ReBuild

Repair Guidance Notes

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The aim of these Notes is to guide consultants and contractors through the application of "Repair Standard EN 1504" and other related concrete repair standards for the evaluation, design specification and concrete repair process.

1.0 Background

There are a number of causes of deterioration in concrete buildings and structures. Even when they are adequately built,properly used and well-maintatined, the environment will affect a structure and components will degrade or wear out. The largest single cause of deterioration in reinforced concrete structures is corrosion of the reinforcing steel. In addition, there are number of deterioration process that attack the concrete directly, some from processes within, such as alkali-silica reaction, and some from external sources, such as ingress of chloride ions from atmosphere.Some are realted to initial construction problems while others are due to subsequent use or lack of maintenance of the structure.

This section summarises the major causes of defects,damage and decay in concrete buildings and structures; any attempt to remedy problems must start with a through understanding of the cause and extent of the deterioration. It is essential that a detailed investigation is carried out as part of the appraisal process, the results are interpreted and their repair options fully evaluated to ensure that the right repair option is selected. Carbonation and chloride attacks are two major causes of reinforcement corrosion. It is not required to address the corrosion mechanism here but to understand their significance in rapid deterioration of reinfoced concrete structures.

2.0 Degradation of Concrete

2.1 Design and Construction Defects

It is very much important to take care of 5 C's such as constutients, cover, compaction, curing and coating during concrete construction and further protection for the duarbility of the reinforced concrete structures. The deterioration takes place due to following factors:

- Constituents: Improper concrete constituents, high water-cement ratio, cast in chlorides, alkali-aggregate reaction
- Cover: Poor cover to the reinforcement
- Compaction: Poor compaction leading to honeycombing and voids
- Curing: Improper curing
- Coating: Absence of protective coating in aggressive environment

Concrete degradation also takes place due to alkali-aggregate reactivity, sulphate attack, high-alumina cement concrete and chemical attack.

2.2 Causes for Structural Damage

- Inadequate design
- Settlement or other ground movement
- Overloading or change of use
- Fire
- Impact
- Seismic effects
- Wind

3.0 Fixing Concrete

There are many mechanisms that can affect plain, reinforced and prestressed concrete structures. The mechanism will produce deterioration in one or more forms:

- Corrosion of reinforcement or unsheathed prestressing stand
  - Visible damage (cracking, spalling, rust staining)
  - Hidden damage (delamination, reduction in cross-section of reinforcement)
  - Non-visible and potential defects
- Corrosion of post-tensioning bar or strand within ducts
  - Hidden corrosion within the duct, unlikely to result in visible damage
- Damage to the concrete
  - Carbonation or ingress of chlorides
  - Acid or sulphate attack of the cement matrix
  - Abrasion or impact damage
  - Fire

Following the diagnosis and quantification of the extent of damage, repairs will have to be undertaken. These general principles of repair include:

- Treating exposed steel.
- Filling holes left by the removal of spalled or damaged concrete.
- Arresting and preventing further degradation.
- Strengthening of weakened structures.

All repair works should be carried out with repair products and systems specifically formulated for the intended purpose, with appropriate quality control and performance certification in place, such as compliance with the standard comes into force.

3.1 Arresting degradation

The purpose of the repair will be to ensure that significant deterioration does not occur in the future. Sometimes this is simply the removal of the cause and replacement of damaged concrete. Where corrosion of reinforcement is involved, the planning process requires significantly more consideration.

The two main initiators of reinforcement corrosion are carbonation and chloride ion. To arrest deterioration, these must be removed or neutralised.

3.1.1 Carbonation

All areas of concrete where the depth of carbonation exceeds the depth of cover will potentially be able to corrode in the presence of moisture and oxygen. The repair strategy must include breakout and removal of all carbonated concrete in contact with the reinforcement, or provide an alternative strategy where corrosion of the reinforcement is prevented (eg, corrosion inhibitors, moisture-excluding surface coatings, electrochemical realkalisation of the cover concrete).

