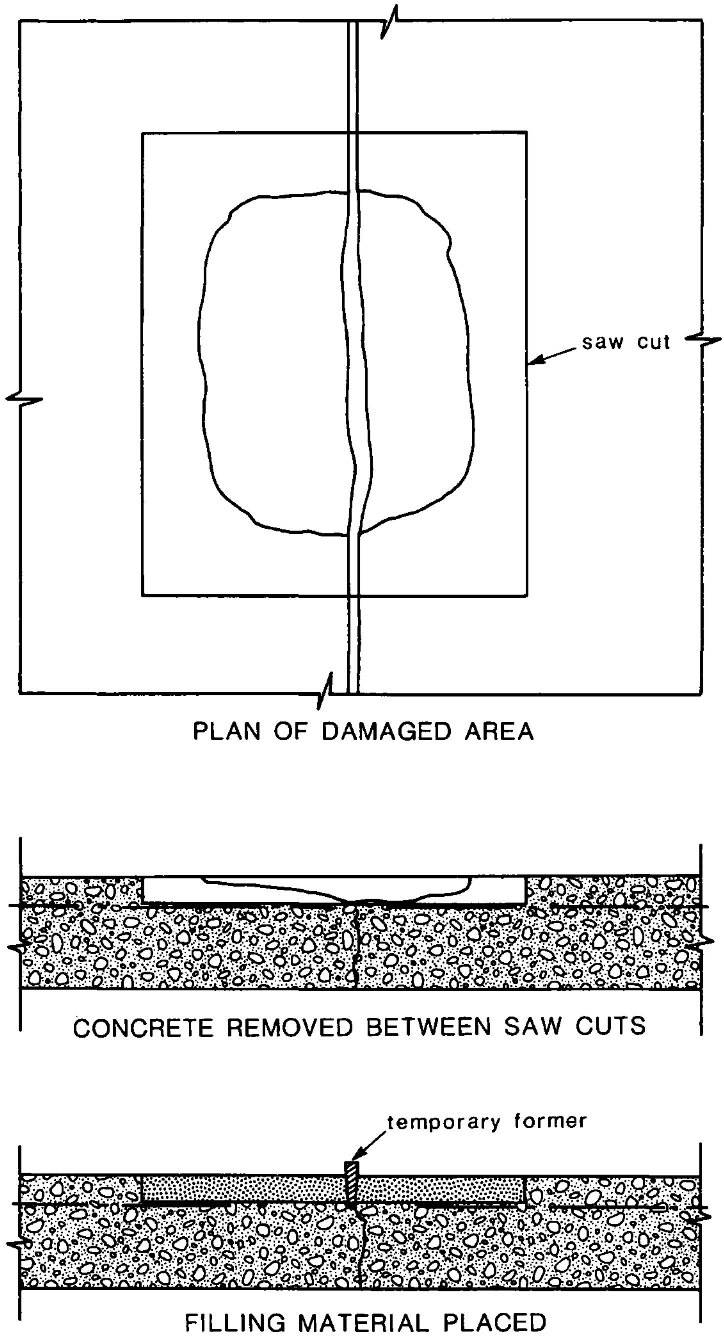

Figure 12.11

then thoroughly washed and left to soak for 24 hours if possible. Any surplus

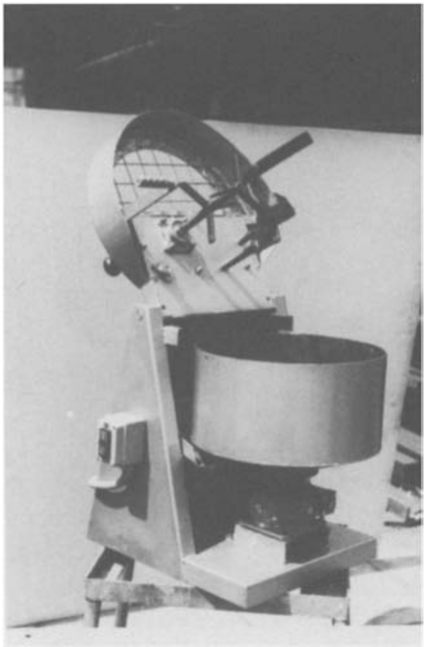

Figure 12.12 Forced action mixer (Edward Benton Ltd)

water is removed and either a proprietary cementitious repair mortar or a 1:3 cement/sand mortar carefully weigh batched and mixed should be used, compacted into the crack, finished with a trowel and cured by covering with polythene sheeting.

If it is decided by site observation that the crack has been caused by movement of some part of the building, the opened crack should be filled with a joint sealant to allow small movements to continue.

12.5.5
Reconstruction of slabs

Wide cracks in ground floor slabs, which may be caused by overloading or loss of support, will eventually cause the break-up of the whole slab. It is best to remove the slabs affected and reconstruct them. After inspection and compaction of the subgrade, the sub-base should be prepared at the correct level by using either well graded crushed rock material or lean concrete, 150mm thick, compacted with a plate vibrator.

