Repairs to Concrete

1. INTRODUCTION

Most people think of concrete as a maintenance-free building material, and in most structures it is. Sometimes, however, defects arise that the owner considers unacceptable. These may be present from the time of construction or may develop over time. They may affect one or more aspects of the structure's performance, or they may simply be unsightly. Whatever the cause and whatever the symptom, repairs are then necessary.

There are many types of concrete defect and many repair techniques. For most repairs several different options will be available, ranging in convenience, effectiveness, and cost. An effective repair is carried out not simply to hide or disguise a defect, but to address any aspects of performance that are affected and to manage the extent and rate of future deterioration in accordance with the needs of the structure's owner.

This Information Bulletin describes the process of selecting the most appropriate repair for a given application, and outlines the main features of methods and materials for repairing various common defects that may affect concrete performance. It does not cover treatment for cosmetic defects such as efflorescence or discoloration, moisture-related problems, or damage caused by exposure to specific chemicals. Readers should refer to the references listed in Section 10 for more detailed information.

2. REPAIR STRATEGIES

The New Zealand Building Code and current asset management practices require concrete elements to continue to satisfy performance requirements for a defined period of time. For new structures this will be a minimum of 50 years unless the specified intended life of the structure is less than this. Repair must therefore not simply provide an immediate fix but must also address the strategic needs of the structure's owner.

The repair strategy is the entire process of managing deterioration on a concrete structure. It accounts for economic, technical/structural, performance, statutory and environmental factors, and includes the strategic, technical and practical considerations listed in *Table 1*. The strategic considerations need to be discussed with the owner before developing the repair specification. The technical aspects need to be considered by the specifier and appropriate technical specialists. The practical aspects need to be considered by the specifier and the contractor.

Table 2 summarises the sequence involved in establishing a repair strategy. It is an overview of the repair and remediation process outlined by DD ENV 1504-9:1997, a draft standard published by the British Standards Institution that is intended to form the basis of repair specification in the UK and Europe. Sections 3 to 9 discuss the actions in Table 2.

3. CONDITION ASSESSMENT

The first step in the repair process is to accurately describe the nature and extent of the damage present, its possible causes and likely significance.

Table 3 lists general types of defect that may be present.

Table 4 lists factors that contribute to concrete defects. Damage is rarely caused by just one factor. All contributing factors need to be identified and addressed to achieve an effective repair, although it may not be possible or necessary to rectify them all. For construction related factors, possible future deterioration should be addressed at the same time as existing defects. Factors relating to continuing exposure conditions must be removed to achieve a permanent repair. If the damage is related to a single event the likelihood and consequences of it occurring again must be assessed.

Sometimes the cause of the damage is obvious, for example construction-related defects such as honeycombing or minor impact damage.

In other cases, particularly the deterioration of an existing structure, a more detailed condition assessment may be needed to establish its cause, extent and severity. A condition assessment should include discussion with personnel involved in the construction and maintenance of the structure, and review of construction records, maintenance records and repair history, including drawings, specifications and laboratory test results. It may also involve in-situ testing, laboratory examination and testing of samples taken from various parts of the structure, and structural analysis. When conducted as the first stage in the repair process, the condition assessment can also provide information on estimated quantities of the repair work

Personnel with knowledge and experience of the performance of the particular type of concrete structure should carry out the condition assessment to ensure that all contributing factors are identified and appropriate repair options selected. A Chartered Professional Engineer with appropriate experience should assess cases where structural performance is in question, i.e. where the bulk properties are affected. A materials specialist should be consulted when concrete or reinforcement durability is an issue.

4. MANAGING DETERIORATION

The second step is to choose an approach for managing the damage.

If possible, the source of the deterioration should be addressed, e.g. by installing physical barriers to prevent impact, redirecting run-off, eliminating causes of cavitation, or improving containment of aggressive chemicals. If the source cannot be removed, its effects must be reduced.

Options for treatment of the structure include:

- do nothing, but perhaps monitor changes in condition; reanalyse and perhaps downgrade anticipated performance (e.g. load capacity, abrasion resistance);
- evaluate and possibly shorten the estimated remaining service life;
- replace damaged concrete (e.g. patch repair);
- prevent or reduce further deterioration (e.g. surface treatment);
- improve or refurbish all or part of structure (e.g. strengthening);
- rebuild all or part of structure;
- demolish all or part of structure.

The best approach may not be obvious except where:

- "do nothing" is appropriate because the deterioration does not affect performance;
- demolition is appropriate because the structure is in such poor condition or because it no longer fulfils functional needs (e.g. an industrial floor is not strong enough for a proposed new use of the building, or a bridge is under capacity and the combination of repair and strengthening is more expensive than replacement).

The most appropriate approach will be determined by a combination of technical requirements, including the ease of removing the source of damage, and the owner's strategic needs. Economic analyses are usually used to assist in ranking the technical options for large repairs. A combination of approaches may be taken on a large structure with widespread damage.

5. REPAIR PRINCIPLE

The "repair principle" describes what must be achieved for a repair to successfully address shortcomings in performance and the risk of future damage. It must reflect the cause and extent of damage, the required remaining service life of the structure and the service conditions anticipated during that time. A repair method or material selected without consideration of the principle behind it may not be as effective or long lasting as the owner of the structure expects, particularly if the deterioration is of an ongoing nature.

An example of this is the treatment of cracks. Cracks caused by load-induced movement of the structure can be filled or sealed to restore structural performance or to protect against ingress of moisture and other contaminants. Filling or sealing will not be effective for cracks caused by reinforcement corrosion because these methods do not alter the conditions in the concrete that caused the steel to corrode.

A second example is reinforcement corrosion itself. Reinforcement corrosion involves chemical reactions at two sites on the steel (the anode and the cathode) that are exposed to slightly different electrochemical conditions, a metallic connection that allows the electrical current (i.e. electrons generated by the chemical reactions at the anode) to flow between them, and an electrically conductive solution (water in the concrete pores) that allows the flow of ions through the concrete between them. Repair principles may therefore involve controlling chemical reactions at the anode or at the cathode, the flow of electrical current or the flow of ions. Except for directly controlling the electrical current flow by cathodic protection, addressing one of these processes in isolation will impact on the others. For example, appropriate repair materials will restore the electrochemical conditions that normally prevent steel from corroding in concrete, i.e. they will passivate the anode[1]. This is achieved by restoring the alkaline environment around the bar and removing chloride ions, which catalyse corrosion reactions. The effect will, however, be restricted to reinforcement within the repair. Adjacent reinforcement, if electrically connected, will not be passivated and may start to corrode – a phenomenon known as the incipient anode effect.