3.1.2 Chloride

All areas of concrete where the free chloride ion content of concrete at the reinforcement depth exceeds 0.2% by weight of cement (typically taken to be 0.4% for chloride salts penetrating from the environment and 1.0% for chloride cast in to the concrete) will potentially be able to corrode in the presence of moisture and oxygen. The repair strategy must include breakout and removal of all chloride-contaminated concrete in contact with the reinforcement, or provide an alternative strategy where corrosion of the reinforcement is prevented (eg, corrosion inhibitors, catholic protection, electrochemical chloride extraction of the cover concrete).

3.1.3 Combined Carbonation and Chloride

It is rare for carbonation and penetrating chloride to occur coincidently. However, it is more common to find carbonation of older buildings where the concrete contains cast-in calcium chloride. The process of carbonation releases more free chloride ion which can push the free chloride ion content above the limit of 0.2%, initiating corrosion over time. The repair strategy is the same as for chloride above.

3.2 Minimum Requirements before Work Begins

Six options are commonly used, singly or more often in combination, for effective concrete repair:

- Do nothing but monitor
- Reanalyse the structural capacity of the weakened element
- Prevent or reduce further deterioration
- Improve, strengthen or refurbish all or part of the structure
- Replace all or part of the structure
- Demolish – completely or partially

The pre-repair assessment should include of the following:

- Original design approach
- Condition during construction
- History of the structure
- Client's current requirements
- Approximate extent and likely rate of increase of defects (without repair)
- Importance of whole life costing of the works, which is strongly recommended as the basis for selecting the final repair strategy, looking at the value over the intended remaining life of the structure, rather than just the capital costs of the works.

As part of this assessment, full consideration is required of safety and structural implications arising from the present and future condition of sub-standard structures in need of repair.

3.2.1 Residual Structural Capacity

Structural weakening needs very careful consideration by engineers experienced in the repair process:

- Weakening at the point of repair (eg,due to loss of concrete section in a compression member, or lose in cross-section of reinforcing bar due to corrosion), can be calculated through a standard structural appraisal to give the residual structural capacity.
- Weakening post-repair is less obvious and the following factors must be considered:
  - The physical and structural properties of the repair products and systems to be used at the applicable service temperature, in particular the elastic modulus, creep and shrinkage of the materials; where the repair is to take compressive loads, consider the effects of creep at elevated service temperature.
  - Locked-out stress' occurs when tensioned reinforcement is broken out and repaired, thereby losing its tensioned state: this weakening effect can only be reduced by removing load from the structure prior to repair (eg,propping and load restrictions) and/or minimising the area of concrete to be broken out, even if new bar is added to replace the bar sectional area lost due to corrosion.
  - Maximum service temperature of structural repair materials – some organic materials, such as epoxy resin and other adhesives, may have a glass transition temperature of less than 60 degree C meaning that they are unsuitable for structural use if service temperature exceeds this value.
  - Treatment of prestressed structures needs particular care, as the repair work will need to ensure the full structural capacity of the elements can be de-stressed and then re-stressed, pre-tensioned elements are often replaced owing to the difficulty or providing repaired element with the same structural capacity as the original.

3.3 Treating Exposed Reinforcing or Prestressing Bar

Corroded steel must be carefully assessed for loss of cross-sectional area. With conventional reinforcement, significant corrosion can occur without significant weakening of the structure, but with prestressed strand, even slight pitting corrosion can cause significant weakening. Preparation by grit blasting or high-pressure water jetting (at least 700 bar) is preferred as this will remove all corrosion product and contaminants. Generally, further treatment of the bar is not necessary where it is to be surrounded by a strongly alkaline repair material. However, many repair products are not compatible with the concrete initially used (eg, materials are often formulated to be stiff, suitable for trowel application, rather than a free-flowing concrete and may not full encapsulate the reinforcement). Also the matrix may not be cementitious at all, but be based on an epoxy or rather resin system that will not passivate the reinforcement. Therefore, most concrete repair products and systems include primers for the reinforcement.

3.4 Filling Patch Surfaces

It is strongly recommended that the patch surfaces left following removal of defective concrete are filled using materials that are of similar physical and chemical properties to those they are replacing, particularly where the material is in contact with the reinforcement. Therefore, cementitious concrete repair products should normally be used unless there are over riding technical reasons to use other binder formulations (eg. epoxy or polyester resin).

