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Infrastructure Corrosion and Durability - A Sustainability Study

Chapter: A State-of-the-Art on Concrete Repairs and Some Thoughts on Ways to Achieve Durability in Repairs

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A State-of-the-Art on Concrete Repairs and Some Thoughts on Ways to Achieve Durability in Repairs

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Introduction

Reasons for repairs can mainly be classified into two categories: one-time events or causes of a recurring and enduring nature [1]. Typical one-time events include structural overloading, earthquakes, or fires, the severity of which will require a mandatory intervention. Recurring causes may include shrinkage or thermal cracking, corrosion, and chemical attack. Generally, such recurring causes tend to work together in combination rather than independently, so that deterioration is the outcome of a complex physico-chemical and mechanical synergy of phenomena and factors.

When a new repair is applied, its performance will be affected by a coalescence of phenomena which have occurred over the past service life of the structure, and new issues which could arise in the future. Therefore, designing robust repairs requires an understanding of how each phenomenon or parameter affected the structure in the past and will affect the post repaired structure over its service life. By taking a rational approach to a repair problem, we can understand it to ensure a robust repair is designed and utilized in practice. As pointed out by Vaysburd [2], the prevailing way repair/rehabilitation projects are typically approached may be described by two extremes: unorganized complexity, which, by acknowledging all the complex interactions involved, does not allow for a proper rational analysis of the system, or organized simplification and reductionism, which, in order to suggest easy and practical ways to tackle the problem, miss the picture of the system behavior as a whole.

The aim of this chapter is to provide the reader with a general overview of the different phenomena and factors involved with durability of repair and suggest the major aspects which the repair design should focus on. However, it is important to keep in mind that any repair problem needs to be addressed as a unique problem first, and the designer, by developing awareness of the several challenges involved, should be able to make mindful choices, adequate to the specific application that is being considered. By the end of the chapter, the reader will hopefully:

- Understand the complexity of the repair problem, and the related challenges.
- Have learnt the basics of the many types of phenomena which can necessitate repairs, and jeopardize repair effectiveness.
- Recognize that a rational approach to the analysis of repair durability can be adopted as a means to relate between deterioration phenomenon, properties of the different repair components, interactions between the different components, and the ultimate robustness of the repaired system.
- Develop awareness of the most relevant factors which affect robust repair design, namely: interfacial behavior and compatibility between the repair material and the existing construction.
- Be able to execute robust repairs as a result of proper consideration of durability.

Phenomena and Complex Structural Interactions Affecting Durability

When considering the durability of concrete structures and their repairs, researchers often have to overlook or simplify some aspects of the problem, due to its complexity. Indeed, a rational, analytical approach to the study of durability is difficult to develop due to the different levels of complexity that cannot be easily identified:

Level 1: The various mechanical, physical and chemical phenomena causing degradation are often strongly interrelated. In fact in some cases, the nature of some phenomena may not have been fully understood.

Level 2: Not only is the durability of the composite affected by the durability of each component, but the durability of each component is affected by the response of the system as a whole.

Level 1: Physical and chemical phenomena involved

A brief summary of the common phenomena which cause degradation of concrete structures is provided hereafter:

Mechanical

Abrasion: Under many circumstances, concrete surfaces are subjected to wear and tear. The rate of abrasion of concrete is dependent on the quantity, shape, size and hardness of the particles coming into contact with the concrete, and also on the quality of the concrete. Abrasion resistance of concrete generally increases with increases in the volume fraction and quality of coarse aggregates in the mix [3]. Typical surface damage induced by abrasion is shown in Figure 1.

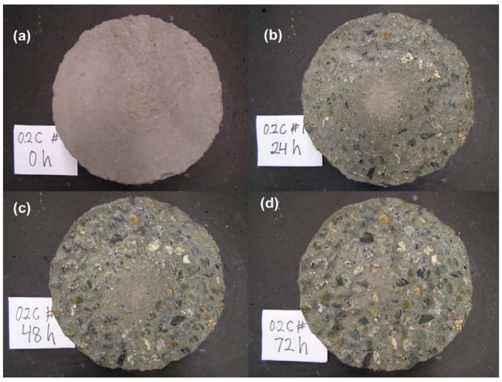


Figure 1: Concrete abrasion from experimental tests performed at the Civil Engineering Department of the University of British Columbia (ASTM C1138) [4]. Time of exposure: (a) 0 hours, (b) 24 hours, (c) 48 hours, (d) 72 hours.

Improper placement: Concrete which is improperly placed will have durability concerns. It must be properly consolidated. Under vibration will lead to defects such as honeycombing, and entrapped air voids. Honey combing results when the spaces between coarse aggregate particles do not become filled with mortar. Air voids are similar to but not as harmful as honeycomb. Over vibration may also be a problem. Segregation of the coarse aggregate from the mortar may occur if the concrete is subjected to excessive vibration or when placed using pump and drop.

Physical

Freeze-thaw: Problems related to freeze-thaw attack of concrete arise when unbound water in concrete freezes. When water freezes it expands by around 9%. This causes hydraulic pressure within the concrete pore structure. As concrete reaches its saturation point, and over many cycles of freezing and thawing, this pressure causes tensile forces to build up in the concrete matrix. If these forces exceed the internal tensile strength of the concrete, it will cause the concrete to deteriorate by way of general disruption, cracking, scaling or pop outs leaving it exposed to further attack and ultimately failure (Figure 2).

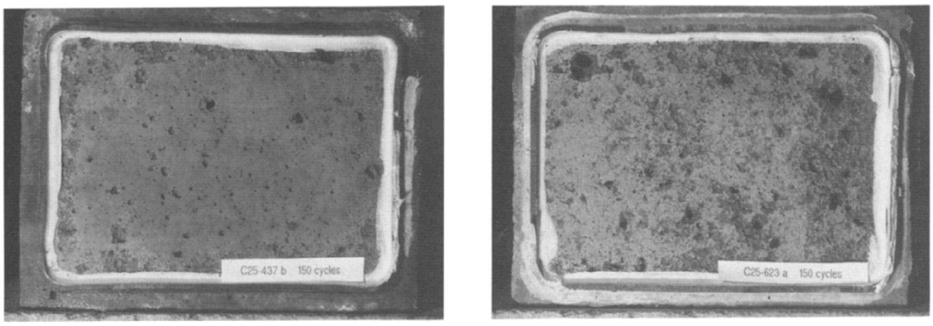


Figure 2: Damage induced in different types of concrete after 150 freeze-thaw cycles [5].

Drying shrinkage: As concrete cures, the withdrawal of water from concrete stored in unsaturated air causes drying shrinkage. Because of a loss in volume, concrete shrinkage can lead to cracking when base friction or other types of restraints are present.

Carbonation shrinkage: Natural concrete carbonation is a chemical process by which atmospheric CO_2 reacts with portlandite ($Ca(OH)_2$) in hydrated cement paste to form calcium carbonate ($CaCO_3$). The predominant chemical reaction is:

$$CO_2+Ca(OH)_2 \rightarrow CaCO_3+H_2O$$

The calcium carbonate formed has a higher density (and hence lower volume) than that of the calcium hydroxide, and there is therefore a reduction in volume. The reduction will cause the concrete to shrink with time, and may lead to the formation of carbonation induced shrinkage cracks.

Plastic shrinkage: Plastic shrinkage of concrete occurs due to the loss of water to the environment which cannot be fully replenished by bleeding while it is still in a plastic state. Plastic shrinkage is more likely to occur in arid, windy environments. The differential change in volume may induce strains in the concrete as it is setting leading to plastic shrinkage cracks (Figure 3).