[1] Steel embedded in Portland cement concrete is usually in a passive state, i.e. it does not normally corrode because a protective iron oxide film is produced on the steel surface in the alkaline conditions. If the concrete alkalinity is reduced, e.g. by reaction with carbon dioxide (“carbonation”), or if the concrete is contaminated with chloride ions the iron oxide film will no longer be stable. When moisture and oxygen is present the steel will then start to corrode.

Table 5 summarises the repair principles given in DD ENV 1504-9:1997 that may be applied to different types of defect.

6. REPAIR METHODS

The factors listed in Tables 1 and 2 must be considered when selecting repair methods. A combination of methods that addresses more than one principle may be appropriate. For example, the approach to repairing concrete damaged by reinforcement corrosion may involve patch repair to restore steel passivity and damaged concrete, supplemented by discrete anodes installed to cathodically protect adjacent rebar from incipient anode corrosion and a surface treatment to reduce the moisture content of the concrete and thereby its electrical resistivity.

Table 6 lists repair methods suitable for addressing the repair principles given in Table 5. These methods are described below. Section 7 describes materials that may be used.

6.1 Surface Protection to Prevent or Reduce Future Deterioration

Surface protection covers treatments applied to prevent or reduce future deterioration by protecting against ingress of moisture and aggressive agents, by increasing physical and chemical resistance and by controlling the transfer of moisture through the concrete. They may be applied over the original concrete or over repair materials. Unless specifically described as suitable for waterproofing, most surface treatments will not resist water applied under pressure.

Surface treatments will not be effective unless the substrate is sound and adequately prepared before application. Mechanical or abrasive cleaning processes may be used. Chemical methods based on solvents or acids are not recommended, but detergent based products and some proprietary cleaners that are part of a repair system may be acceptable. All loose material, dirt and organic growth must be removed, and the surface may need to be filled, levelled and smoothed with special cementitious mortars before applying the coating to ensure that it bonds well, achieves a uniform thickness with no sharp penetrations and does not form pinholes as it dries.

Vapour-permeable surface treatments reduce the amount of moisture in the concrete and thus increase its electrical resistivity, and may thereby reduce the rate of reinforcement corrosion. They will only be effective if the only means of moisture ingress is through the treated surface and if the concrete is already partly dry when treated. They may be less effective in reducing chloride-induced pitting corrosion because very little moisture is needed to support pitting corrosion.

6.1.1 Protection Against Ingress

Protection against ingress of water and aggressive agents is achieved by sealing the concrete surface, including cracks. Additional external cladding may need to be erected if these methods are unsuccessful.

Most of the methods used to protect against moisture ingress will reduce the bond of subsequent treatments that are not part of the same system. Before selecting a surface treatment, the likely need for future remedial or aesthetic treatments should be considered.

Penetrating sealers are designed to prevent the ingress of liquids but to allow moisture already in the concrete to evaporate. The depth of penetration depends on the composition of the sealer and the quality of the concrete. They may reduce moisture ingress at cracks by blocking fine cracks or by lining crack surfaces with a hydrophobic layer but they do not seal, bridge, or repair cracks.

Surface coatings provide a continuous barrier on the concrete surface to block the passage of liquids and reduce or block the passage of air. Different coating types have different characteristics. Surface coatings must be flexible enough to withstand anticipated movement of the substrate. To bridge active cracks, the coating must be elastomeric, be separated from the surface at the crack (see below), or incorporate a flexible fibre in the region of the crack. Coatings are more susceptible than penetrating sealers to problems associated with moisture in the substrate, which can cause blistering, loss of adhesion to the substrate, or deterioration of the coating itself.

Surface hardeners improve the abrasion resistance of new concrete surfaces that dust as a result of poor finishing techniques and inadequate curing, but they are not suitable for heavily-trafficked surfaces.

Bandaging may be necessary to enable coatings to bridge active cracks where crack movement is likely to exceed the elastic range of the coating. For thinner coatings this is achieved by placing a flexible tape or fabric over the crack before applying the coating. The long-term durability of this repair technique is open to question.

Crack filling can be used to prevent the ingress and passage of moisture, and to stiffen the cracked member. This is normally done by injecting the repair material into the crack through injection ports sealed to the concrete at regular intervals. The crack is sometimes flushed with water or with compressed air to remove dirt and fine particles. The surface of the crack is then sealed with a filled resin. The repair material is injected starting at the lowest injection port (or at one end of a horizontal surface) to displace water and air, moving along the line of ports in succession as grout appears ahead of the injection point, and plugging the filled ports behind as the crack progressively fills. Non-active cracks may be filled with a rigid material, which will strengthen the affected member if it penetrates the crack system fully and bonds to the crack wall (both of which can be checked by coring samples from the repaired area). Active cracks must be filled with flexible fillers, which will not contribute to the strength of the member. Cracks should be filled when they are at maximum width because most filling materials will perform better in compression than in tension.

Converting cracks to joints should be considered where the crack is relatively straight and appearance is important or anticipated movements will be larger than can be accommodated by normal crack filling materials. The crack is routed at the concrete surface to widen and straighten it, then sealed with a joint sealant suitable for the conditions and anticipated movement across the crack. A bond breaker must be used to prevent the sealant sticking to the bottom of joints where movement is expected. This approach is not suitable for sealing cracks exposed to hydrostatic pressure. Wet cracks can be filled prior to sealing to keep the sealant dry until it has cured.

Waterproofing is used to prevent the passage of water through concrete under pressure. Waterproofing techniques include tanking membranes, waterproof barrier coatings and pore blocking materials applied to the upstream surface to prevent ingress of water, and waterproof barrier coatings and pore blocking materials applied to the downstream face to prevent moisture egress into spaces where it may damage other building components, finishes and fittings. Tanking membranes are typically used to prevent groundwater passing through buried concrete and, overseas, on bridge and parking decks to protect against the ingress of de-icing salts. They are generally applied to new concrete. Attention must be paid to substrate preparation and detailing at membrane joints and edges, and the membrane must be protected against damage caused by traffic loads, impact and abrasion. They are not permeable to water vapour so should not be applied to the downstream face. Pore blocking materials and barrier coatings applied to the upstream face may not be as waterproof or provide the robust physical barrier or longevity of a tanking membrane. Nevertheless, when applied to the downstream surface they may be effective in reducing the rate of flow to a manageable level, particularly where the downstream face is not exposed to physical damage, the flow rate is relatively low, or the damage localised.