Repair materials fall into three basic categories:

- Structural – where the repaired element is to be under compressive load. Materials are usually based on normal density cementitious products, modified with additives to reduce shrinkage and improve adhesion but still retaining comparable elastic modules, creep and shrinkage to that of the concrete it replaces. Note that while the laboratory tests for product may suggest suitability for structural applications, each specific repair situation must be considered on its merit (eg. compare the properties of old concrete that has completed full shrinkage and creep under compression, with new material that will have finite shrinkage and creep in the repair situation)
- Semi-structural – where the repair product is in contact with reinforcement but is under no direct compressive load, such as repair to beam soffit. Materials are usually based on lightweight cementitious products that are unlikely to have the same elastic, creep and shrinkage as concrete.
- Cosmetic – where the hole does not extend to the depth of the reinforcement. Materials are usually based on lightweight products, with either cementitious or polymer binder, and are unlikely to have the same elastic modulus, creep and shrinkage as concrete.

Most repair products and systems in this category will include a priming system to promote adhesion with the existing concrete. Such 'bonding aids' must be used strictly in accordance with the manufacturer's instructions and in particular the time between applying the bonding aid and applying the repair mortar must be strictly followed for the ambient temperature, humidity and wind conditions.

3.5 Preventing Further Degradation

To prevent future degradation, measures must be put in place to stop the initiator of degradation. In most repair situations, the durability of the concrete can be significantly enhanced by use of a surface protection system. The exact performance requirements of the surface protection system will depend on the conditions of exposure and mechanism at work.

3.6 Strengthening of Weakened Structures

Strengthening may be required where structures are assessed to be below their original structural capacity. Methods include:

- Adding extra reinforcement and casting additional concrete.
- Adding extremely bonded reinforcement to increase tensile and/or shear capacity.
- Adding external post-tensioning.

Where structures are strengthened, the ambient service temperature and possible fire effects need to be carefully considered along with the design principles of the strengthening. As mentioned above, the glass transition temperature of resins used to bond steel or synthetic fibres to concrete may be relevant, particularly in a fire situation.

4.0 Framework of Whole Repair Process

The principles and methods of repair are derived into two groups; the first deals with defects in concrete as a material, the second addresses defects caused by corrosion of the reinforcement. Table 1 summarises the process of assessment, specification, site execution and maintenance and monitoring of structures and Table 2 summarises the repair principle.

Step 1: Assess Damage

- Present condition
- Original design approach
- Environment and contamination
- Conditions during construction
- Conditions of use
- History of structure
- Future use

Step 2: Choose Options

- Considering intended use, design life and service life
- With the required performance characteristics
- Likely long-term performance of protection or repair works
- Opportunities for additional protection and monitoring
- Acceptable number and cost of future repair cycles
- Cost and funding of alternative protection or repair options, including future maintenance and access costs
- Properties and methods of preparation of existing substrate

- Appearance of protected or repaired structure

Step 3: Choose Repair Principle(s)

Defects in concrete

- Protection against ingress
- Moisture control
- Concrete restoration
- Structural strengthening
- Physical resistance
- Resistance to chemicals

Reinforcement corrosion

- Preserving or restoring passivity
- Increasing resistivity
- Cathodic control
- Cathodic protection
- Control of anodic areas

Step 4: Choose Method (s)

- Appropriate to type and cause for combinations) and extent of defects
- Appropriate to future service conditions
- Appropriate to protection or repair option chosen
- Compliance with the Principle chosen
- Availability of products and systems complying with relevant standards

Step 5: Choose Materials

- Minimum performance characteristics for all intended uses
- Minimum performance characteristics for certain intended uses
- Performance characteristics for specific applications

Step 6: Specify Ongoing Requirements

- Record of the protection or repair works that have been carried out
- Instructions on inspection and maintenance to be undertaken during the remaining design life to the repair part of the concrete structure.

The requirement for quality control of the repair works covering testing to verify the suitability of the substrate before repair and quality control tests and checks carried out during and after repair should be specified.

The minimum performance standards of the repair material for a range of engineering properties, related to end use should be established. For example, a surface protection system for concrete, such as film-forming paint, will have different performance requirements depending on whether it is intended to protect against ingress of chloride ions, or reduce carbonation of the concrete, or control moisture penetration into the surface, and whether the paint is to be applied over active cracks in the concrete.

