RELIABLE CONCRETE REPAIR-A CRITICAL REVIEW

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ABSTRACT
This paper highlights the importance of achieving durable and long-term predictable repair of reinforced concrete structures. The performance of concrete repair in past and current engineering practice, including all types of repair and application of different materials, is often unsatisfactory. One of the reasons for this lays in the fact that knowledge regarding bonding mechanism and bond properties at the interface of repair material and concrete substrate is still lacking. This paper intends to give a critical review on the parameters which have to be taken into account when designing appropriate connection between concrete substrate and new repair material. What is more important than achieving a strong bond between overlay and concrete substrate, is reaching monolithic behaviour which should ensure an even distribution of stresses and uniform load transfer in the repaired structure. As a consequence, this paper does not emphasize just tensile strength of bond, which is in literature often stated as a fundamental issue, but also other important matters for controlling debonding mechanism in concrete repairs. One of the promising repair materials which has been developed recently is Engineered Cementitious Composite. Therefore, application of this material is additionally overviewed.

INTRODUCTION
Structures with poor concrete quality are susceptible to premature deterioration which results in early requirement of repair. It is estimated that around 50% of Europe's annual construction budget is spent on refurbishment and repair (Tilly and Jacobs 2007). The demand for maintenance and refurbishment is additionally emphasized considering the fact that the majority of concrete structures built in 1960s and 1970s has already exceeded their designed service life. Therefore, achieving durable and reliable repair of existing concrete structures is one of the biggest challenges in civil engineering today.

The aim of concrete repair is to restore the load carrying capacity of a concrete structure or a member (Bissonnette, Courard et al. 2011) and to maintain its function and durability for a specific period of time. Lately, in connection with a sustainability, shift towards integrating maintenance and increasing the designed service life of the structure was made (Heinemann 2012). According to the European standard for repair (EN1504-1:2005), repair products and systems can be divided in two main groups: non-structural and structural, depending on whether applied to restore the geometric and aesthetic aspect, or structural integrity and durability of the structure (element). In this paper the emphasis is on patching as the most commonly used repair technique which can be applied in both structural and non-structural repair. This method consists of replacing the lost, unsound or contaminated concrete with the appropriate repair material (Rodriguez, Munoz et al. 2006).

The restored fragment should not be "an alien body" in original concrete (Król and Halicka 1996). It needs to be compatible with the concrete substrate and to have sufficient bond strength in order to enable uniform transfer of stresses in the system. Regarding that, concrete repair is a complex problem that requires the designer to understand concrete properties both on micro-structural and macro-structural level. Therefore, multi-disciplinary knowledge based on mechanics, chemistry, and physics needs to be linked and combined in order to make a step toward achieving durable and long-term predictable (reliable) repair.

According to the present state-of-the-art report, main criteria for performance of repairs are stated. Important issues causing premature failures of repairs are indicted. In recent years, Engineered Cementitious Composite (ECC) has been developed as one of the promising materials capable of enduring some of the critical shortcomings of the repairs (Li, Horii et al. 2000). Therefore, in this paper, some of the most important benefits and drawbacks of using this material in concrete repairs are overviewed (Li 2008; Li 2009).

CAUSES OF REPAIR FAILURES IN CURRENT ENGINEERING PRACTICE

According to the ConRepNet report (Tilly and Jacobs 2007) the performance of repaired concrete structures in the past and current engineering practice is disappointing. Case histories and data provided by this investigation are especially valuable as they provide information of performance of repairs designed and made under pressures imposed by real site conditions. The most common types of repair were patching (60% of repairs), coating and crack injection. 50% of reported repaired structures failed, most of which within only 10 years. Failures of repair were attributed mainly to:

1. incorrect diagnosis of underlying problem
2. incorrect design of repair
3. incorrect choice of the applied repair material
4. poor workmanship

Misidentification the underlying cause of damage is the first step toward unsuccessful repair. What makes this problem difficult is considering and understanding all factors involved in the deterioration process (deterioration mechanisms, environmental exposure conditions, mechanical loading, etc.). The assessment of the defects and establishment of extent of damage have to be properly done (EN1504-9:2008 ; Król and Halicka 1996; R.T.L.Allen, S.C.Edwards et al. 2005; Tilly and Jacobs 2007). Investigation of reasons of damage implies gathering information by different methods, from visual examination and studying records to testing in the field (destructive, semi-destructive and non-destructive measures). The European standard for repair (EN1504-9:2008) classifies some common causes for deterioration and factors that influence it (Table 1). It has to be noted that the table provided here does not give details on each deterioration mechanism which need to be thoroughly examined for the particular case.