6.1.2 Increasing Chemical and Physical Resistance

Chemical-resistant sealers, coatings and overlays may be applied to concrete in particularly aggressive environments, such as where concrete is exposed to acid in industrial or geothermal environments.

Physically resistant toppings may be applied to reinstate surfaces damaged by mechanical action such as abrasion, erosion, or freeze-thaw. Floors are the most commonly treated surface.

Weak material and surplus concrete need to be removed from damaged or uneven surfaces, and extra material may need to be removed from the substrate to accommodate the required thickness of topping material. Surface preparation techniques depend on site constraints and the amount and nature of material to remove, and include hydrodemolition, grinding, milling, abrasive blasting and, for floor surfaces, captive shotblasting.

Toppings may be bonded or unbonded. Bonded toppings are used for thin layers (less than about 50mm), where the damage is restricted to the surface. Unbonded toppings are preferred where cracks or other signs of distress in the substrate may reflect through the topping, or where the topping is likely to be replaced in the future, e.g. a sacrificial wearing surface. Unbonded toppings are separated from the substrate by a layer of material such as polythene which allows the substrate and topping to move independently.

6.1.3 Moisture Control

Moisture control involves reducing moisture flow to an acceptable rate rather than preventing water flow altogether, e.g. to prevent adhesion problems with flooring materials. It may be achieved by the methods described above for preventing moisture ingress.

6.2 Repair

Repair is the process of reinstating damaged concrete. It may also involve altering the chemistry of the existing concrete to make it more resistant to deterioration.

6.2.1 Concrete Restoration

Concrete restoration involves replacing damaged or contaminated concrete, irrespective of the cause of damage. “Patch repair” describes reinstatement of either discrete areas or entire surfaces. Substrate preparation and application of the repair material are critical to the performance of the patch repair and are described below. Alternatively, the entire element may be replaced if warranted by the extent of damage and anticipated future use of the structure. Replacement of elements is not discussed in this Information Bulletin.

Other aspects that are not discussed but may need to be considered are the effects of changes in load distribution caused by the damage and during repair, creep and shrinkage of original concrete and repair materials, vibrations that may affect the bond of the repair, moisture movement, safety, and differences in the long term structural behaviour of original concrete and the repair material.

Substrate preparation for patch repair includes removal of damaged or poor quality concrete that may form an area or plane of weakness and preparation of a sound surface free from debris or contaminants that may impair the adhesion of the repair material or the long term effectiveness of the repair. Concrete is removed by hydrodemolition or by cutting or impact (e.g. chiselling) followed by waterblasting to remove loose material. Impact techniques are not always preferred because they may damage otherwise sound concrete. The depth to which concrete is removed depends on the repair principle and method. For concrete damaged by chloride-induced reinforcement corrosion for example, all concrete surrounding the reinforcement that contains more than a particular amount of chloride ion may need to be removed if the concrete is to be patch-repaired, but only physically-damaged concrete needs to be repaired if the structure will be cathodically protected. The depth of removal should be relatively uniform. Care must be taken to avoid damaging reinforcement and to avoid reducing structural capacity without providing additional support. The edges of the repair area must be perpendicular to the outer surface to reduce shrinkage of the repair material and thereby improve its bond. The repaired area should be as symmetrical as possible, with no re-entrant corners.

Reinforcement surface preparation involves removing corrosion products and loosely adhering concrete from exposed surfaces of reinforcement to achieve a steel surface cleanness of SA 2.0. This can be achieved by water jetting the steel surface during hydrodemolition of the concrete. If concrete is removed by chiselling, the steel must be cleaned by wet or dry abrasive blasting to remove any loose particles and chemical contaminants. Damaged reinforcement, prestressing steel and anchorages and other components should be replaced or additional reinforcement added as necessary. These processes are not covered in this Information Bulletin.

Application of a patch repair involves ensuring that the repair material adheres well to the concrete substrate and any exposed reinforcement, with no entrapped air at the interfaces or in the bulk of the material, and its hardened properties develop to their full potential.

Depending on the product system used, exposed reinforcement may be coated with a bonding agent or a coating to give extra protection against reinforcement corrosion, particularly if there is to be a delay between preparing the steel and replacing the cover concrete. Rebar coatings can, however, reduce the steel-concrete bond so should be applied with care or in strict accordance with manufacturer's recommendations where proprietary systems are being used.

For cement-based repairs the substrate may need to be moistened before the repair is applied to prevent the bond being weakened by the concrete sucking water from the repair material. Alternatively, a bonding agent may be applied to the prepared substrate to ensure intimate contact between substrate and repair and to satisfy the water absorption of the concrete.

The repair material may be applied manually, by casting into formwork, or by pneumatic (spray) methods.

Manual application includes several techniques. For localised or shallow repairs to cover concrete the repair may be packed in by hand or trowelled on, ensuring that cavities behind reinforcement or other inserts are completely filled. Small cavities that are deeper than they are wide may be repaired by "dry packing", where a very stiff repair material is rammed into the cavity. Porous surfaces may be filled by "bag-rubbing", where the repair material is rubbed into the surface with a cloth, or by trowel application of a thin plaster "fairing coat".

Cast concrete repairs are suitable for larger or thicker sections than can be conveniently repaired by hand. Formwork is attached to the substrate, and the repair material placed within by pouring from the top or pumping from the bottom. It may be compacted by external formwork vibrators, or instead rely on the fluidity of the concrete and placement sequence to displace air and water in the form. Bonding agents are not usually used because it may not be possible to erect and fill the form within the "open time" of the bonding agent, bond instead being achieved by a combination of pre-moistening of the concrete immediately prior to erecting the formwork and concrete with good workability and wetting properties.