Table 2: Principles and methods for protection and repair of concrete

Principle	Examples of Methods based on the Principles
Protection against ingress	Hydrophobic impregnation Impregnation Coating (including crack-bridging) Filling cracks Transferring cracks into joints Erecting external panels Applying membranes
Moisture control	Hydrophobic impregnation • Coating (including crack-bridging) • Over cladding • Electrochemical drying treatment
Concrete restoration	Hand applied mortar Recasting with concrete Sprayed concrete Replacing elements
Structural strengthening	• Adding or replacing embedded or external reinforcing bars • Adding reinforcement anchored in pre-formed or drilled holes • Bonded plate reinforcement • Adding mortar or concrete • Injecting cracks, voids or interstices • Filling cracks, voids or interstices • Prestressing – (post-tensioning)
Increasing physical resistance	Overlay or coating Impregnation
Resistance to chemicals	Overlay or coating Impregnation
Preserving or restoring passivity	Increasing cover with additional mortar or concrete Replacing contaminated or carbonated concrete Electrochemical realkalisation of carbonated concrete by diffusion Elecctrochemical chloride extraction
Increasing resistivity	Hydrophobic impregnation Coating
Cathodic control	Limiting oxygen content (at the cathode) by saturation or surface coating
Cathodic protection	Applying an electrical potential
Control of anodic areas	Active coating Barrier coating Applying inhibitors to the concrete

5.0 Surface Protection Systems

The use of coatings and waterproofing systems as part of a repair strategy is becoming increasingly common. These not only provide an enhanced appearance but also an enhanced durability. This repair Note presents a brief introduction to coating concrete, including a review of the relevant Standard EN 1504 Part 2.

5.1 Surface Treatments for Concrete

Anti-carbonation represents a widely used and relatively well known family of systems for enhancing the durability of reinforced concrete. Historically, there have been two basic figures expressed for such coatings: an R value denotes the resistance to carbon dioxide and an S_d value denotes the vapour permeability. Silanes are also fairly common place as surface treatments for concrete; as are waterproofing systems that either sit on the surface of the concrete or soak into the concrete and block the pores. These are the commonest types of treatments, and are technically termed hydrophobic impregnations, impregnations of coatings.

In applying surface treatments to concrete, it is necessary to remember a number of key elements. Concrete is a porous material. The pores may contain air or moisture; consequently, anything applied to the surface will need to be able to cope with this. The moisture may be present near to the surface but will also be present at depth in the concrete. It is likely that the concrete to be treated will be external and therefore may be exposed to water just before, during or after the application and this needs to be considered in selecting a material. Some surface treatments are more able to cope with the presence of moisture than others. Urethanes have excellent adhesion and crack bridging properties but can turn into expanding foam if applied in the presence of moisture and so are often used in conjunction with a water-borne epoxy primer, which will be applied to the surface as a sealant.

The moisture may also contain significant quantities of soluble salts. Coatings and surface treatments are therefore often termed 'breathable', where they will allow the passage of water vapour out of the concrete but will not allow liquid water to penetrate. This ability to 'breath' prevents blistering due to water pressure and can allow the concrete to dry out. However, where significant amounts of soluble salts are present this can cause the salts to recrystallize and break-up the surface of the concrete under the coating system.

Concrete also contains cracks. These can be the result of its structural behaviour, thermal stresses during the original casting, or long-term shrinkage of the concrete. They can be subject to short-or long-term movements and an uncracked area can develop cracks as time progresses. Technically, any coating covering cracks that appear from nothing is subject to infinite strain, which makes for interesting calculations for required structural properties.

Finally, as with any surface treatment to any substrate, the condition of the surface needs to be considered. Some surface preparation will be required for any structure. The type and nature of the preparation will depend on the material to be applied. Conversely, the suitability of the material depends on the practicality of achieving this required level of surface preparation as well as process of applying and curing the material.

5.2 Surface protection systems

There are three basic approaches used in applying surface protection to concrete.

- Hydrophobic impregnation (H) – These materials penetrate the concrete and leave a water – repellent lining on the surface of the pores. They encourage the concrete surface to shed water but do not prevent water ingress under significant pressure.
- Impregnation (I) – these materials impregnate the concrete and block up the pores.
- Coatings (C) – coating system are those that adhere to the outer surface of the concrete.