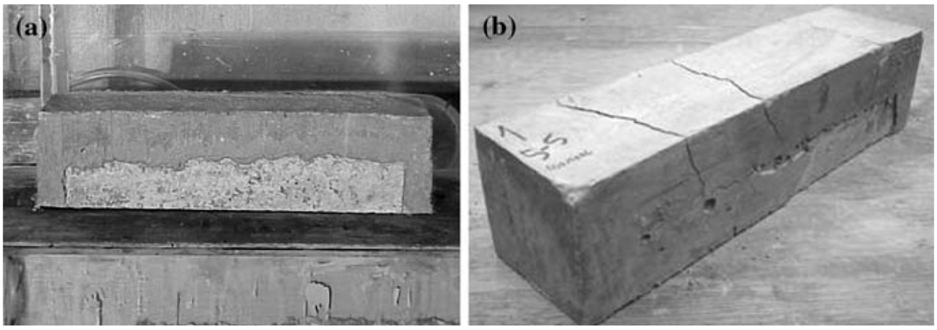


Figure 3: Substrate-overlay specimen after (a) demolding and (b) cracking due to plastic shrinkage (stresses arise as the substrate tends to restraint the shrinking overlay) [6].

Autogenous shrinkage: When no moisture movement from or to the cement paste is permitted, shrinkage occurs. This shrinkage is the result of withdrawal of water from capillary porosity due to the hydration of the hitherto unhydrated cement. This is also known as 'self-dessication', and could lead to crack formation.

Creep: The gradual increase in strain with respect to time under a sustained stress is due to creep. The amount of paste content and its quality are some of the most important factors influencing creep. A weaker paste structure undergoes higher creep. Therefore, it can be said that creep increases with increase in water/cement ratio. Age at which a concrete member is loaded will have a predominant effect on the magnitude of creep. Creep magnitude is much higher at early ages, so structures which are loaded soon after curing are more susceptible to creeping induced damage.

Thermal cracking: Thermal cracking occurs due to excessive temperature differences within a concrete structure or its surroundings. The temperature difference causes the cooler portion to contract more than the warmer portion which restrains the contraction. Thermal cracks appear when the restraint results in tensile stresses that exceed the in-place concrete tensile strength. Thermal cracking often occurs in mass structures where there may be a large gradient between temperature at the surface which cools rapidly, and internal concrete which is still at a higher temperature from hydration.

Chemical

Acid attack: Concrete is generally resistant to chemical attack, however, as it is highly alkaline it cannot resist acids. Acids can breakdown the $Ca(OH)_2$ and the Calcium-Silica-Hydrate (CSH) in concrete. For acids with pH <5.5 the attack can be quite severe.

Acid attack is a common phenomenon and needs to be accounted for in areas where acid rain is prevalent. Concrete sewage pipes may break down quite easily due to the formation of sulfuric acid in flowing sewage. Concrete used in industrial plants where it may come into contact with miscellaneous acids is also susceptible to deterioration.

Alkali-silica reaction: Aggregates containing certain constituents can react with alkali hydroxides in concrete. The reactivity may be harmful if it produces a significant expansion. In general the main form is the Alkali–silica reaction (ASR). Aggregates containing poorly crystalline or metastable silica minerals may react with hydroxides in the cement paste to form a gel which swells and absorbs moisture from the vicinity. As it swells, it induces pressure, expansion, and cracking of the aggregate and surrounding concrete.

Chloride induced rebar corrosion: Corrosion is an electrochemical process very much like the one that produces power in an ordinary electrical cell. In a cell which is generating current, the anode is the positive electrode from where electrons are generated and then flow to the negative, cathode electrode (Figure 4). OH ions are reduced at the cathode and flow back to the anode to form rust at the anode. In concrete, the rust can grow to a volume several times that of the steel from which it was formed. Some of the products have a volume upto 6.15 times that of the original rebar (Jamali et al, 2013). The result is that the growing rust will crack the cover through delamination and spalling.

The surface of the corroding steel functions as a mixed electrode that is a composite of anodes and cathodes electrically connected through the body of steel itself, upon which coupled anodic and cathodic reactions take place. Concrete pore water functions as an aqueous medium, i.e., a complex electrolyte [7]. The areas where iron is more easily oxidized form the anodic regions, while the other areas are cathodic [8].

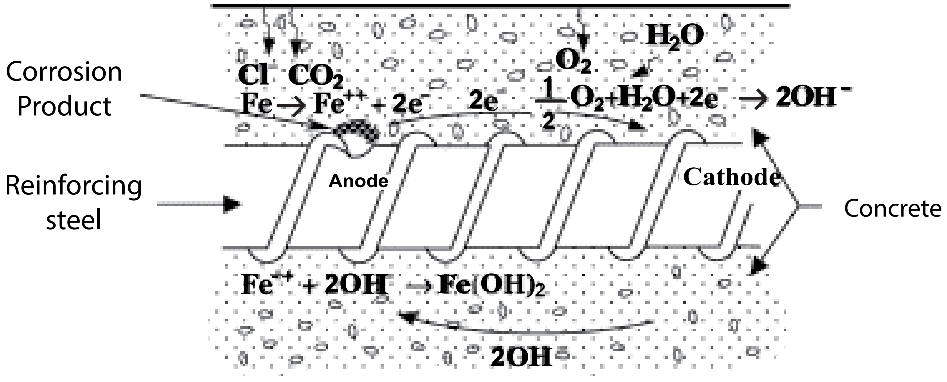


Figure 4: Corrosion of rebar [7].

Fortunately, experience with reinforced concrete structures shows that even under aggressive environmental conditions, the reinforcement embedded in concrete will be protected against corrosion during normal service life, provided that the mix is properly designed, placed, compacted, and sufficient concrete cover is provided [3]. In good quality, well-compacted concrete, reinforcing steel should not be susceptible to corrosion, even though active sites resulting from in homogeneities in the steel or non-uniform stress concentrations are likely to be prevalent. This is because the high alkaline conditions ($p^H > 12$) present within concrete cause a passive oxide barrier to form on the surface of the steel and prevent corrosion. It is only when this passivation layer is destroyed that the embedded steel becomes susceptible to corrosion.

Chloride ions have a particularly powerful effect on rebar corrosion in concrete. Relatively low concentrations of chloride ions which penetrate into the concrete can accelerate corrosion by destroying the passive barrier that originally protects the reinforcing steel and also increases the conductivity of the aqueous solution formed there, thereby accelerating the reaction.

Chlorides can be introduced into concrete via two main routes; (a) as contaminates in the original mix, and (b) as a result of post-setting exposure to de-icing salts, seawater or other chloride-bearing media. In the case of (a) the presence of chlorides will initiate immediate corrosion reactions, which may be quite severe. In the case of (b) the chloride content of the concrete will build up with time possibly leading to a condition where the concrete is no longer able to protect the reinforcement from corrosion.

Carbonation induced rebar corrosion: Naturally occurring Carbon Dioxide (CO_2) in the atmosphere diffusing into concrete reacts with dissolved aqueous Calcium Hydroxide ($Ca(OH)_2$), and Calcium-Silica-Hydrate (CSH) to form Calcium Carbonate ($CaCO_3$) thereby lowering the overall concentration of CO_2 within the concrete at that location and time. This phenomenon is known as carbonation. The formation of $CaCO_3$ in carbonated concrete causes a decrease in the pH of concrete to <9, where embedded rebar will have already begun to actively corrode. Carbonation depths in concrete can be estimated using the following formulation:

$$x_c = k\sqrt{t}$$

where x_c is the carbonation depth (mm), k is the carbonation coefficient ($yrs^{-0.5}$), and t is time (yrs). Note that this is an approximation, valid only for conditions of constant temperature, humidity, and CO_2 concentration.

Sulfate attack: Sulfates either present in the original mix as contaminants, or which enter the concrete by penetration are capable of reacting with the hydrated cement paste. The mechanism of distress for sulfate attack is an expansive pressure caused by the transformation of monosulfoaluminate to ettringite. This mechanism can be described as a sequence of processes as shown in the equations below. First, the external sulfate reacts with calcium hydroxide to saturate the pore solution and precipitate gypsum ($CaSO_4 \bullet 2H_2O$). The increased concentration of SO_4 promotes the transformation of monosulfoaluminate to ettringite ($3CaO \bullet Al_2O_3 \bullet 3CaSO_4 \bullet 32H_2O$).

$CH + SO_4 \rightarrow CSH_2 + 2OH$

$C_4ASH_{12} + 2CSH_2 + 16H \rightarrow C_6AS_3H_{32}$

This transformation causes an increase in solid volume, which results in the deterioration of concrete by inducing cracking, softening, and spalling. The expansion mechanism is caused by pressure from ettringite crystal growth or swelling due to absorption of water. Another measurable concrete property identified with the sulfate attack is a decline in the compressive strength.