The new slab thickness should be designed to suit the loading and the subgrade conditions. Before concreting, a polythene sheet should be placed over the top of the sub-base to act as a damp-proof layer. The concrete for the new slab should have a cement content of 330kg/m^3 of concrete, and a workability of

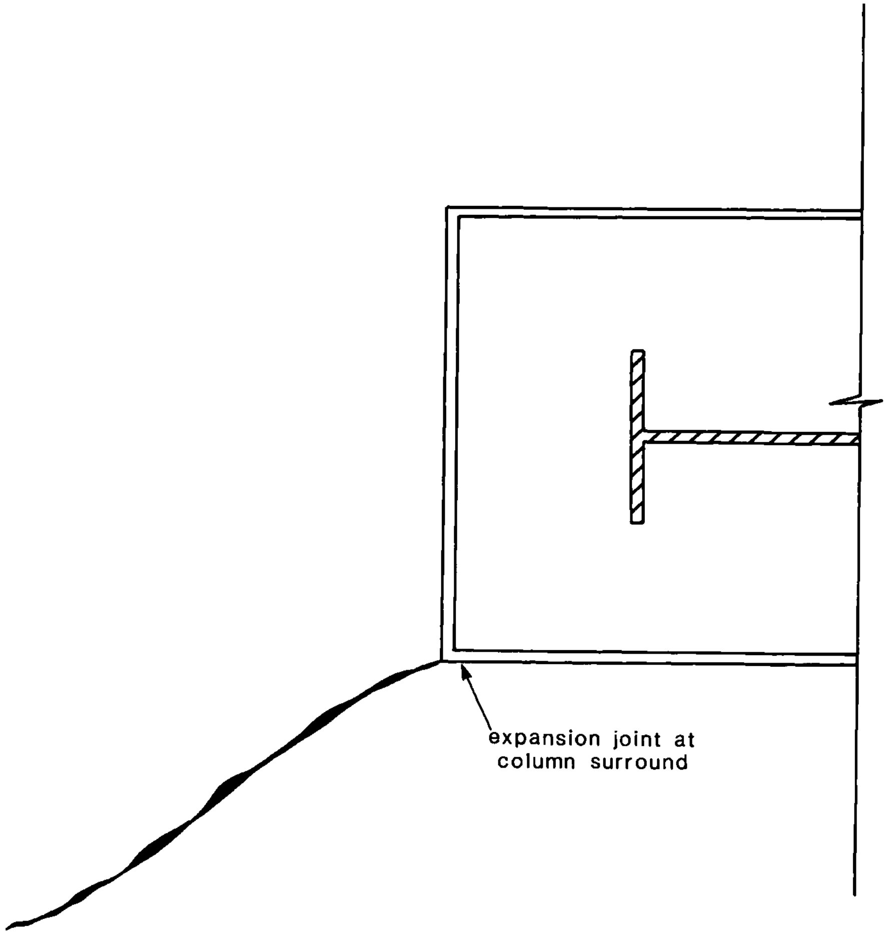

Figure 12.13 Typical cracking at obstructions

50 mm slump. If it is open to the weather it should have an air-entraining admixture added to the mix so that the concrete can resist frost attack and the action of de-icing salt. It should be fully compacted with vibrating pokers or beam when placed, and after finishing it should be cured by covering with polythene for at least 7 days, and should not be loaded or trafficked for 28 days.

Rocking slabs can be removed, the subgrade inspected and the slabs reconstructed in a similar manner as above, or the voids beneath the slabs can be filled with a resin grout using the 'Balvac' system. In this system (Figure 12.15) a series of holes are drilled through the floor slab which is then covered with a plastic sheet sealed down at its edges to the concrete slab. A pipe is inserted through one of the holes in the floor and a suction applied to create a partial vacuum under the plastic sheet and the floor slab. Water and air are forced out from under the slab and replaced with a resin mix which is poured through the