6.0 Mortars, Structural Adhesives and Other Repair Products

6.1 Repair Mortars

Repair mortars and concretes for the structural or non-structural repair of concrete, to replace defective concrete and to protect reinforcement, in order to extend the service life of a concrete structure exhibiting deterioration. They may be used in conjunction with other products. Repair mortars and concretes are used for several repair application as shown in Table 3.

Table 3: Repair using mortars and concretes

Concrete restoration	Applying mortar by hand
	Recasting with concrete
	Spraying mortar or concrete
Structural strengthening	Adding mortar or concrete
Preserving or restoring passivity	Increasing cover to reinforcement with mortar or concrete
	Replacing contaminated concrete

6.1.1 Overview of Requirements

The performance requirements for repair mortars and concretes are:

- Compressive strength
- Chloride ion content
- Adhesive bond
- Restrained shrinkage/expansion
- Carbonation resistance
- Thermal compatibility
- Elastic modulus
- Skid resistance
- Coefficient of thermal expansion
- Capacity absorption (water permeability).

Repair mortars and concretes are categorised into structural repair and non-structural repair work. Structural mortars and concretes are distinguished by having a high compressive strength, stronger adhesion to the substrate, before and after thermal cycling and shrinkage tests, and requirements for the elastic modules of greater than 15/20 GPA.

6.2 Structural Bonding

The products intended for application to concrete should provide a durable structural bond to an additional applied material, such as carbon fibre plates, steel or concrete, including:

- Bonding external plates to the surface of concrete for strengthening purpose.
- Bonding hardened concrete to hardened concrete in repair and strengthening situations.
- Casting of fresh concrete to hardened concrete using an adhesive bonded joint where it forms a part of the structure and is required to act in a composite manner.
- Structural bonding products are used for structural strengthening in particular for bonded plate reinforcement and for bonding mortar or concrete.

6.2.1 Overview of Requirements

The performance requirements address the following performance aspects of the materials:

- Suitable for application, including to vertical surfaces and soffits, horizontal surfaces and by injection
- Temperature range of suitability for application and curing and suitability for application to a wet substrate.
- Adhesion of plates to plates, concrete and corrosion protected steel and of hardened or fresh concrete to hardened concrete
- Durability of the complete system under thermal or moisture cycling.

The following characteristics of the bonding material should be considered

- Open time and workable life
- Modulus of elasticity in compression and flexure
- Compressive and shear strength
- Glass transition temperature
- Coefficient of thermal expansion
- Shrinkage

The detailed performance requirements, specified test methods to be used, and sets out the quality control and conformity evaluation requirements that materials producers need to follow when producing products to meet the standard.

6.3 Concrete Injection

The products intended for filling of cracks, voids and interstices in concrete on injection method should be based on either a hydraulic binder or a polymer binder, and different products characteristics are specified for different materials. Injection used to avoid the harmful consequences of voids and cracks in concrete, to achieve impermeability and watertightness; to avoid penetration of aggressive agents that might induce corrosion of steel reinforcement, and to strengthen the structure by strengthening the concrete.

6.3.1 Overview of Requirements

The primary performance characteristics of injection products are:

- Basic characteristics, related to adhesion, shrinkage, compatibility with steel and concrete, glass transition temperature and water tightness. These are essential for any intended use.
- Workshop characteristics, which indicate the conditions in which the products can be used (width, moisture state of the crack).
- Reactivity characteristics including the workable life and strength development.
- Durability of the hardened product under the prevailing climate conditions.

Other characteristics may need to be considered for certain intended uses of the product, such as:

- Glass transition temperature, where the temperature of the hardened product in the crack may be higher than 21 degree C and the product is formulated with reactive polymer binder.
- Chloride content and corrosion behaviour for injection of reinforced concrete
- Water tightness for waterproofing injection.

6.4 Anchoring

Anchoring is used for adding reinforcement anchored in preformed or drilled holes in concrete in structural strengthening method. Anchoring products may include hydraulic binders or synthetic resins or a mixture of these, installed at a fluid or paste consistency, to grout reinforcing steel bars in hydraulic concrete structures.