Pneumatically applied concrete (also known as "shotcrete", "sprayed concrete" or "Gunite" (originally a proprietary name for a particular process)) can be built up in large volumes without formwork and is suitable for extensive or structural repairs, particularly where access is difficult, formwork would be costly and large vertical or soffit surfaces need to be restored. No bonding agent is required because the force at which the concrete is applied and rebound of aggregate from the surface produce a mortar-rich layer in intimate contact with the substrate. Pneumatically applied concrete is built up in several layers. Reinforcement (traditional bars or mesh, or steel fibres in the concrete) may be needed for thicknesses greater than 50 mm. Care must be taken to prevent voids (known as "shadowing") behind reinforcement. The quality of application is highly dependent on the skill of the operator, and it is recommended that the proficiency of individual operators be demonstrated by trial applications or previous experience before a contract is let.

"Jacketing" is the replacement and possible augmentation of all cover concrete on an element such as a pile, pier or column, often with a material that is less permeable or more resistant to physical degradation. It is common on structures where chloride contamination has caused extensive corrosion or where the surface is deeply eroded by flowing water.

Patch repairs are cured by conventional means (or, for proprietary materials, according to supplier's instructions) to enable the full development of strength and other properties. A surface sealer or coating may be applied to the entire surface of the element after repair to restore a uniform appearance and/or to reduce the ingress of moisture and aggressive agents.

6.2.2 Cathodic Protection (CP)

CP entails actively reversing the corrosion current by electrically connecting another metal (the anode) to the reinforcement so that the other metal corrodes instead of the reinforcement, even if the concrete surrounding the reinforcement is still chloride-contaminated or carbonated. This is achieved by connecting the reinforcement and the other metal to an electrical supply so that electrons flow from the other metal to the reinforcement ("*impressed current CP*") or by electrically connecting the reinforcement to a metal such as zinc that will naturally corrode in preference to steel ("*galvanic CP*"). CP systems are described by the anode configuration (e.g. mesh anode, ribbon anode, surface anode, internal anode) or anode material (e.g. titanium/mixed metal oxide, thermally sprayed zinc, zinc hydrogel).

Proprietary galvanic cathodic protection systems are available for incorporating into concrete pile jackets to prevent ongoing corrosion and for countering (i.e. induced corrosion in adjacent areas) incipient anode effects.

CP systems must be designed by specialists specifically for the structure concerned, taking into account the size of the elements to be protected, the depth and quality of cover concrete, the reinforcement configuration, and environmental conditions. NACE and Australian standards prescribe the parameters for effective protection.

CP systems must be maintained throughout the life of the structure, involving regular monitoring of performance and replacement of anodes and other components. This represents an ongoing cost to the owner, but for major structures such as wharves in a marine environment which are required to remain in service for an indefinite period, it may be the most cost effective solution. It may also be appropriate where logistics or other considerations make repeated repairs undesirable. CP can also be applied as a preventive treatment before corrosion causes any damage.

6.2.3 Restoring or Preserving Reinforcement Passivity

Ongoing corrosion can be prevented by repassivating the reinforcement. This can be achieved by restoration of the cover concrete with new material and/or increasing its thickness as described in section 6.2.1, electrochemical chloride extraction (sometimes called "desalination"), or realkalisation.

Electrochemical chloride extraction was introduced in the 1990s as a treatment for reinforcement corrosion induced by chloride ion contamination of concrete exposed to de-icing salt. It may also be appropriate for removing chlorides from concrete exposed to sea spray or splashes from seawater, but is not suitable for elements in permanent contact with seawater. The process removes chloride ions from the cover concrete by temporarily connecting the reinforcement to a power supply in the same way as for impressed current CP. The reinforcement develops a negative charge, which drives the chlorides towards the positively-charged anode on the surface, where they are collected in an electrolyte solution and removed for disposal. The steel surface is considered to be repassivated once chloride contents at the steel fall below a prescribed concentration. The treatment remains effective until fresh contamination or diffusion of chlorides from concrete below the reinforcement reaches a level where corrosion may be induced again.

Electrochemical realkalisation is another extension of the CP process used to repassivate reinforcement. It is similar to electrochemical chloride extraction, except that it uses an impressed current to drive positively charged alkali metal ions (sodium, lithium or potassium) from an externally-applied electrolyte into the concrete towards the reinforcement, reversing the process of carbonation that reduces concrete alkalinity. The steel surface is considered to be passivated once a specified concrete pH is reached. Its effects are permanent. Its greatest potential is as a preventive treatment, where carbonation-induced corrosion is imminent but has not yet caused any damage, particularly where cover depths are low.

Realkalisation by diffusion of alkalis from a concrete, mortar or solution applied to the concrete surface is another possible means of repassivating the reinforcement. It is not recommended because of difficulty in ensuring that the alkalis penetrate the concrete uniformly and to sufficient depth.

6.2.4 Cathodic Control

Cathodic control of reinforcement corrosion involves controlling the rate of corrosion by restricting the availability of oxygen to steel at the cathode. This may be achieved by coating the concrete surface with an oxygen barrier, saturating the concrete or applying a cathodic inhibitor. It is difficult to achieve a perfect barrier coating and to ensure that concrete is fully saturated, so these two methods are not recommended. Another approach is to use chemical corrosion inhibitors (see section 6.2.6).

6.2.5 Anodic Control

Anodic control of reinforcement corrosion involves restricting the electrochemical reactions at the anode. This may be achieved by coatings applied to the reinforcement that act either as a physical barrier to water, chlorides and oxygen, or that provide a sacrificial layer (e.g. zinc) that corrodes in preference to the steel. Severe corrosion can result if a barrier coating is incomplete or damaged after application, so they must be applied carefully and protected after application. Sacrificial coatings will only be effective until they are consumed. Chemical corrosion inhibitors can also be used to prevent reactions at the anode (see section 6.2.6).

6.2.6 Chemical Corrosion Inhibitors

Corrosion inhibitors may be used to control electrochemical reactions at the anode or the cathode. Anodic inhibitors react with metal corrosion products at the anode, forming a protective film on the steel surface. Cathodic inhibitors react with other reaction products at the cathode, precipitating a deposit on the steel surface that acts as a barrier to oxygen. Ambiodic or mixed inhibitors form a hydrophobic film on the steel surface that protects both anode and cathode from aggressive agents.