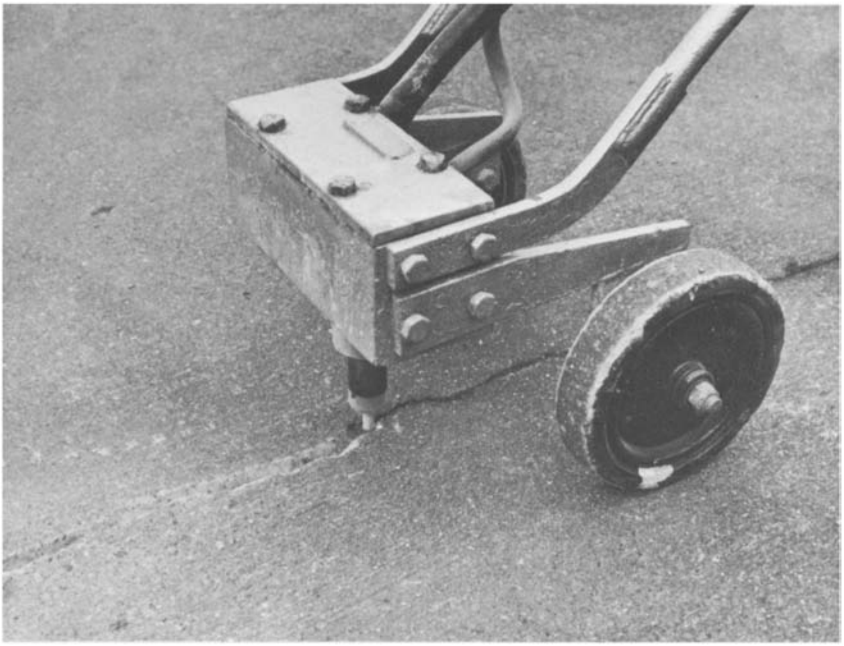

Figure 12.14 Using a crack router with 12 mm head to chase out the crack (British Cement Association)

other holes in a systematic manner. The resin takes a few hours only to harden, depending on temperature, and the floor can be put back into use.

12.6 Screeds

12.6.1 *Definition*

A floor screed is a layer of substantial thickness, usually of mortar made up of ordinary Portland cement and clean sharp concreting sand to BS 882 or occasionally of small aggregate concrete, laid and thoroughly compacted on a prepared concrete base slab and brought to a designed level to receive other flooring. The screed may be floated or trowelled smooth to provide a suitable surface for the specified flooring or finish.

As traditionally laid a screed is not intended to act as a wearing surface.

Figure 12.15 Grouting voids under concrete paving slab, and repairing cracks in slab, by Balvac vacuum injection process (BICC Ltd)

12.6.2
Common defects in cement/sand screeds

12.6.2.1 *Curling.* Screeds laid 25 to 40 mm in thickness will curl due to thermal and moisture shrinkage unless they are properly bonded to the base concrete. Proprietary bonding aids are often used instead of satisfactory preparation, but these aids are best used to assist bonding on to a properly prepared base concrete.

Screeds laid 50 mm thick with only partial bond are a high risk because they are thick enough to suffer high moisture shrinkage stresses but too thin to be able to withstand them. With partial bond the shrinkage stress will often overcome the bond stress and curling may become excessive.

12.6.2.2 *Poor compaction.* Screeds have to be laid at a satisfactory moisture content to suit the screed layer and methods of laying. Low moisture content with corresponding low workability coupled with low compactive effort will often cause failure.

12.6.2.3 *Use of unsuitable sand.* Fine sand is sometimes used in screeds by layers who consider that by using them they can achieve a closed fine surface. A medium grade concreting sand to BS 882 will have sufficient fines in the grading to produce a closed surface with a much lower water demand. Fine sand is a common cause of failure.

12.6.2.4 *Use of free-fall tilting drum mixers on site.* Even when the materials are accurately batched the use of free-fall tilting drum mixers causes wide discrepancies in the cement content in different portions of the mix. In a 1:3 mix, variation can be as much as from 1:1 to 1:8. This is due mainly to cement balling at the low moisture contents required in screed mixes. Forced action mixers should be used. If the batching accuracy is poor then variations can only increase. Areas laid at low cement content may fail under impact loads and are especially vulnerable if covered with a thin flooring material with low load distribution capacity.

If a screed fails due to excessive curling or fails due to impact loadings, patch repairs will be unsuccessful. The whole of the screed and flooring will have to be removed, the base slab properly prepared by retexturing and cleaning, and the screed replaced.

12.6.3
Cover to small pipes or cables

It is better if at the planning stage all pipes and cables can be routed into properly constructed ducts but if a pipe is laid in the thickness of the screed it must be properly bedded and the cover over the pipe should be 25mm minimum. Cracks will often appear in the screed over the top of the pipes and these can be controlled by covering the pipes with a close mesh reinforcement. Care has to be taken to ensure that the screed material is properly compacted around the pipe and the reinforcement. The danger is that the crack will ultimately reflect up through the flooring and that the edges of the crack will then crumble and fail.

12.6.4
Curing

Too often it has been found necessary to meet planned programme dates by artificially ‘drying out’ the floor screed with little thought given to the effects of drying shrinkage and curling. This could be even more severe when cables are buried in the screed for underfloor heating. It is important that when the screed is sufficiently hard it should be covered with polythene to control moisture for at least 7 days. Heating may then be gradually applied.