Level 2: Repairs as Composite Systems

When it comes to repairs, durability is made more complex by the addition of new materials to the existing structure. A typical case study could be represented by a reinforced concrete girder strengthened by means of a cement based jacket. The beam could be that of a bridge or a viaduct, both typically exposed to variable and severe environmental conditions. The composite system will be considered as a chain made of 5 different parts: steel reinforcement, the old concrete, the new repair layer, the old concrete-steel interface, and the old concrete-repair interface. The substrate repair interaction becomes a key factor in the prediction of construction performance and durability, and a special attention should be given to materials compatibility and interfacial behavior. A list of issues related to the durability of each single component is provided in Figure 5.

An analogy can be given between the health of a structure and the health of a human being. Deterioration phenomena in structures can be thought of similar to disorders which affect the health of a human being. The disorders can either occur within a human for whatever reason (i.e., genetic disorders), or may be brought on by exposure to the environment (i.e., sicknesses caused by viruses or bacteria in the environment). Similarly, in structures, degradation phenomena arise due to both external and internal physic/mechanical/chemical causes, as listed in Section 3. In human beings vulnerability to a disorder is controlled by the strength of one's immune system. Similarly, in structures, vulnerability is controlled by internal factors such as material properties and material interactions. This is graphically explained in Figure 6.

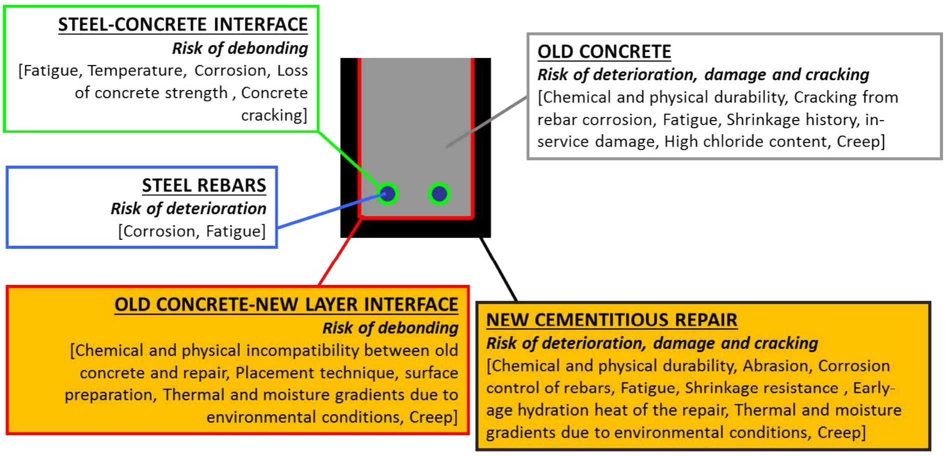


Figure 5: The various parts of a composite system.

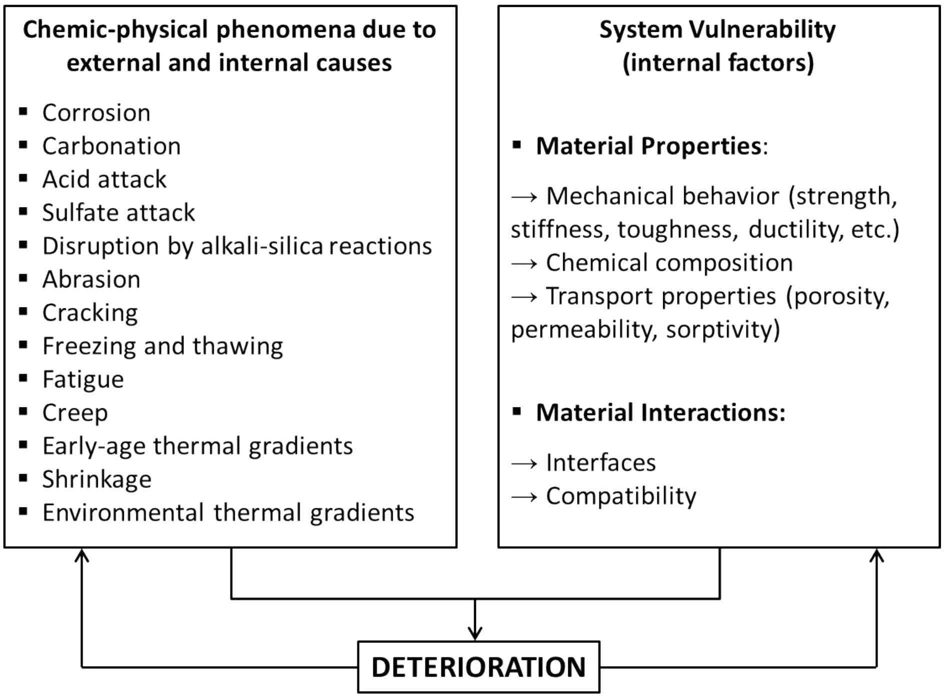


Figure 6: Internal and external causes concurring towards structure deterioration.

A Rational Approach to Prediction of Repair Performance

Regardless of the type of repair applied (either structural or non-structural), the time-dependent performance of the structure will be affected by the addition of the new material. Repair service life prediction will require that the structural analysis is accordingly updated.

Regular structural analysis involves that strains imposed by loading, vibrations, etc., are assessed first and eventually processed throughout laws defining compatibility, material mechanical behavior and equilibrium (Figure 7). Time-dependent effects need to be implemented at different levels of the structural analyses and to this aim; they can be classified into two main categories as follows:

- Phenomena causing variations in material properties: corrosion, carbonation, acid attack, sulfate attack, disruption by alkali-silica reactions, abrasion, cracking, freezing and thawing, fatigue, and creep.
- Phenomena such as shrinkage and thermal variations that, beyond causing variations in material properties, impose strains that can jeopardize bond and promote material cracking. Shrinkage and thermal strains may change the overall strain distribution in the element and need to be properly combined to those imposed by loading.

Strains induced by external factors should be combined to those induced by shrinkage or thermal gradients, while, at the same time, the material properties should be consistently updated to take into account their evolution with time as well as the effect of continuing degradation (Figure 7). The system nonlinearity is increased by the fact that the time-dependent structural performance also affects the material degradation, which, in turn, beyond altering the mechanical behavior, will influence physico-chemical properties of materials. For instance, concrete cracking and damage, beyond increasing the system deformability, will enhance its permeability and, hence, vulnerability to chemical attack and corrosion (Figure 7).

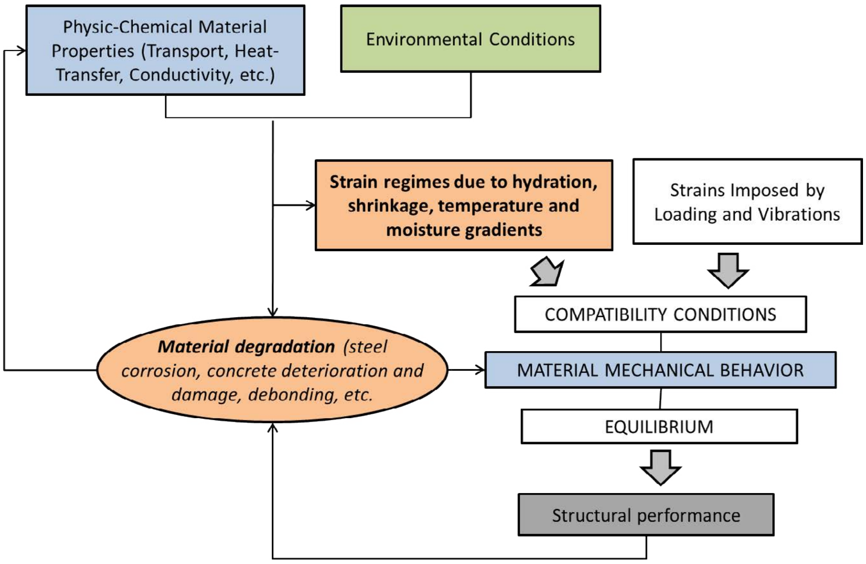


Figure 7: Implementation of time-dependent effects in structural analysis.