Inhibitors may be added to the repair material as an admixture. Alternatively they may be applied to the concrete surface after repair ("migrating corrosion inhibitors"), diffusing through the concrete pores to the steel either as a vapour or in solution. However it is introduced into the concrete, the effectiveness of an inhibitor depends on the quantity that reaches and then remains at the steel surface. This is difficult to control, particularly when the inhibitor is applied to the concrete surface. Insufficient or non-uniform distribution of the inhibitor can aggravate corrosion. The greatest potential for corrosion inhibitors therefore may be for elements with low cover, relatively poor quality and continually damp concrete where they can migrate easily to the reinforcement, and where the surface is treated to prevent the inhibitor leaching from the concrete.

6.3 Structural Strengthening

Structural strengthening may be carried out to improve the performance of a structure under existing loads or to enable it to perform satisfactorily under additional loads. It may be carried out in conjunction with repair if the structure has already incurred damage. It may involve strengthening the existing concrete section, creating a composite by bonding another load-bearing material to the concrete, prestressing, or relieving the load on an element.

The behaviour of new materials and the strengthened elements must be compatible with the original materials and other elements otherwise problems may develop in foundations and adjacent elements.

6.3.1 Concrete Strengthening

Concrete strengthening may involve *enlarging the concrete section* by adding extra cover concrete (slabs and walls) or jacketing (beams, columns) to increase the concrete's load bearing capacity or stiffness. Collars at the top of columns may be used to increase support to the superstructure and increase its shear capacity without reducing space around the columns or significantly altering their appearance. Precast elements may be used as well as cast in situ concrete. The new concrete must be well bonded to the original to allow the transfer of shear stresses between the two materials. Although they may be connected by dowels, the interface between them should be prepared as for a repair and the new material should have minimum shrinkage and similar creep, thermal and flexural properties to avoid disbonding.

Extra reinforcement may be embedded into holes drilled in the existing concrete, or cast into new concrete on the outer surface and tied to the existing reinforcement. The dowels may be fully bonded, e.g. to repair a crack. Where used to strengthen a crack or joint where one side moves relative to the other, one end of the dowel may be sleeved rather than bonded to the concrete to transfer shear stress but allow the movement to continue.

Filling cracks with a rigid material may restore the original strength of an element cracked by load-induced movement, but will not improve its design strength.

6.3.2 Composite Elements

Composite elements with increased load bearing capacity are created by bonding another load-bearing material to the outer surface of the concrete. Changes in load distributions in the structure need to be considered when such techniques are used.

Steel plate bonding is the traditional method of improving flexural and shear strength. In this process steel sections (e.g. plates, channel, and angle) are bonded to the concrete surface with epoxy adhesive. The steel and concrete surfaces must be cleaned to remove any contaminants, debris, surface layers or coatings that might reduce the bond. The relative strengths of the steel, concrete and adhesive will determine the strengthening that can be achieved: yielding of the steel will cause the adhesive to fail, and high strength steel may induce failure in a relatively low strength concrete. The plate dimensions may be limited by the dimensions of the structure or the need to minimise extra dead weight or defects in the bond. The adhesive should be as thin as possible to minimise creep of the epoxy and differential movement of steel and concrete. The long term resistance of the adhesive to moisture and to mechanical and thermal stress needs to be considered. The risk of fire damage and steel corrosion must also be assessed.

Fibre reinforced polymer (FRP) sheets or strips can be bonded to the concrete surface with adhesive in the same way as steel to improve load bearing capacity and seismic performance. They have largely replaced steel plate bonding. FRP is corrosion-resistant, resistant to many chemicals, light, has high strength and elastic modulus, high resistance to fatigue and wear, is linearly elastic until failure, and it can be applied to complex substrates. Installation is relatively quick and tidy although, as for other bonded repairs, surface preparation is important. Its properties may be unidirectional, bidirectional or isotropic depending on the orientation of the fibres in the particular product used. Differential strains between FRP and the substrate must be limited. Increasing the flexibility of the element will increase the shear demand and this must be accommodated. The risk of fire damage must also be assessed. Some compositions may need protection from UV light. The effect on potential moisture-related problems should be considered when encasing large areas with an impermeable FRP wrap.

External post-tensioning can be used to increase the flexural and shear capacity of reinforced and prestressed concrete and has been applied to correct deflections and cracking in beams, slabs and cantilevered elements. Tendons may be bonded or unbonded. The system adds little weight to the structure, and a wide range of strengthening requirements can be met by varying the tensioning force and configuration. Loss of prestress due to concrete creep and shrinkage is much less than in new concrete. Options for attaching the tendons to the structure include anchorages into abutments or diaphragms at the ends of beams and rigid supports or deviators fixed to the beam webs. The method used to anchor and stress the tendons will be determined by the room available around the element. Cracks may need to be cleaned and filled before stressing because debris and interlocking aggregate may prevent them from closing. Aesthetics and the risk of fire damage need to be considered.

6.3.3 Load Reduction

Loads can be reduced by shortening the span or imposing an opposing stress. For example, additional steel or concrete supports can be introduced to shorten a span, or existing supports can be moved to alter equilibrium stresses. Supplementary members are quick to install but will significantly restrict space around the structure.

7. MATERIALS

Proprietary materials from reputable suppliers should be used wherever possible to ensure that the formulation is suitable, the material is consistent between different batches and applications, and technical support is available. They are designed for specific purposes, and suppliers must be consulted to identify the most appropriate materials for a particular application. They must be applied according to the supplier's instructions to achieve the intended performance. For some products, use of contractors trained and approved or licensed by the supplier is a condition of the product's warranty.

7.1 Surface Treatments to Prevent or Reduce Further Deterioration

7.1.1 Penetrating Sealers

The most common penetrating sealers are based on silicon, although low viscosity solvent-based coatings applied as primers may also fall into this category.

Silanes and siloxanes are commonly used surface impregnations that line and block pores in the concrete with hydrophobic silicone molecules. They are available dissolved in organic solvents to be sprayed on, and as gels or creams that avoid the safety and environmental problems associated with the solvent carriers. They are not suitable for surfaces that are immersed or subject to ponding.

Silicate-based solutions are also available. These react with calcium hydroxide in the concrete to form products that block the pores. They are also used as surface hardeners.

7.1.2 Coatings

Coatings range in thickness from thin surface sealers to thicker high build coatings and elastomeric membranes through to overlays. They include the following materials:

Epoxies: good chemical resistance and hard wearing, but brittle and have poor UV resistance.

Polyurethane: good chemical and weathering resistance, flexibility and toughness.

Polyester, vinyl ester/acrylate: excellent chemical and temperature resistance, cure at low temperatures.