12.6.5
Floating screeds

To improve insulation it is sometimes necessary to lay a resilient layer of insulating material and lay a new screed on top of it. This screed should have a minimum thickness of 65 mm. In more heavily loaded buildings, e.g. parts of hospitals and offices, a minimum thickness of 75 mm may be specified. The greatest care must be taken in constructing a floating screed, as the weak support of the resilient insulating materials will enhance any weakness in the screed. It is also difficult to compact a screed on a resilient material so extra care is needed. Compaction on an insulation quilt is even more difficult than on rigid board insulation.

It is almost certain that some differential curling will occur at joints in a floating screed. Light mesh reinforcement, e.g. D49 to BS 4483 may be used to control any shrinkage cracking which may occur but it will not prevent the curling of screeds. If the reinforcement is continuous through joints, this will help to avoid steps caused by differential curling. Any reinforcement should be placed approximately central in the screed depth.

12.7 Toppings

12.7.1 *Definition*

High-strength toppings provide the wearing surface and are intended for conditions requiring particularly good resistance to abrasion and wear.

12.7.2 *Materials and preparation*

High-strength toppings with ordinary Portland cement as the matrix are often referred to as 'granolithic' toppings because originally only granite aggregates were used.

Today, while granite aggregates are often used, flint or quartzite gravel, basalt and hard limestone aggregates can also be used. The mix proportions are 1:1:2 by weight of cement/sand/10 mm aggregate. The sand should be medium grade concreting sand to BS 882 and the coarse aggregate should be hard, clean, 10 mm aggregate again to BS 882. The minimum amount of water is added to the mix to enable full compaction to be achieved when the topping is placed.

Old floors should be thoroughly shot-blasted or scabbled, cleaned, and saturated with clean water before bonding a cementitious topping to it. The strength and thickness of the old floor should be investigated in a survey. If the strength is doubtful or the thickness is 100 mm or less it would be better to lay an unbonded topping, described later.

12.7.3 *Bonded toppings*

With bonded toppings, bonding aids are often used; these include polymers, resins and cementitious grout. When using proprietary materials it is always best to read the manufacturer's instructions carefully and follow them. Variations apply with different brands. A cementitious grout mixed to a creamy consistency can be brushed onto the floor immediately before placing the topping mix. The topping mix should be laid 20 to 40 mm thick in bay sizes of up to 20 m^2, whose

Figure 12.16 Laying of granolithic floor topping (British Cement Association)

length and breadth should be as nearly equal as possible so that the shape of each bay approximates to square.

The construction joints in the old floor must reflect up through the topping. It will be compacted onto the old floor and trowelled level.

Further trowelling will occur at intervals while the topping is hardening, and after the final trowelling the topping should be cured by covering it with polythene for at least 7 days (Figure 12.16).

12.7.4
Unbonded toppings

An unbonded topping is in effect a separate slab laid over the old floor. No preparation is necessary but any construction joints in the old floor must be reflected up through the new slab. Properly lapped sheets of polythene are laid as a damp-proof membrane over the base slab and a 30 N/mm^2 concrete having a cement content of at least 330 kg/m^3 should be placed and compacted on to it, of 100 mm minimum thickness in bays of approximately 15 m^2. Before this concrete has hardened the high-strength topping mix, previously de scribed, should be placed and compacted on to its surface 10 to 15 mm thick. The trowelling at intervals during hardening and final curing are an important part of the process.

12.7.5
Resin and polymer toppings

Resin and polymer toppings are in common use because although they are in many cases more expensive than cementitious toppings they normally cure very much faster and the floor can be put back into use quickly. They provide seamless floors and are therefore more hygienic, and they offer a greater variety of colours and are chemical resistant.

12.7.5.1 *Epoxy resins.* Epoxy resins have a wide application in industrial flooring from heavy to light duty. They have high physical strength, good bonding characteristics, high impact resistance and can be made to give a non-slip finish. They are also highly chemical resistant.

Steam cleaning may cause damage to an epoxy resin floor and certain resins can taint food, but many epoxy resin formulators can eliminate these disadvantages.

12.7.5.2 *Polyester resins.* Polyester resins are used in heavy to medium industrial flooring where they are mixed with cement and fine, hard aggregate and laid in thicknesses up to 15 mm. They differ from epoxy resins in that they can be laid over a wider temperature range and have a better resistance to heat. They have not such good bonding characteristics, mainly because of the shrinkage which occurs during hardening. Certain brands, particularly 'Estercrete', claim to have eliminated this disadvantage.

12.7.5.3 *Polyvinyl acetate (PVAc).* Polyvinyl acetate is in common use as a bonding aid when thin mortar toppings are applied to existing concrete either for repair work or to produce a floor topping. The liquid can be applied straight on to a clean, sound surface and allowed to dry. On wetting by the application of the fresh mortar topping, sufficient 'grab' develops by slight re-emulsification of the film for a good bond to form.

The bond will be permanent in all except the very wettest exposure conditions in which case an alternative should be used.