Design of Robust and Optimized Repair

In repair systems, while one cannot control the environmental conditions, designers can still ensure durability by controlling material degradation and ascertaining a monolithic behavior. The most relevant factors are the choice of an appropriate repair material and placement technique that ensures adequate interface behavior and compatibility.

Substrate-repair interface

Effectiveness of repairs is affected by the behavior of the interface between the old concrete and the new material applied. Thinking of a repair as a composite system, that interface is typically referred to as the *weakest link of the chain*, that is, the part that is likely to fail first and jeopardize the structural performance. Interfaces should therefore be optimized to ensure that repairs behave as monolithic structures within the service life. Moreover, porosity and micro-cracking around the interface should be regarded as important factors affecting fluid transport within the repair system.

Interfacial Transition Zone (ITZ): When concrete hardens, there develops around the aggregate a zone which is more porous than the bulk matrix. That thin weak zone at the aggregate-cement paste interface is called the Interfacial Transition Zone (ITZ). The ITZ has a lower quality than the cement paste and thus represents a weak link. Main reasons for ITZ weakness can be summarized as follows (Figure 8):

- Cement particles near the aggregate surface or the substrate are packed less efficiently than those in bulk cement paste (wall effect).
- Local changes of the water-cement ratio may occur do to the bleeding effect. In fresh concrete, the tendency for water (the lightest component in the mixture) to try to rise to the surface often leads to the formation of water pockets beneath the coarse aggregate particles.
- With some aggregates, there is some chemical reaction between the Portland cement and the aggregate.

Similarly, when a new cementitious repair casts over an existing substrate; a thin Interfacial Transition Zone forms along the contact surface between the two materials (Figure 9). The ITZ is characterized by less hydrated cement and higher porosity (and hence a lower density), also with pores being generally larger. Furthermore, there is a lower content of Calcium Silicate Hydrate, a component that is well known for contributing to the bulk paste strength gain, and a higher content of lower quality components. Large, oriented crystals of calcium hydroxide and, generally, a greater concentration of ettringite are also seen in the ITZ.

In repair systems, ITZ porosity, weakness, and possible micro-cracking affect both the repair-substrate bond and system vulnerability to fluid transport (water, chlorides, etc.). Therefore, effective durable repairs require a robust Interfacial Transition Zone. Design and execution of repairs should take into account the fact that the ITZ quality and overall thickness are affected by the following factors:

- Substrate preparation, that is, cleanliness, soundness, surface energy and moisture content at the time of casting the repair
- Mix-design and curing of the repair material
- Substrate composition
- Thermal and shrinkage strains and cracking
- Direction of casting

Provided that the quality of the ITZ affects substrate-repair bond, the influence of those parameters listed above will be discussed in the next section. It is worth mentioning that the ITZ thickness has a significant statistical variability within any interfacial area and this aspect thereby affects interfacial strength, damage, and durability. Understanding and mastering the interfacial thickness variability would allow for the development of more reliable interfaces (that is, more robust and durable composites). Further research in this area is still required.

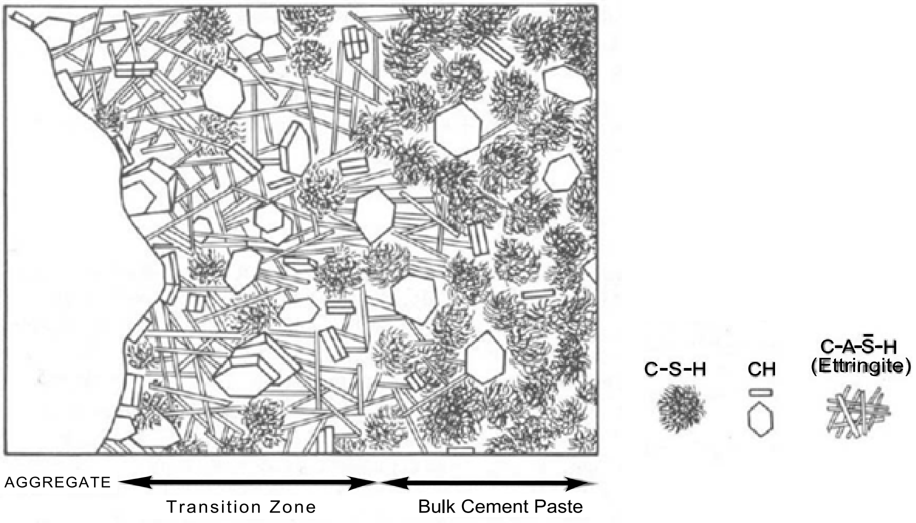


Figure 8: Aggregate-bulk paste Interfacial Transition Zone (typical thickness=20-40 μm) [9].

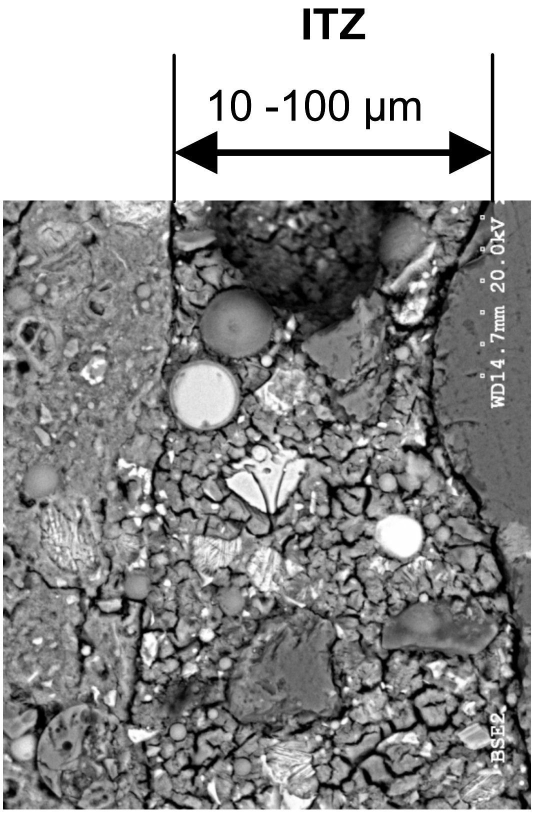


Figure 9: Imaging of a substrate-repair interface through scanning electron microscope.

Substrate-repair bond: As mentioned above, satisfactory bond between the new material and the existing structure is a critical step towards the achievement of effective durable repairs. Interfacial bond optimization should be approached at least from two different angles. First of all, regardless of the type of repair applied (either structural or non-structural), there will be a variable time-dependent stress condition affecting materials and bond. Interface stresses can be induced by several causes, such as loading, vibrations, shrinkage, and thermal gradients. Those stresses are variable within the service life and can be significantly different from one area to another. Interface performance and bond strength are a function of the nature of the stresses applied. An example of combined effect of loading and drying shrinkage is shown in Figure 10 for a R/C girder strengthened with a new layer of cementitious material. Drying shrinkage occurs at a variable rate along the longitudinal axis, since water evaporates faster in the outer parts (Figure 10a). Strains induced by loading and shrinkage also vary within each cross section (Figure 10b,c). If the old and the new concrete were not connected, the new concrete could shrink without stresses (other than the ones induced by possible non-uniform shrinkage distribution, as discussed below) and the old concrete would not be affected (no bond, Figure 10c). However, as long as the two materials adhere to each other (perfect bond, Figure 10c), compatibility of deformations involves a reduction of shrinkage strains in the new layer with additional strains in the existing restraining concrete, resulting in additional stresses in the two materials and along the interface. These stresses are also a function of mechanical properties and dimensional compatibility of the two materials, as discussed below.