6.4.1 Overview of Requirements

The primary performance characteristics of anchoring products are:

- Pull-out resistance
- Chloride ion content
- Glass transition temperature
- Creep under tensile load

6.5 Reinforcement Protection

- The part 7 of Standard EN 1504 covers active coatings and barrier coatings for production of existing steel reinforcement in concrete structure under repair.

6.5.1 Application

Reinforcement protection is covered by control of anodic areas:

- Active coating of the reinforcement
- Barrier coating of the reinforcement.
- This covers the use of coatings on the reinforcement; whether to provide protection or to provide a base layer to which repair mortar or concrete can subsequently be added.

6.5.2 Overview of Requirements

The primary performance characteristics of anchoring products are:

- Corrosion protection
- Glass transition temperature
- Shear adhesion (of coated steel to concrete)

6.6 Achieving Successful Repairs

The objective is to assess the concrete repair projects by determining appropriate materials selection and executing the work, taking the whole-life cost of the repair system into account. While designing the repair system following provisions should be made:

- Structural stability during repair work
- Aesthetic performance of the repair
- Concrete removal considering health, safety & environment

6.7 Performance-based Repair & Rehabilitation

The durability and longer-term performance of repaired concrete structures is a key issue in any repaired project. The repair should be performance-based rather than perspective based approach. It is postulated that the management of concrete structures could be improved by implementing a proactive monitoring and maintenance system rather than taking remedial intervention only after damage happens.The repair failures can be avoided provided the causes of failure of repair system are taken care which is related mainly to:

- Wrong diagnosis of the cause of initial damage or deterioration of the structure
- Inappropriate design of the intervention works
- Inappropriate specification or choice of materials used
- Poor workmanship

Reactive maintenance is likely to be instigated only when visible indications appear (eg. cracking or spalling of concrete), with an intervention being made to slow the rate of deterioration and extend the length of useful service life of the structure. Proactive maintenance, such as the early application of a coating to slow the ingress of aggressive species, could potentially delay the onset of corrosion and extend the useful service life. The implementation of this concept is illustrated in Fig. 1, which presents a time-line representation of the two alternative philosophies and includes a notional indication of their respective costs. The relative cumulative maintenance cost in case of proactive maintenance approach is less than reactive approach with better structural performance in long run whereas comparative initial cost is higher. The graph indicates that the proactive cost is evenly distributed in life time whereas the cost for maintenance in reactive approach is considerably very high during major repair.

Recently changes in owner attitudes to construction are reflected by their increasing interest in through-life costs, which is not only the capital costs of the construction but particularly in the operational costs associated with delivery of function performance for a defined life span. This change is an important development in achieving a more balance and holistic approach to extending the life span of existing buildings and structures.

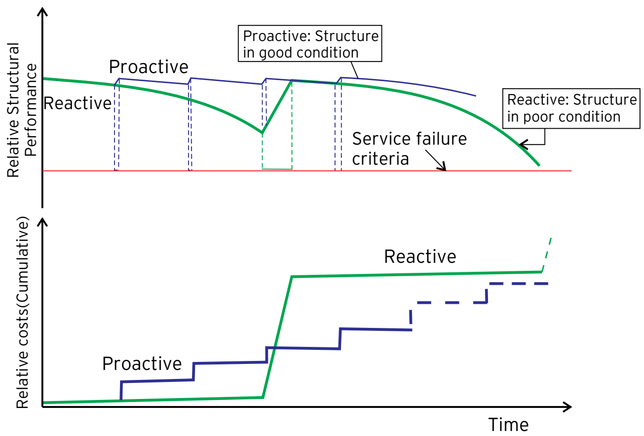

Fig. 1: Alternative approaches to the management and maintenance of structures

6.8 Ongoing Monitoring of Concrete Repairs

After completion of repair of the structure, it should be monitored by visual inspection in every two years, detailed inspection with non-destructive tests in every six to ten years and special inspection as required to inspect a particular defect. Further the building or structure should have a regime of routine maintenance to keep the structure in good order.

7.0 Conclusion

Understanding the cause of the defects and damages after the structural assessment the right kind of material can be specified. In following article the materials and methodologies for repair are discussed in details.