12.7.5.4 *Styrene butadiene rubber (SBR).* SBR is a satisfactory alternative to PVAc in those situations where the slight water-sensitivity of PVAc is a problem. Unlike PVAc, the dried film does not develop 'grab' on re-wetting so it will act as a de-bonding layer if allowed to dry out. Consequently fresh mortar should be applied while a tack coat of SBR is still wet in order to overcome this problem. However, SBR will only form a film if allowed to dry out properly so a system must be isolated from water for a few days after the screed or topping has been placed in order for the full properties to develop.

12.7.5.5 *Acrylic resin.* All acrylic resins systems, like SBR, have excellent water-resistance and they form very useful admixtures for mortars, improving the bond strength and, to some extent, the chemical resistance. Jointless, non-dusting thin floor toppings can readily be produced with this material.

12.7.5.6 *Styrene-acrylic resin.* By blending tough styrene with acrylic resin, very hard-wearing floor toppings can be produced at a reasonable cost using 1:3 cement/sand mortars as the base and the dispersion as the mixing liquid.

12.7.5.7 *Polyurethane resin.* Polyurethane resins require dry conditions at the time of application if the best results are to be achieved. Formulations have been developed for floor finishes. A typical product would be used as a multi-coat system in conjunction with coloured plastic flakes to give a durable, decorative, non-slip surface.

Two coats of polyurethane are often used to prevent dusting on concrete floors.

12.7.5.8 *Proprietary screeds and toppings.* Many companies offer services and supply of materials for floor screeds and toppings and it is essential that the recommendations and information given by the manufacturer are closely followed on site.

In all cases the site preparation of the concrete floor repair will be as previously described for conventional materials, and in all cases adequate curing is important.

A typical company, Ronacrete Ltd., use a basic polymer of styrene butadiene and have provided materials for many years which can improve the compressive, tensile and bond strengths of a screed or topping. This will allow the thickness of the screed to be reduced and is useful when overlaying insulation material or when rehabilitating existing buildings. When mixed, compacted and cured properly there is a marked decrease in water vapour permeability, which can allow the screed to be used as a damp-proof membrane.

By using scientifically designed mixes it is also possible for them to gain strength more rapidly and hence reduce curing and time allowance before trafficking, which is often essential on repairs to industrial floors.

Due to the general inadequate training of most operatives and lack of knowledge of repair materials by their managers it is often necessary to obtain professional advice. This can be obtained from suppliers of proprietary materials or from specialist architects or consulting engineers.

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2. British Standard 882:1983, Aggregates from natural sources for concrete. British Standards Institution, London.
3. British Standard 4483:1985, Steel fabric for the reinforcement of concrete. British Standards Institution, London.
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5. British Standard 5385: Part 3:1989, Code of Practice for the design and installation of ceramic floor tiles and mosaics. British Standards Institution, London.

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Repair materials suppliers

Fosroc Ltd, Vimy Road, off Leighton Road, Leighton Buzzard, Bedfordshire LU7 7ER; Sealocrete (UK) Ltd, Atlantic Works, Oakley Road, Southampton S09 4FL; S.B.D. Ltd, Denham Way, Maple Cross, Rickmansworth, Hertfordshire; Ronacrete Ltd, Ronac House, Selinas Lane, Dagenham, Essex RM8 1QL.

Appendix A: Sources of information

United Kingdom

Barbour Builder Ltd, New Lodge, Drift Road, Windsor, Berks. SL4 4RQ. Tel. (main office) (0344) 884121. Fax (0344) 884845. Enquiry Service Tel. (0344) 884999.

British Cement Association, Waxham Springs, Slough SL3 6PL. Tel. (0753) 662727. Fax (0753) 660399/660499.

British Precast Concrete Federation, 60 Charles Street, Leicester LE1 1FB. Tel. (0533) 536161. Fax (0533) 514568.

British Standards Institution, Information and Sales Depts, Linford Wood, Milton Keynes, Bucks. MK14 6LE. Tel. (0908) 320033. Fax (0908) 320856.

The Building Centre, 26 Store Street, London WC1E 7BT. Tel. (071) 6373151. Fax (071) 5809641.

Building Research Establishment, Bucknalls Lane, Garston, Watford, Herts. WD2 7JR. Tel. (0923) 664800. Fax (0923) 664010.

Cement Admixtures Association, Harcourt, The Common, Kings Langley, Herts. WD4 8BL. Tel. (0923) 264314. Fax (0923) 270778.

Concrete Repair Association, 1st Floor, 241 High Street, Aldershot, Hants. GU11 1YW. Tel. (0252) 342072. Fax (0252) 333901.

Concrete Advisory Service Ltd, 35 Cowbridge Road, Pontyclun, Mid Glamorgan, CF7 9EB. Tel. (0443) 237210. Fax (0443) 237271.

Concrete Society Headquarters, Framewood Road, Wexham, Slough SL3 6PJ. Tel. (0753) 662226. Fax (0753) 662126.