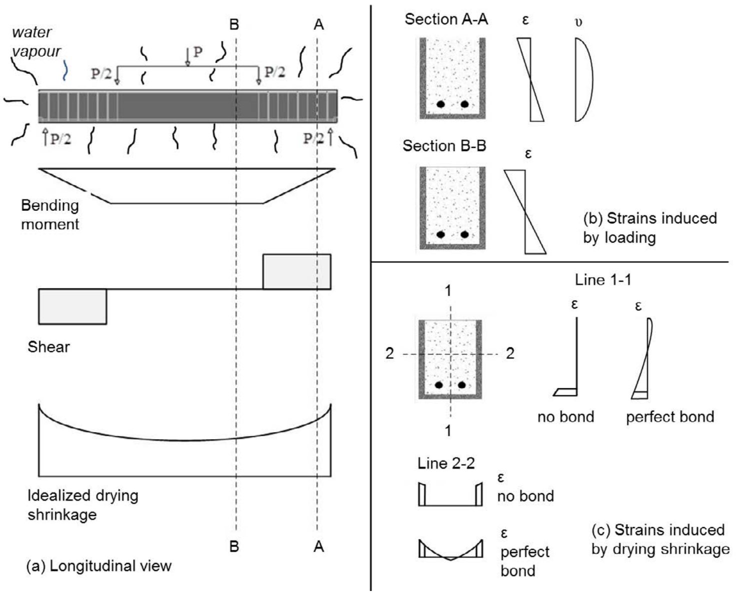


Figure 10: Combined effect of drying shrinkage and loading on the development of normal and shear strains (ε and v, respectively) in a repaired beam.

The second requirement is the durability requirement on bond. Bond should remain satisfactory during the entire service life; in fact, bond decrease and local interface damage will affect the performance of the entire structure (fluid transport will be promoted; materials can be overstressed, etc.).

Factors affecting substrate-repair bond can be summarized as follows:

- Surface roughness, cleanliness, and soundness.
- Substrate moisture content at the moment of casting the repair.
- Chemical bond due to either:
    - o application of bonding agents, or
    - o cementitious adhesion that develops between substrate and repair after casting of the repair material against the substrate.
- Mix-design and curing of the repair material.
- Substrate properties.
- Thermal and shrinkage strains and cracking.
- Direction of casting.
- Stress condition along the bond plane.

The beneficial effect of high surface roughness is mainly related to friction and mechanical interlock under shear stresses (Figure 11), while in the case of tensile stresses, the effective projected area is locally increased and thus bond strength is enhanced, even though to a somewhat smaller extent than shear. Different studies, however, found that surface cleanliness and soundness can be, at least, as important as roughness to obtain a satisfactory and durable bond strength [10-12].

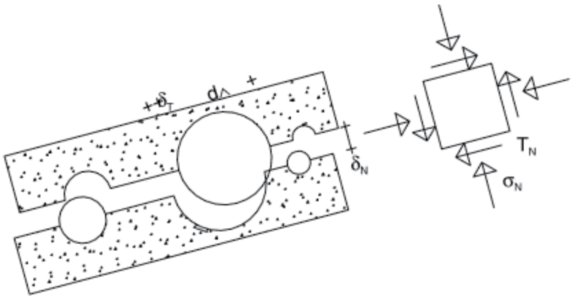
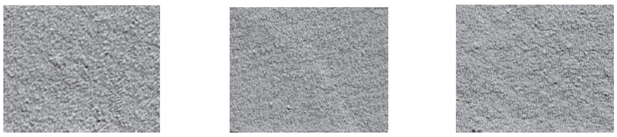


Figure 11: Friction and mechanical interlock [13].

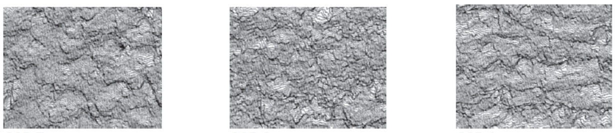
Surface roughening can be achieved through different techniques, namely: acid etching, grinding, abrasive sandblasting, steel shot blasting, scarifing, needle scaling, high pressure water jetting, scabbling, and flame blasting, and milling [14]. Sandblasting and hydro jetting are widely adopted provided that a satisfactory level of roughness can be achieved with limited damage on the substrate surface. The level of roughness, however, cannot be perfectly mastered, for it is a function of many factors, such as size of grit or sand, delivery pressure, operator skill, and operating time. Vigorous mechanical methods (such as needle scaling chipping or milling) lead to very rough surface; on the other hand, micro cracks are likely to be induced just beneath the prepared surface. Different authors, indeed, observed lower bond strength both under tension and shear, although the surface was significantly roughened [10-12,15,16].

Proper assessment of surface roughness is an important factor in defining interfacial bond. However, a qualitative evaluation of the roughness – based on visual inspection – is still the method most commonly used to verify the quality of the substrate. Video density imaging of typical surface profiles obtained with different treatments is shown in Figure 12 [14]. The development of effective and consistent techniques for a more rational and quantitative assessment of the surface roughness remains a need. Several techniques have been developed so far, which can be distinguished between contact and non-contact methods, as well as non-destructive, partially destructive, and destructive methods. Nevertheless, none of these methods is widely accepted yet [17-20].



CSP 1 (acid etched) **CSP 2** (grinding) **CSP 3** (light shotblast)

CSP 4 (light scarification) **CSP 5** (medium shotblast) **CSP 6** (medium scarification)



CSP 7 (heavy abrasive blast) **CSP 8** (scabbled) **CSP 9** (heavy scarification)

Figure 12: Video density imaging of surfaces treated with different roughening techniques [14].

Morgan [10] reported that the optimal condition for bonding cementitious repairs is achieved with concrete substrates just dried-back from a saturated surface dry condition. An excessively dry substrate may lead to moisture absorption from the repair material, causing desiccation. On the other hand, the excess water from capillaries will raise the w/c ratio in the boundary of the fresh repair material and lower its mechanical properties if substrate is excessively wet. The formation of a thin water film can strongly decrease adhesion between the two materials, and dry conditions are therefore considered preferable to wet conditions [10,11,21,22].

Common bonding agents are made of epoxy resins, cement-based slurries, or latex emulsions. Although adhesion can be potentially increased [21,23,24], there is no general agreement yet on appropriateness of the use of bonding agents. As a matter of fact, a misuse of bonding agents can lead to much lower bond strengths than without a bond coat. Jùlio and co-workers [25] assessed the influence of a commercial epoxy resin on bond strength by means of slant shear and pull-off tests. The authors did not appreciate any significant strength improvement. They concluded that the effect of a bonding agents may be neglected if an adequate surface preparation methods is chosen. Some researchers state the increasing necessity of bonding agents as the intensity of surface treatment increases [25]. Also, application of bond coats adds one more step in the construction process, and concern on the performance in event of fire or high thermal variations still remains.

Substrate repair bond can be improved with a proper design of the repair mixture by means of different solutions. First of all, beyond improving the material mechanical properties, the addition of special admixtures such as silica fume can improve the substrate-repair adhesion. Experimental evidence can be found in the experimental results and the Scanning Electron Microscope (SEM) analysis performed by Shin and Wan [26]. Vulnerability of repair material and substrate-repair interface to severe environmental effects such as drying shrinkage is reduced by the addition of silica fume, which enhances the strength of the Interfacial Transition Zone. Experimental data on the effect of other special admixtures (such as fly ash, polymers, latex, and methylcellulose) or fibers are available as well [27-31]. It is worth mentioning that fibers can promote the interface strength by limiting shrinkage and consequent damage [27].

As a general rule, one could say that those solutions that improve the quality of the bulk paste tend to improve also the quality of the ITZ and, as a consequence, the bond strength. On the other hand, the quality of the ITZ is also affected by differential volume changes between substrate and repair (such as shrinkage and thermal volume changes). In general, a lack of compatibility mainly associated with substrate-repair property mismatch can lead to interfacial damage and micro-cracking. Therefore, the repair optimization involves much more careful analysis than simply a blind material enhancement. In fact, the repair optimization cannot be performed without taking into account the properties of the existing structure and the external conditions involved (environment, loading, etc.). This aspect will be discussed further in section 6.2.

The concrete substrate-repair material bond strength is a function of the stress condition along the interface between the two materials. The possible different stress states imposed on an interface can be grouped into the following five categories: (i) combined shear and compression, (ii) "pure" shear, (iii) combined shear and tension, (iv) indirect tension, (v) direct tension, with (i) representing the highest bond strength and (ii) to (v) sorted by decreasing strength. Shear strength usually exceeds tensile strength due to friction and aggregate interlock.