Acrylic: decorative, good weathering and crack bridging properties, water-vapour permeable, resistant to ingress of carbon dioxide and chloride solutions, not suitable for immersion or surfaces subject to ponding.

Vinyl, synthetic elastomers, chlorinated rubber: general barrier coatings, good weathering resistance, but solvent sensitive.

Bitumen: low cost waterproofing, sensitive to solvents, oxidises if exposed to the atmosphere.

Cementitious: good barriers against carbon dioxide and moisture but poor acid resistance. Acid resistance may be better in products containing fine silica. Flexibility can be improved by polymer modification. Good impact and abrasion resistance.

Inorganic silicate paint: largely used to improve visibility rather than to protect concrete. Used in tunnels because it is not flammable.

Silanes and *siloxanes* may also be applied as surface sealers.

7.1.3 Crack Filling and Sealing Materials

Flexible and rigid grouts can be formulated with a range of viscosities to fill a wide range of crack widths.

Flexible crack filling and sealing materials include suitably formulated polyurethanes, polysulphides, acrylamides, epoxies, high molecular weight methacrylate, and polymer modified cementitious grouts. Water flow through cracks can be controlled by grouts formulated to foam or gel in the presence of water, such as polyurethane, acrylate and sodium silicate. Bond breakers include polystyrene and polyurethane rods, expanded polyurethane foam and PTFE tapes.

Rigid crack filling and sealing materials include epoxies and cementitious grouts and mortars.

7.1.4 Levelling and Fairing Mortars

Levelling and fairing mortars and plasters are typically polymer-modified cementitious materials made with relatively fine sand and with polymer modifiers and/or shrinkage compensating additives to improve resistance to drying shrinkage so that they can be applied in thin coats.

7.1.5 Waterproofing Materials

Waterproofing membranes are generally based on bitumen. They may be applied to the cleaned prepared substrate by trowel, spray or as a preformed sheet. Products that bond to the entire substrate surface prevent tracking of water under the membrane from sites prone to water ingress. Polystyrene sheet (which must itself be protected against impact damage) and proprietary panels are used to prevent impact, abrasion or point loads penetrating the membrane. Sheet products based on swelling bentonite clay are also available. These are self-healing and therefore less prone to failure by physical damage.

Waterproofing coatings and pore blocking materials may be based on cementitious slurries, specially formulated epoxies or silicate solutions. An appropriate formulation for the flow rate must be selected.

7.1.6 Toppings to Improve Chemical and Physical Resistance

Chemical-resistant coatings and toppings are generally based resins such as epoxy, polyester or polyurethane rather than on Portland cement. Proprietary repair mortars based on silicate and calcium aluminate cements are also available. An appropriate formulation for the particular environment must be selected.

Physically resistant toppings may be cement or resin-based. Cementitious toppings contain natural or synthetic aggregates selected for their abrasion resistance.

7.2 Repair Materials

7.2.1 Bonding Agents

Proprietary repair systems may incorporate bonding agents consisting of epoxy, polymer emulsion (latex), or polymer modified cement slurry. They are usually applied shortly before the repair material, generally so that the bonding agent is still tacky or able to resoften when the repair material is applied.

7.2.2 Reinforcement Coatings

Coatings applied to protect the reinforcement against corrosion include zinc-based coatings (where the zinc corrodes in preference to the steel), coatings that provide physical barriers against moisture, chloride ions and air (e.g. epoxy), and cement-based coatings that ensure the steel is in an alkaline environment. Barrier coatings must be continuous otherwise the risk of corrosion is increased, and consequently there is some debate whether in practice site-applied barrier coatings offer significant protection given the risk of incomplete application or damage during subsequent repair operations.

7.2.3 Repair Mortars and Concretes

Pre-bagged proprietary materials are recommended to ensure consistent quality.

Repair mortars and concretes are formulated for easy application and good bonding to the substrate. To remain bonded without cracking and without inducing stresses that may damage the original concrete they must have minimal drying shrinkage, similar strength, similar coefficient of thermal expansion to the substrate to withstand temperature changes, similar elastic modulus and similar creep to the substrate to withstand the effects of loading, and similar permeability to the original concrete to moisture being trapped under the repair. If in contact with reinforcement they should also have similar electrical properties and permeability to the remaining original cover concrete to minimise the risk of reinforcement corrosion.

Epoxy patching materials are convenient, bond well, develop strength quickly, are strong, impermeable and have good resistance to chemical and physical attack. Their good bonding and rapid setting makes them suitable for repairing surface damage and joint edges. Their thermal expansion, elastic modulus, chemical and physical properties, however, are significantly different from those of concrete, so they are not effective for deep repairs, repairs in contact with reinforcement, and repairs exposed to diurnal temperature variations. Epoxy has poor UV resistance, although this can be improved by adding fillers. Similar issues apply to other polymer materials such as polyester.

Portland cement-based materials are preferred because of their compatibility with concrete substrates. A wide variety of Portland cement based options is available, including:

- Grout, plaster, mortar or concrete as appropriate for the dimensions of the repair;
- Different aggregate sizes as appropriate for different reinforcement spacings and repair depths;
- Self compacting concretes for casting around congested reinforcement or in enclosed formwork;
- Low density materials for high build applications;
- Fibre reinforcement for increased crack resistance, particularly in thin repairs;
- Shrinkage compensating materials;
- Mortars for underwater application;
- Different strengths for different load requirements;
- Different setting times and rates of strength development for different temperatures and recommissioning times;
- Supplementary cementitious materials for reduced permeability and increased strength;
- Polymer modifiers to improve workability, bond, crack resistance and reduce the need for wet curing;
- Waterproofing admixtures/additives.

Polymer modified Portland cement materials are effective for non-structural repairs but they have a lower elastic modulus than concrete so may not be suitable for major repairs to elements with load components parallel to the repair –substrate interface. Properties vary with individual polymers. PVA modifiers are not water-resistant. Products containing styrene-based polymers provide good strength and bond but may discolour in sunlight. Acrylics have good overall performance. Polymers may be supplied as water based emulsions in two-part products, or as re-emulsifiable powders pre-mixed with other solid components in single-pack products which are mixed with water on site.

Rapid setting mortars and grouts based on calcium aluminate cement and other proprietary cementing systems are also available for applications where the structure needs to be in service within a shorter period than can be achieved with Portland cement, or to provide extra resistance to high temperatures or aggressive chemicals that normal Portland cement cannot withstand. These products must be used strictly in accordance with the supplier's instructions, and must not be diluted with Portland cement products.