Construction Industry Research and Information Association, 6 Storey's Gate, London SW1P 3AU. Tel. (071) 2228891. Fax (071) 2221708.

Federation of Resin Formulators and Applicators, 1st Floor, 241 High Street, Aldershot, Hants. GU11 1YW. Tel. (0252) 342072. Fax (0252) 333901.

Paint Research Association, 8 Waldegrave Road, Teddington, Middlesex TW11 8LD. Tel. (081) 9774427. Fax (081) 9434705.

Rapra Technology Ltd. (formerly Rubber and Plastics Research Association), Shawbury, Shrewsbury, Salop SY4 4NR. Tel. (0939) 250383. Fax (0939) 251118.

Sprayed Concrete Association, 1st Floor, 241 High Street, Aldershot, Hants. GU11 1YW. Tel. (0252) 342072. Fax (0252) 333901.

Transport and Road Research Laboratory, Department of Transport, Old Wokingham Road, Crowthorne, Berks. RG11 6AU. Tel. (0344) 773131. Fax (0344) 770356.

United States of America

American Concrete Institute, 22400 West Severn Mile Road, PO Box 19150, Redford Station, Detroit MI 48219. Tel. 010–1–313–532–2600.

American Society for Testing and Materials, 1916 Race Street, Philadelphia PA 19103. Tel. 010–1–215–299–5400. Fax 010–1–215–977–9679.

Portland Cement Association, Information Services Section, 5420 Old Orchard Road, Skokie, ILL 60077.

Appendix B: Suppliers of testing equipment

Chemical tests

Bayer Diagnostics Ltd, Ames Division, Evans House, Hamilton Close, Houndmills, Basingstoke RG21 2YE. Tel. (0256) 29181. Fax (0256) 52916 (Quantab test).

Camlab Ltd, Nuffield Road, Cambridge CB4 1TH. Tel. (0223) 424222. Fax (0223) 420856. (Hach test).

ELE International Ltd, Materials Testing Division, Eastman Way, Hemel Hempstead, Herts. HP2 7HB. Tel. (0442) 218355. Fax (0442) 52474.

Cover to reinforcement (pachometers)

Burton McCall Industrial Ltd, Samuel Street, Leicester LE1 1RU. Tel. (0533) 538781. Fax (0533) 628351.

CNS Electronics Ltd, 61–63 Holmes Road, London NW5 3AL. Tel. (071) 4851003/5. Fax (071) 4855782.

Controls Testing Equipment Ltd, Controls House, Tring Industrial Estate, Icknield Way, Tring HP23 4JX. Tel. (044) 2828311. Fax (044) 2828466.

Kolectric Ltd, International House, Thame Station Industrial Estate, Thame, Oxon. Tel. (0844) 261626. Fax (0844) 261600.

Steinweg UK Ltd, 12 Marshbrook Close, Alderman's Green, Coventry, West Midlands CV22NW. Tel. (0203) 621355. Fax (0203) 616876.

Crack widths

Avonguard Ltd, 61 Down Road, Portishead, Bristol BS20 8RB. Tel. (0272) 849782.

Controls Testing Equipment Ltd, Controls House, Tring Industrial Estate, Icknield Way, Tring HP23 4JX. Tel. (044) 2828311. Fax (044) 2828466.

Electrode potentials and resistivity

CMT Instruments Ltd, Raynesway, Derby DE27UU. Tel. (0332) 666161.

CNS Electronics Ltd, 61–63 Holmes Road, London NW5 3AL. Tel. (071) 4851003. Fax (071) 4855782.

Colebrand Ltd, Colebrand House, 20 Warwick Street, Regent Street, London W1R 6BE. Tel. (071) 4391000. Fax (071) 7343358.

Controls Testing Equipment Ltd, Controls House, Tring Industrial Estate, Icknield Way, Tring HP23 4JX. Tel. (044) 2828311. Fax (044) 2828466.

ELE International Ltd, Materials Testing Division, Eastman Way, Hemel Hempstead, Herts. HP2 7HR. Tel. (0442) 218355. Fax (0442) 52474.

MAPEL, 7 Eldon Way, Biggleswade, Beds. SG18 8NH. Tel. (0767) 317677. Fax (0767) 314650.

Rebound hammers (sclerometers)

Burton McCall Industrial Ltd, Samuel Street, Leicester LE1 1RU, Tel. (0532) 538781. Fax (0533) 628351.

Screed testers

C&CA Services Ltd, Wexham Springs, Slough SL3 6PL. Tel. (0735) 662130. Fax (0735) 660399.

Controls Testing Equipment Ltd, Controls House, Tring Industrial Estate, Icknield Way, Tring HP23 4JX. Tel. (044) 2828311. Fax (044) 2828466.

Hammond Concrete Testing & Services Ltd, PO Box 75, Dorking, Surrey RH4 2YX. Tel. (0306) 887854. Fax (0306) 888060.