The interfacial bond strength should be defined by a whole curve relating strength values to different combinations of shear and normal stresses. Unfortunately, though, the achievement of some specific failure modes during a bond test can be particularly challenging in general and even more difficult in case of brittle and quasi-brittle cement-based composites. A failure occurring in either the concrete substrate or the repair material rather than at the bond plane has been recorded often. As a result, one can only assume that the bond strength is higher than the stress reached at failure, while neither a strength value can be estimated nor the influence of some factors (such as interface roughness or bonding agents) on the bond strength can be appreciated. Moreover, bond tests may induce a non-uniform stress distribution along the bond plane, which is a function of the material property mismatch between substrate and repair. Finally, some particular stress states, such as direct pure tension or shear, are hard to really achieve. In order to overcome the problems mentioned above, different test set-ups and procedures have been developed. Also, some efforts have been carried out to provide laws interrelating the strength values corresponding to different combinations of shear and normal stresses [32].

Besides affecting the bond strength, the nature of stress applied also affects the influence of the different factors mentioned earlier, such as surface roughness, chemical cohesion or bonding agents. For instance, surface roughness, which mainly affects friction and mechanical interlock, will be more significant under stress conditions where friction and mechanical interlock are invoked as resistant mechanisms, that is, under a combination of shear stresses and significant compressive stresses. In order to better explain this aspect, a case history is provided below.

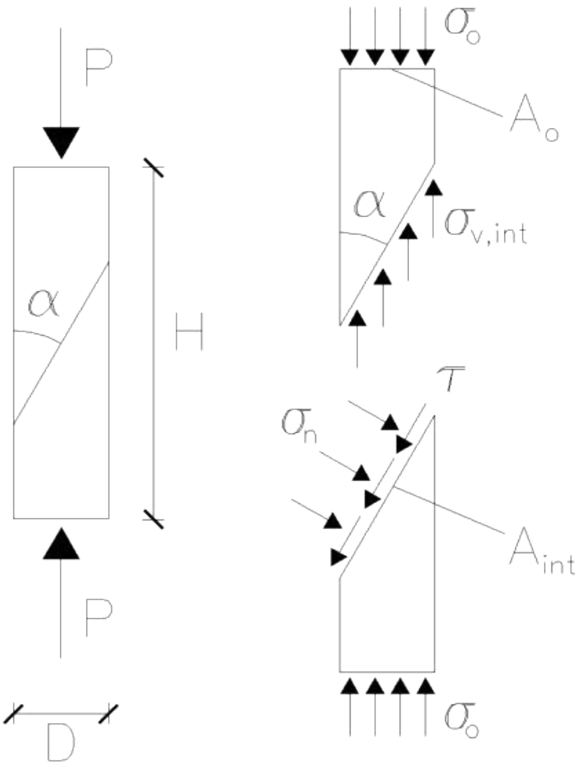


Figure 13: Slant shear test.

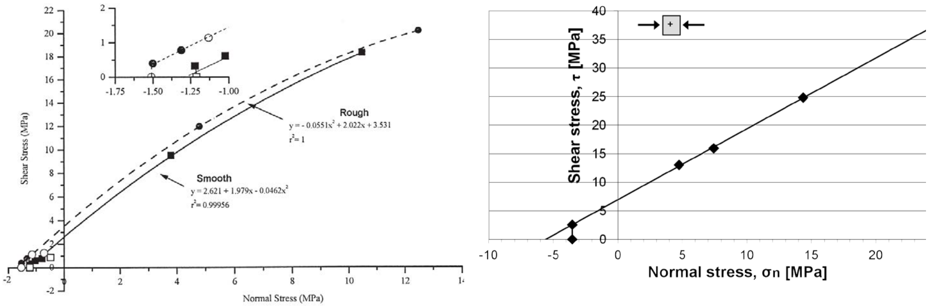


Figure 14: Bond strength failure envelopes by Austin et al. [10] (a) and Zanotti [33] (b).

In order to characterize substrate-repair bond, Austin and co-workers [10] performed several bond tests, including slant shear tests with different inclinations of the bond plane. The standard slant shear test uses a cylinder or a square prism made of two identical halves bonded at a certain inclination α (the standard condition being α = 30°, Figure 13) and tested under axial compression, resulting in a stress state of combined shear and compression along the interface [34]. Results were fitted into a linear interpolation law derived by reference to the well-known Mohr-Coulomb approach (Figure 14):

$$T_n = c+\mu\sigma_n = c+\tan\phi.\sigma_n$$

Where, σ_n, τ_n are the normal and shear stresses acting on the bond plane, respectively, μ=coefficient of friction, 'c' is the adhesion strength (pure shear strength of the bond), and φ is the internal angle of friction.

The development of bond strength normalized to adhesion strength (σ_o/c) as a function of the bond plane α is shown in Figure 15. Interestingly, the critical slant angle, α_{crit}, defined as the inclination at which the load required to produce a bond failure is minimum, and the associated minimum bond strength are dependent upon surface roughness, that is, upon the internal friction angle, φ . Since rougher surfaces have lower critical bond angles (point A vs point D, Figure 15), the minimum bond strength is associated with a lower normal stress-shear stress ratio (σ_o/c) in that case. Also, the results of a slant shear test can be more or less sensitive to both surface roughness and cohesion depending upon the stress field at the bond plane, that is, the inclination of the bond plane (for instance, AB<CD, Figure 15). In other words, the incidence of each factor on interfacial bond strength is strongly related to the stress conditions withstood by the interface.

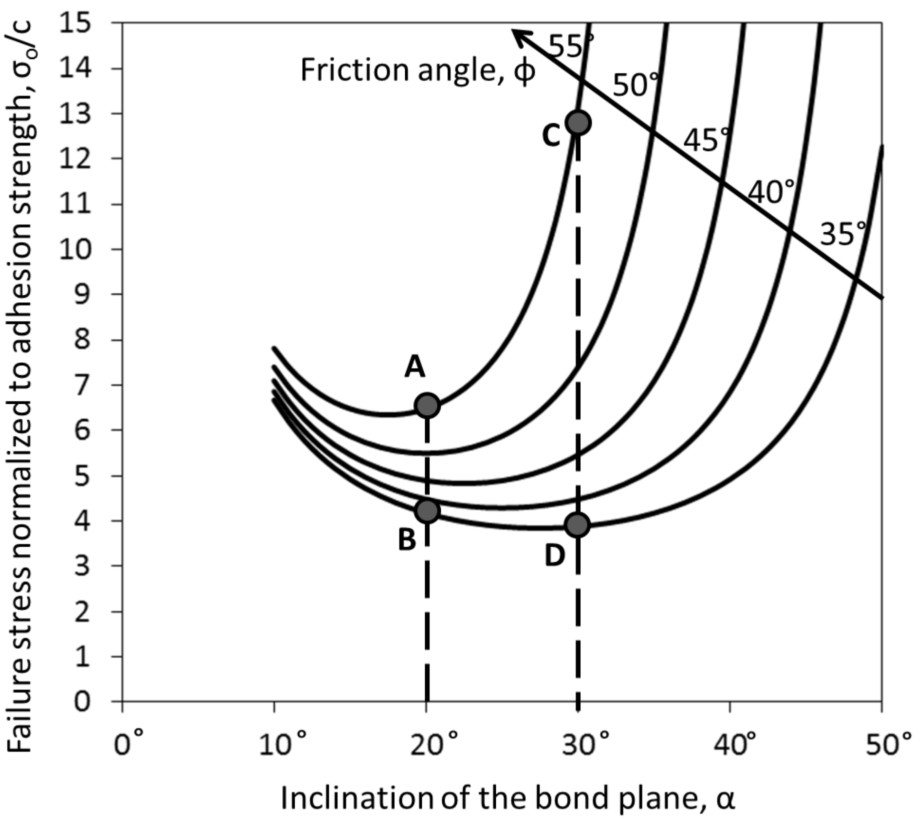


Figure 15: Prediction of the slant shear failure stress as a function of the inclination of the bond plane and the interfacial friction angle, according to Austin et al. [11].