Repair concretes may also be supplied as ready-mixed concrete, formulated to minimise shrinkage and bleeding that could affect bond and permeability, and to approximate the strength of the original concrete.

Pneumatically applied concrete may be applied by the wet process or the dry-mix process. In the wet process the concrete is pre-mixed and pumped through the delivery hose to the nozzle. Wet spray products are typically used for smaller repairs. In the dry-mix process the water and the dry constituents are mixed at the nozzle, so the final mix proportions are largely controlled by the operator. Dry spray products are used for larger repair volumes. Shotcrete generally has a very low water-cement ratio. It may contain supplementary cementitious materials such as fine silica to minimise rebound and slumping and to reduce permeability, and steel or synthetic fibres to control cracking.

7.2.4 Corrosion inhibitors

Corrosion inhibitors may be classified by the means of application (admixture or surface applied), mode of action (anodic, cathodic or ambiodic), or chemistry. Calcium nitrite is a well-known anodic inhibitor supplied as an admixture. Its dosage rate is based on predicted chloride ingress. Organic compounds such as amines, amino esters and amino alcohols are ambiodic inhibitors and are supplied both as admixtures and for surface application. Inhibitors used for applications other than concrete reinforcement corrosion should not be used as they may not be effective in the alkaline Portland cement concrete environment.

7.3 Strengthening Materials

7.3.1 Jacketing

Jackets may be temporary or permanent. The formwork may be timber, metal, precast concrete, rubber, fibreglass or fabric, filled with conventional or proprietary concrete, mortar, grout, epoxy mortar.

7.3.2 Post Tensioning

Steel bar and FRP bar have been used to post-tension elements.

7.3.3 FRP Composites

FRP composites include carbon, aramid, steel or glass fibres embedded in polyester, epoxy, vinyl ester and phenol resins. The properties of a composite depend on its composition and fibre content, form and orientation. Carbon fibre has a higher elastic modulus than steel and exhibits more brittle failure, while the modulus of aramid and glass is lower. Composites are available in many forms including sheets, rods, grids and strands. Steel fibre materials have the potential to improve both ductility and fire resistance if embedded in fire resistant material such as Portland cement.

7.3.4 Additional Reinforcement

Dowels installed as additional reinforcement may be deformed reinforcement, smooth or threaded steel or stainless steel bars, carbon fibre reinforcement or bolts. Steel dowels may be zinc galvanised or epoxy coated.

Proprietary grouts for anchoring additional reinforcement include Portland cement and chemical grouts based on epoxy or polyester. The grout must be compatible with the dowel material, and its heat generation and shear strength appropriate for the installation. Bond strength must not be significantly higher than the strength of the concrete.

8. SPECIFICATION

For all except very minor repairs, a specification is normally required.

Specifications must be clear and concise so that they achieve the desired quality of work and can be used as the basis of payment for the repair contract. They should include:

- information on the original concrete quality and the cause and significance of the damage;
- scope of repair;
- parameters for concrete removal;
- reinforcement details;
- repair materials;
- surface preparation;
- application methods;
- repair quantities;
- environmental and safety requirements;
- aesthetic requirements;
- acceptance criteria;
- guarantee requirements.

The extent of damage is difficult to estimate until repair work starts so specifications must be sufficiently flexible to allow for variation in volumes of concrete removal and restoration, surface preparation and reinforcement replacement. Allowance must be included for site access and protection, and for temporary structural support during the repair. Contingencies for increases in the scope of work relating to structural integrity should also be included.

9. INSPECTION AND MAIN-TENANCE REQUIREMENTS

Completion of a repair is not the end of the story. The structure must continue to be inspected and maintained throughout its service life. Warranties for proprietary repair systems may impose certain conditions, such as regular cleaning, reapplication of surface treatments and ongoing monitoring and maintenance of cathodic protection systems.

Effective ongoing maintenance is best achieved by developing a formal inspection and maintenance programme for the structure that documents future requirements, identifies personnel responsible for carrying them and ensures that they are included in annual maintenance budgets. The programme will include procedures for:

- recording details of all repairs, maintenance and preventive treatments in such a way that the complete history of the structure is available to its owner and manager;
- ongoing monitoring of the condition of the structure and performance of repairs;
- evaluating condition;
- maintaining protective systems such as sealants and surface treatments;
- forward programming of maintenance.

10. FURTHER READING

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Table 1: Considerations in Formulating a Repair Strategy.

STRATEGIC (Specifer to Discuss with Owner)	TECHNICAL (Specifier and Contractor to Consider)	PRACTICAL (Specifier and Contractor to Consider)
• Structure type. • Structure condition. • Design life (new structure). • Remaining service life required. • Aesthetic requirements. • Past and future use. • Potential benefits from structural improvements. • Number and cost of subsequent repair cycles. • Management and cost of future maintenance. • Immediate and long term costs and budget constraints. • Value added by remediation.	• Type, cause and rate of concrete deterioration. • Ability to remove the source of distress. • Structural performance and sensitivity. • Likelihood and consequences of failure. • Previous repairs and modifications. • Compatibility between treatments needed on different parts of the structure. • Durability and repair history of nearby or similar structures. • Long-term performance of treatment and its effect on subsequent treatments. • Technical support from material suppliers. • Past and future service conditions (environmental and loading).	• Regulations affecting the repair operations, e.g. OSH, RMA, Building Code and Historic Places Act. • Health and safety risks to workers and public during repair. • Level of supervision provided by contract. • Availability of repair materials and skilled applicators. • Access to the site and affected parts of the structure. • Operating schedule of the structure. • Impact on users during repair (noise, reduced access). • Impact on adjacent parts of structure (water, dust). • Effects on structural performance during repair. • Availability of power and/or telecommunications on site. • Availability of skilled maintenance personnel. • Weather patterns. • Susceptibility to vandalism, impact or damage by natural exposure conditions.

Table 2: Process for Establishing a Strategy for Managing Deterioration on a Concrete Structure (Based on DD ENV 1504-9:1997 Published by BSI).