Ultrasonic pulse velocity and voids detection

CNS Electronics Ltd, 61–63 Holmes Road, London NW5 3AL. Tel. (071) 4851003. Fax (071) 4855782.

Controls Testing Equipment Ltd, Controls House, Tring Industrial Estate, Icknield Way, Tring HP23 4JX. Tel. (044) 2828311. Fax (044) 2828466.

Hammond Concrete Testing & Services Ltd, PO Box 75, Dorking, Surrey RH4 2YX. Tel. (0306) 887854. Fax (0306) 888060.

Dr. R.J. Savage, Ulverley House, Woodland Way, Kingswood, Surrey KT20 6NU. Tel. (0737) 832037.

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Appendix D: Specifications for concrete repair

J.D.N.SHAW

Material standards and test methods

At present, there are very few standard specifications for the repair of reinforced concrete in the UK. In 1986 the Department of Transport published some specialist specifications for the repair of highway structures BD27/86 (1) which is used in conjunction with guidance note BD23/86 (2). The principal repair method covered by BD27/86 involves the use of a proprietary factory preblended quality controlled material which gives a highly flowing concrete mix with either less than 3 kg soluble alkali per cubic metre of repair concrete, or to be certified to be based on non-reactive aggregates. Concretes complying with this specification have been used for the repair of highway structures around the UK but most of the volume of this type of repair concrete has been used for repairs to structures on the M6 Midland Links.

The specifications for repairs on the Midland Links are based on BD27/86 but for the repair of crossheads the specification is much more stringent, requiring a much higher flow and to conform to both the maximum 3 kg soluble alkali per cubic metre, and non-reactive aggregates. Because the repair concrete is placed against mature concrete there are also tight requirements regarding the dimensional stability of the repair concrete. This has required the incorporation of shrinkage-compensating cements in the mix design. Since 1991 the majority of the repair contracts on the Midland Links have involved the use of cathodic protection techniques. On these contracts the specification has required that the replacement repair concrete complies with the same specification for the highly flowing concrete but, in addition, requires a resistivity below 15000 ohm cm after 28 days wet cure.

It is stressed that all the repair contracts on the Midland Links have been considered as proving trials for more comprehensive specifications which are currently being drafted by the Department of Transport for the repair of highway structures. These new specifications are likely to be published within the next year.

BD27/86 also specified the use of monomeric isobutyl trialkoxy silane for the treatment of concrete surfaces to reduce the ingress of chloride ions into highway structures. The specification for the impregnation of highway structures was revised in 1990 and published as BD43/90 (3).

Up to now the UK have not produced any standard specifications for the patch repair of reinforced concrete buildings and, as a result, repair specifications have tended to be very varied and many have been based on specific proprietary repair materials often manufactured in Europe, especially Germany, where the repair of reinforced concrete has been a more formalised industry for more than ten years. In 1988 the Concrete Society, recognising that a UK specification for reinforced concrete repairs was required, formed an industry-wide working party to produce a model repair specification for the patch repair of reinforced concrete. This was published in 1991 as Concrete Society Technical Report No. 38 (4). This report follows the stages of a repair specification from identification of cause(s) and location of defects, through removal of defective concrete cover, surface preparation, of both parent concrete and reinforcement, and reinstatement (generally with proprietary repair materials including reinforcement primers, repair mortars and protective surface coatings). Methods of measurement and the preparation of the bill of quantities are also covered in detail. It is hoped that TR38 will help standardise the preparation of tenders and the execution of concrete repair contracts in the UK over the next few years. Certainly it will help many building owners and their advisers to prepare more consistent repair tender documents when they need to repair their reinforced concrete structures.

When the EC Construction Products Directive is fully implemented, through the UK Construction Products Regulations 1991, it will be mandatory for all major construction contracts in the European Community to be open to all building materials manufactured in the EC, provided they conform to agreed performance criteria and, in most cases, have obtained a CE mark. It is now not permissible to specify named proprietary repair materials or indeed to specify repair materials by generic descriptions.

In general there will be two different methods of achieving a CE mark: (i) through The European Organisation for Technical Approvals (EOTA); or (ii) by testing to Harmonised European Standards. EOTA—The British Board of Agrement (BBA) is the UK member of EOTA—can only grant a European Technical Approval (ETA) if the approvals procedures have been agreed and ‘harmonised’ throughout Europe. An approval by the European Standards EN (Euro-Norm) route requires that a product be tested to a European Standard established through CEN, the European Standards Organisation to which all the National Standards organisations in EC and EFTA belong. EOTA is primarily intended to establish ETAs for novel construction materials for which no National Standards exist.