Substrate-repair compatibility

Compatibility is a broad concept related to how the different parts of a composite system interact with each other to withstand the effects of external and internal factors. In fact, synergy between the different components of the repair system can either improve the resistance to external loading and environmental attack or enhance the vulnerability (Figures 5 and 6).

Compatibility can be defined as a balance of physical, chemical and electrochemical properties and dimensions between a repair material and the existing substrate that will ensure that the repair can withstand all the stresses induced by volume changes and chemical and electrochemical effects without distress and deterioration over a designated period of time. Therefore, compatibility ensures that the combined system withstands the applied stresses and maintains its integrity and protective properties against environmental exposure. Dimensional stability, chemical, electrochemical and permeability compatibility are amongst the most important characteristics which need to be considered when selecting a repair material (Figure 16) [35]. In this section, we elaborate on the different types of compatibility, and the factors the designer must consider when selecting a compatible repair material.

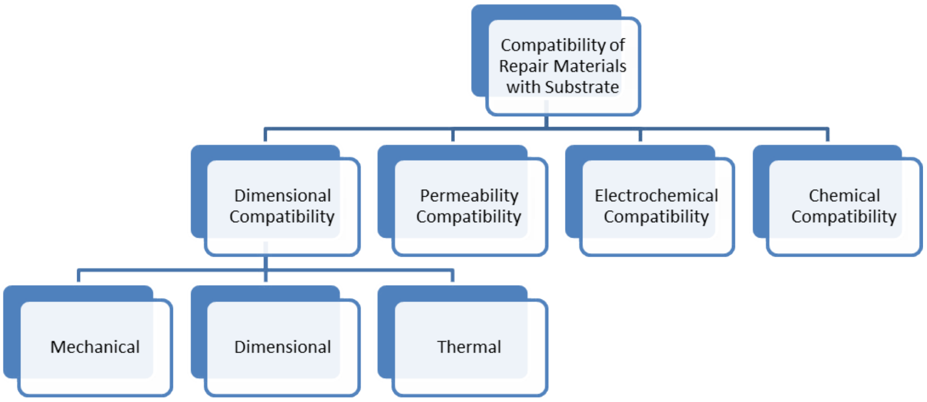


Figure 16: The most important types of compatibility that need to be considered in repair design.

Dimensional compatibility: The dimensional stability of a repair material is one of the most important factors and is controlled by volume changes due to shrinkage, thermal expansion, and the effects of creep and modulus of elasticity. An ideal repair material would be volumetrically stable, i.e., it would undergo neither shrinkage nor expansion once in place, and would display similar modulus of elasticity and thermal expansion characteristics to the substrate concrete.

The importance of volume changes due to shrinkage of repair materials becomes apparent as high shrinkage causes stress at the repair interface and leads to cracking and de-bonding and, indeed, can cause total failure of the repair system. Similarly, an incompatibility in the thermal coefficients of the new and old materials will also lead to interfacial stresses, Figure 17.

Ideally, a material that is not restrained at all could deform and develop strains due to volume changes induced by shrinkage, moisture movements and thermal variations. No stress and crack would occur under a regime of free deformation. However, internal and external restraints tend to counteract free deformations, and, as a consequence, stresses arise within the material itself as well as along the contact area with other adjacent materials. External and internal restraints can be caused by [36,37]:

- Adjacent materials undergoing different deformations (Figure 10). For instance, shrinkage in the new repair is counteracted by the old substrate which likely has already shrunk as much as it had to. Also, steel rebars (which do not undergo shrinkage) represent one more restraining factor. Furthermore, materials with different thermal properties tend to undergo different deformations due to thermal gradients and those differential volume changes produce one more restraining factor.
- Non-uniform distribution of strains within the material itself. For instance, drying shrinkage is not uniform within a concrete element, with water evaporation occurring faster in the outer parts and slower in the core. Also, the temperature increase associated with the heat of cement hydration at the very early age of a concrete element is not uniform due to the heat exchange with the outer environment.

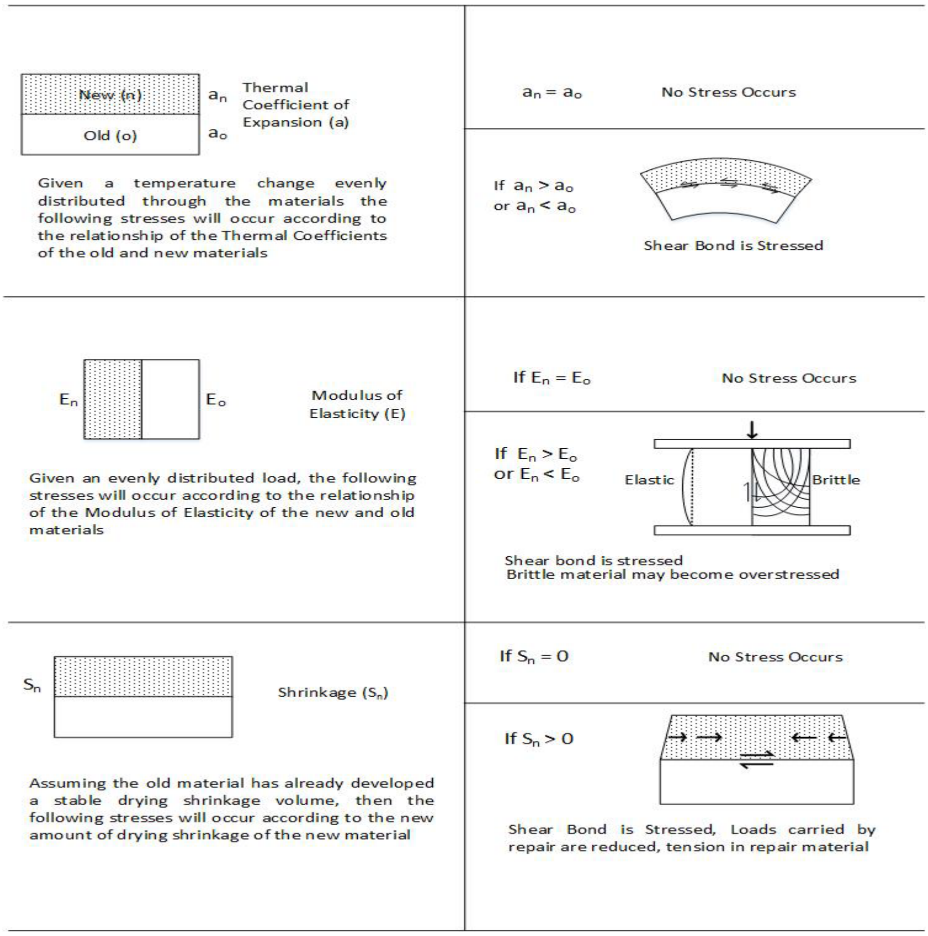


Figure 17: Different types of volumetric compatibility [38].

The modulus of elasticity is the property which controls the load distribution in a combined system composed of two materials. Low modulus materials deform more than high modulus materials under a given load. When the external load (compressive or tensile) is applied parallel to the bond line (Figure 18), materials with different elastic moduli will transfer stresses from the low modulus material (lower load-bearing effectiveness) to the high modulus material, leading to stress concentration and failure of the high modulus material [39]. When the external load is applied perpendicular the bond line (Figure 18), the low modulus material will undergo greater barreling and create dimensional incompatibility. Similarly, if the perpendicularly applied external load is tensile, mismatching elastic modulus is likely to cause adhesion failure. The higher modulus material imposes a severe constraint on the transverse contraction of the lower modulus material. High concentrated stresses can then occur in the lower modulus material very close to the interface and initiate failure. Therefore, when selecting a repair material, the designer should ensure that both substrate concrete and the repair material possess similar elastic moduli [40].