Action	Aspects to Consider
1. Assess condition, identify cause and extent of defects	• Present condition. • Original design approach. • Environment and contamination. • Construction conditions. • Past and future service conditions. • Past and projected future use.
2. Select approach for managing deterioration (e.g. do nothing, repair, demolish etc.	• Intended use, design life. • Required residual life performance characteristics. • Long-term performance of treatment. • Additional future protection and monitoring. • Number and cost of repair cycles. • Cost and funding of alternative options, including future maintenance, compliance and access costs. • Substrate properties and preparation. • Appearance of treated structure.
3. Identify treatment principle	Treatment principles are: *For concrete defects* • Protection against ingress. • Moisture control. • Concrete restoration. • Structural strengthening. • Physical resistance. • Chemical resistance. *For reinforcement corrosion* • Preserve/restore passivity. • Increase resistivity. • Cathodic control. • Cathodic protection. • Anodic control.
4. Select method of treatment	• Type, cause and extent of deterioration. • Effect of site conditions on treatment process. • Effect of site and service conditions on durability of treatment. • Facility to maintain the treatment. • Repair/replacement/monitoring approach selected. • Treatment principle. • Appearance of treated structure. • Cost and availability of products/systems of suitable type and quality.
5. Select materials	• Characteristics of materials for the specific application. • Cost and availability.
6. Define future inspection and maintenance requirements	• Record work carried out. • Provide instructions for inspection, maintenance and repair during the remaining life of the structure. • Establish a system to manage maintenance of the treatment.

Table 3: Typical Defects.

Surface Feature	Bulk Property	Functional
• Discoloration. • Efflorescence. • Soft surface. • Eroded or abraded surface. • Surface scaling. • Popouts. • Crazing. • Spalling. • Delamination.	• Volume change. • Displacement. • Disintegration. • Reinforcement corrosion. • Cracking.	• Spalling at joints. • Sealant failure. • Dampness. • Water leakage.

Table 4: Factors Contributing to Defects.

Construction		Service Conditions	
Workmanship	Materials	Continuing Exposure	Single Event
• Design (load capacity, detailing for dimension change and moisture control). • Mix composition (inappropriate binder composition and content, water content, admixture content, batching error, inappropriate workability for placing methods). • Unstable formwork or shoring. • Incorrectly placed reinforcement. • Handling and placement (careless placement, inadequate compaction, over-vibration, incorrect finishing procedure). • Inadequate curing (exposure to drying, cold temperatures during curing period, excessive thermal gradients).	• Aggregates (unsound, reactive or contaminated). • Cementitious binder (inappropriate type or quality of cement, SCM or admixtures). • Water (organic, chemical or particulate contamination). • Reinforcement (incorrect material or size).	• Soil and groundwater (acid, sulphate, chlorides or other soluble salts). • Seawater or seaspray. • De-icing salt. • Sewage. • Aggressive natural water. • Industrial chemicals. • Erosion. • Cavitation. • Abrasion. • Thermal stress. • Vibration. • Regular overloading. • Settlement. • Wind loading. • Freeze thaw. • Atmospheric contaminants (carbon dioxide, sulphurous gases). • Bacteria. • Stray electrical currents.	• Fire. • Overload. • Accident. • Earthquake. • Subsidence. • Flooding. • Spill. • Explosion. • Impact. • Lightning strike.

Table 5: Repair Principles (Based on DD ENV 1504-9:1997 Published by BSI).

<table>
<tr><th>Defect</th><th>Cause</th><th>Repair Principle</th></tr>
<tr><td rowspan="3">Concrete defects: Cracks, spalls, delamination, disintegration</td><td>Mechanical (e.g. impact, overload, settlement, explosion, vibration)</td><td>• Concrete restoration.
• Structural strengthening.</td></tr>
<tr><td>Chemical (e.g. alkali aggregate reaction, aggressive chemicals, biological agents)</td><td>• Protection against ingress.
• Moisture control.
• Increase chemical resistance.</td></tr>
<tr><td>Physical (e.g. abrasion, erosion, shrinkage, salt crystallisation, fire, freeze thaw)</td><td>• Protection against ingress.
• Moisture control.
• Increase physical resistance.
• Structural strengthening.</td></tr>
<tr><td rowspan="3">Reinforcing and prestressing defects (uniform corrosion, pitting, stress corrosion, concrete cracking and spalling)</td><td>Carbonation</td><td>• Preserve or restore steel passivity.
• Anodic control.</td></tr>
<tr><td>Contamination by Chlorides</td><td>• Cathodic control (creating conditions that restrict chemical reactions at the cathode).
• Cathodic protection (making the reinforcement into a cathode).
• Anodic control (creating conditions that restrict chemical reactions at the anode).
• Preserve or restore steel passivity (creating conditions in which the steel is electrochemically passive)</td></tr>
<tr><td>Stray Currents</td><td>• Increase electrical resistivity of concrete (to restrict the flow of ions through it).</td></tr>
</table>

Table 6: Repair Methods (Based on DD ENV 1504-9:1997 Published by BSI).

Repair Option	Principle	Methods
Prevent or Reduce Future Deterioration	Protection against ingress	• Impregnation. • Surface coating. • Bandaging cracks. • Filling cracks. • Converting cracks to joints. • Erecting external panels. • Applying membranes.
	Increase physical resistance	• Overlays or coatings. • Impregnation.
	Increase chemical resistance	• Overlays or coatings. • Impregnation.
	Moisture control	• Hydrophobic impregnation. • Surface coating. • Overcladding.
Repair	Concrete restoration	• Manually applied repair. • Cast concrete repair. • Sprayed concrete repair. • Replacing elements.
	Cathodic control	• Reduce oxygen supply at cathode by saturating the concrete or by coating the surface. • Apply a cathodic inhibitor.
	Preserve or restore passivity	• Increase cover with additional mortar or concrete. • Replace contaminated or carbonated concrete. • Electrochemical realkalisation . • Realkalisation by diffusion. • Electrochemical chloride extraction.
	Cathodic protection	• Apply an appropriate electrical potential by impressed current or by connection to a sacrificial anode.
	Anodic protection	• Apply zinc-based coating to reinforcement. • Apply barrier coatings to reinforcement. • Apply penetrating inhibitors to the concrete surface.
Structural Strengthening	Structural strengthening	• Externally embed extra reinforcement. • Embed extra reinforcement in preformed or drilled holes. • Steel plate bonding. • FRP bonding. • Adding mortar or concrete. • Crack injection. • Filling cracks. • Prestressing.

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