In the case of concrete repair materials a European Standard Technical Subcommittee TC 104 SC8 is currently working on the preparation of harmonised standards for the repair and protection of concrete. Under European rules this precludes the preparation of a harmonised procedure for EOTA members to grant ETAs for repair materials. Existing National Agrément

Certificates—in the UK a number of proprietary repair systems already have BBA Certificates—will continue to be valid until the EN for repair materials is finalised.

The initial task of SC8 is to produce a performance-related standard for repair materials. Practical test methods for concrete repair and protection materials are currently being drafted. Once the test methods are in place it will be necessary to agree minimum acceptable levels of performance for repair products or systems for different service requirements and service conditions. At a later stage a European Code of Practice for concrete repair will be established. In some countries, in particular Germany and Holland, detailed Codes of Practice for the repair of reinforced concrete are already established and these are being taken into consideration in the drafting of the European Standard (5–7).

The work of SC8 has been divided into six Task Groups.

TG1: Surface Protection Materials
TG2: Repair Mortars and Concretes
TG3: Structural Adhesives
TG4: Materials for Crack Repair
TG5: Anchoring Materials
TG7: General Principals for the Repair and Protection of Concrete

Until recently there was another task group TG6 covering cathodic protection systems for reinforced concrete but the work has now been transferred to CEN TC 262 SC2, which specifically covers cathodic protection systems to prevent corrosion of steel. Task Group 7 was recently formed and the exact scope of its work will not be agreed until autumn 1992.

Clearly TG1 and TG2 are the most important for the majority of repair situations. The first task of these groups is to agree the critical performance criteria and how to measure these criteria by practical test methods. It is vital that the performance is tested by realistic and practical test methods which will give clear indications of the long-term performance and durability of repair and protection systems in service, and thus ensure that the repair systems are fit for service, providing the repairs are carried out properly.

Where appropriate ISO standards exist, CEN rules make it mandatory for these to be considered first, possibly modified to make them more practicable, followed by existing national standards and also, in the case of repair materials, by appropriate RILEM test methods. Over the past few years RILEM have been particularly active in the field of concrete repairs.

Task Group 1 covers surface protection systems, including both coatings and water-repellant systems, and has classified its work into the following six categories.

1. Hydrophobic impregnations to make exposed concrete surfaces impermeable to water and water-borne contaminants.

2. Coating systems for concrete not subject to mechanical loads.
2a. Not subject to freeze/thaw.
2b. Subject to freeze/thaw cycles.
3. Crack-bridging coating systems.
3a. Not subject to freeze/thaw.
3b. Subject to freeze/thaw.
4. Coating systems for concrete liable to chemical attack.
4a. Not subject to mechanical load.
4b. Subject to mechanical load.
5. Coating systems for waterproofing concrete not subject to traffic.
6. Crack-bridging coating systems for waterproofing concrete subject to traffic.

Test methods to cover the performance characteristics that are considered necessary are currently being drafted. Work being undertaken by CEN TC 139 on Masonry Coatings is being taken into consideration to ensure no duplication of work.

The following list summarises the key performance requirements that are currently being considered by the task group TG1 on surface treatments. Other test methods covering performance requirements for specialist applications will also be considered.

1. Tensile bond strength
2. Cross hatch bond performance
3. Thermal compatibility.
3a. Reaction to freeze/thaw stress
3b. Reaction to 'thunder shower' stress
3c. Reaction to thermal cycling.
4. Permeability to gases
4a. Water vapour
4b. Carbon dioxide
4c. Oxygen.
5. Permeability to liquids
5a. Water
5b. Chloride ion solutions
6. Artificial weathering.
7. Crack bridging ability.
8. Cleanability.
9. Chemical resistance.

Task Group 2 covers repair mortars and repair concrete, including reinforcement primers and bonding agents where they are part of the repair system. This group is currently drafting test methods to measure the following critical performance parameters.

1. Tests to ensure that the mixed materials have the right application characteristics and maintain them for an adequate time at the application temperature to enable repairs to be carried out correctly.
2. Tests for strength and rate of strength development to ensure the materials are more than adequate for any proposed end-use.
3. Tests to ensure that the repair materials are sufficiently dimensionally stable and compatible with the concrete being repaired.
4. Tests to ensure the materials have low permeability to gases or liquids. This includes resistance to carbonation.
5. Tests to ensure the repair material has good integrity and bond strength to concrete under environmental or load cycling likely to be encountered in service.

A similar range of test methods to cover the critical performance characteristics for other repair materials are being drafted by the other task groups TG3, TG4 and TG5.

In several cases similar test methods are required by all the task groups and also by other CEN technical committees. Care is being taken to ensure a minimum number of European test methods are drafted and that any duplication of work is avoided.

Once the test methods have been agreed it will then be necessary to decide which values are deemed acceptable for different service conditions. In some cases there will be considerable differences in the values that are acceptable under different climatic conditions or degrees of exposure to adverse conditions. This task is likely to prove difficult, particularly where the tests agreed are not widely known and there is little experience of the results generated by these methods.

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