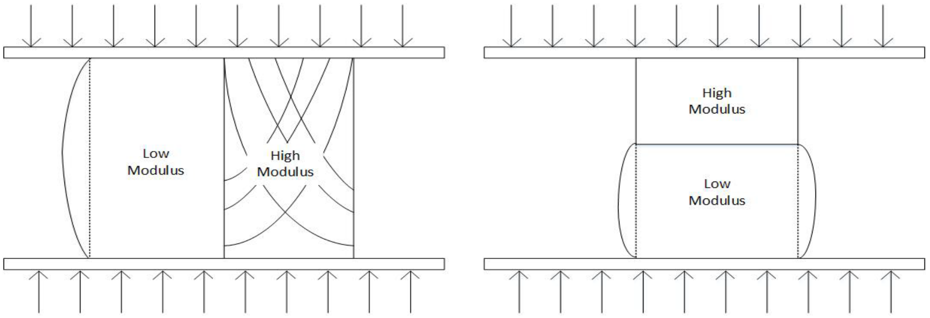


Figure 18: Effect of elastic moduli mismatch [41].

There is laboratory evidence that an elastic modulus mismatch can enhance the stress gradient along the interface. Robins and Austin [32] performed an experimental program to compare the bond performance of two plain and two polymer-modified cement mortars for patch repairs. All the repair mortars had a compressive strength lower than that of the concrete substrate. Their results clearly show the effect of the stiffness mismatch between substrate and repair on the normal and shear stress distribution at the interface: the higher the mismatch, higher the stress gradient. The trend is for an increase in stress at the ends of the interface, with the maximum normal and shear stresses occurring at the side where the repair material is the lowest.

Finally, depending on the application, volumetric changes due to creep may also need to be considered. Creep is defined as a time dependent strain increase under a sustained stress. Therefore, creep considerations are generally more important in structural repairs rather than nonstructural repairs. As creep tends to occur in the cementitious part of a repair material, consideration should be given to the amount of cementitious material used when designing a material, if creep is to be a concern. The effect of the creep deformation is to cause a shear stress at the bond line potentially causing debonding and failure. Interestingly, materials which exhibit creep behavior such as concrete will show relaxation behavior, that is a decrease in stress over time, under a constant creep strain.

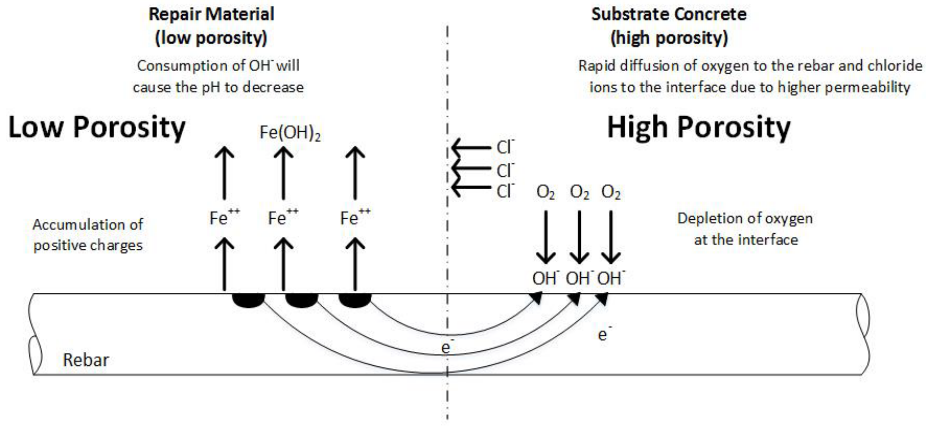
In general, a significant mismatch in the mechanical behavior of the existing structure and the new part added for repair should be always considered carefully, especially in the case of structural repairs. A situation of unbalance resulting from material and geometrical properties of the repair can compromise the final structural response. Also, when a new repair system is applied, the change in the balance of masses and weights could completely change the seismic response of the structure.

Permeability compatibility: Permeability is the capability of the concrete to transport liquids or vapors. Permeability of concrete is mainly governed by the capillary pores in the cement paste. Pores that are too large will result in a high permeability, while pores that are small will result in a low permeability. Capillary porosity is governed by the initial w/c ratio of the concrete mix. Therefore, mixes with low w/c ratio will have lower permeability. It is important to recognize however, that permeability may not be a constant material property. Cracks/micro cracks may occur in the cement matrix with time due to the degradation phenomena described in Section 3. As much as possible, the repair materials should have similar vapor transmission capabilities as the base material. Conventional wisdom dictates that concrete structures should have as low permeability as possible to prevent ingress of deleterious materials, and increase durability. However, careful consideration should be given to permeability of the repair material when designing a repair system. Large impermeable patches can impair the escape of moisture from the base concrete, leading to blistering at the bond line or within the weaker of the two materials [42]. In climates with deep frost penetration, if a low permeability repair material is used, deterioration of the critically saturated substrate concrete can result in failure of the substrate concrete and delamination of the repair material, with the substrate concrete still bonded to it [10]. Also, as mentioned in the previous section, if there is a large permeability differential between the repaired area and the rest of the concrete, the risk of premature failure due to corrosion may increase.

Electrochemical compatibility: Corrosion is an electrochemical process, as discussed before (Section 3). Conduction of electrical current in concrete occurs via ions in the evaporable water within the concrete, and any increase in the volume of water and concentration of ions increases the conductivity. An important aspect of repair performance relates to the ability of the repair system to inhibit subsequent corrosion of reinforcement, both within the repair area and in the surrounding non-repaired reinforced concrete. The first task to perform when a repair is applied is therefore to remediate the existing rebar, and re-establish an electrochemical balance (either through electrochemical chloride extraction or electrochemical re-alkalization). Eventually, the new repair material will have to restore passivation, resist ingress of contaminants, and be electrochemically compatible.

Electrochemical incompatibility is associated to a difference in the conductivity of the repair and base materials, which causes certain areas to become isolated from adjacent undamaged areas. The difference may actually cause the rate of corrosion to accelerate and cause premature failure.

If there is a large permeability differential between the patched area and the rest of the concrete, due to the buildup of O_2 and Cl^- ions in certain areas, anodic regions are produced on either side of the patch, accelerating the rate of corrosion and causing premature failure of the patch or adjoining concrete [42] (Figure 19). Similarly, a situation of chloride contaminated substrate generates an electrochemical potential difference that will promote the corrosion process.



(b) Later stages – high corrosion activity due to the uneven distribution of oxygen and chloride ions

Figure 19: Electrochemical incompatibility [42].

Chemical compatibility: Chemical compatibility involves selection of a repair material such that it does not have any adverse effects on the repaired component or structure. All aspects of chemical compatibility must be considered in the selection of repair materials. For example, when concrete that is being repaired includes potentially reactive aggregates, a repair material with low alkalinity must be specified in order to avoid alkali-silica reactions [38,42].

Summary

Deterioration and failure of repaired structures represents a concern of our time. Worse still, application of repairs can in fact exacerbate deterioration or reduce the structural performance.

In order to be effective, the repair process needs to be addressed in a holistic manner. Before applying a repair, it is essential to perform a full survey of the condition of the existing structure, and the major factors that are affecting its performance and durability. Engineers designing repairs need to be aware of the internal and external factors which necessitated the repair in the first place and appreciate the constant interaction that occurs between the different parts of the system (Figures 5-7).

Finally, to ensure longevity of both new and repaired constructions, it is important for building managers to constantly monitor the structural health, and plan accurate maintenance at regular intervals so as to avoid the need for costly and complicated measures.

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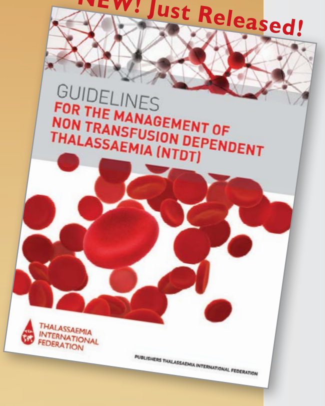

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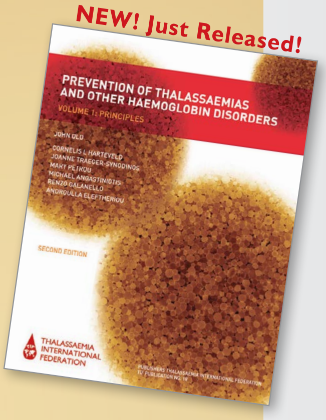

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