Table 1: Common causes of defects (EN1504-9:2008)

Concrete				**Reinforcement corrosion**		
Mechanical	**Chemical**	**Physical**	**Fire**	**Carbonation**	**Corrosive contaminants**	**Stray currents**
Abrasion	Alkali-aggregate reaction	Freeze/thaw		Cement content & type	At mixing: chloride salts	
Fatigue		Thermal effects				
Impact	Aggressive agents (e.g. sulfates, salts,	Salt crystallization		w/c ratio	From external environment: sea water, road salt, other contaminants	
Overload		Shrinkage		Curing		
Movement (e.g.		Erosion		Rainfall		
	Biological action	Wear		Temperature & humidity		
Explosion						
Vibration						

Adequate choice of the repair material is also essential for achieving durable repair. They are generally classified as cementitious materials, polymer modified cementitious materials and polymer concrete. In this review, polymer modified cementitious materials and polymer concrete are considered together as polymer based materials. There is no universal repair material which can be applied in each case. Every damaged structure imposes different demands on the properties and repair material should be properly selected to meet these requirements (Zhou 2010). Criteria for choosing a repair material are the cause of damage, environmental conditions, desired service life, cost and availability, compatibility with the substrate, curing period, resistance to aggressive environment, hardening time, etc. Mechanical properties of a repair material are also very important as they influence on magnitude of stresses induced by differential shrinkage. All of the stated factors are classified (Table 2) with the advantages (indicated by dark color) for the specific demand. Generally, cement based materials show good performance as they fulfill one of the most important requirements-compatibility with concrete substrate. They are cost effective and easily available. On the other hand, they demand longer curing period than polymer based materials, and induce larger shrinkage, especially when no coarse aggregates are used. Polymer based materials show superior behavior in aggressive environments, have better mechanical properties, excellent bond properties, faster hardening and lower permeability. Although lower permeability has beneficial influence on durability, it has to be carefully considered as the moisture could be entrapped by the repair material (Heinemann 2012). Polymer based materials cannot be used at high temperatures and are harder to finish and place than conventional cement based materials (Martinola, Sadouki et al. 2001; Vaysburd, Emmons et al. 2004; Li 2009; Zhou 2010). Also, from the aesthetic point of view, use of polymers is not desirable as they have different appearance than conventional concrete and, moreover, when epoxies are used, the color can change when exposed to UV-light (Heinemann 2012). In addition, it has to be emphasized that, although the use of polymer based materials has increased significantly in recent years (probably as a consequence of the pronounced indication by the suppliers that they have advantages over cement based materials), this is not supported by the evidence from past performance. According to ConRepNet report (Tilly and Jacobs 2007), 55% of patched repairs with cement based materials failed, compared to 50% with polymer based materials. It seems, therefore, that this marginally better performance of polymer based repairs does not justify their use, considering the higher costs. As a conclusion, there is still an open question about advantages considering bond properties, durability and general performance of each repair material.

Table 2: Comparative properties of cemenetitious materials and polymer based materals

Repair material / **Properties/behavior**	**Cementitious materials (CM)**	**Polymer-modified CM and polymer concrete**
Mechanical properties		
Shrinkage		
Comparable properties to substrate		
Curing period		
Cost		
Availability		
Placing and finishing		
Aggressive environment		
Aesthetic aspect		
High temperature		
Durability	?	

The problem of early failure of repair very often lies in a gap between expected properties of repair materials and performance at the construction site. Material properties are usually prescribed by suppliers, verified by experiments in laboratory conditions, but applied at the certain structure or element without considering real exposure conditions and complexity of the specific problem. Measured properties are additionally greatly dependent on used test method, test set-up and loading rate. For instance, several different testing procedures are applied in order to obtain bond strength between new and original material, but little information is available about comparison of these test methods and the resulting bond strength values (Momayez, Ehsani et al. 2005). Consequently, very often, the true material property of the product for the desired application can be significantly overestimated.

Other problems affecting poor performance of repair are execution conditions and poor workmanship. Although repair techniques have been continuously improving by new repair methods and materials on the market, the hope for better performance at the construction site turned out to be illusionary. The use of adequate design and appropriate materials is a prerequisite but not the only limiting factor for reliable repair. Therefore, there is an urgent need for technical training and skills improvement of field personnel as they represent truly the backbone of the concrete repair industry (Vaysburd, Emmons et al. 2004; Tilly and Jacobs 2007).

PARAMETERS INFLUENCING THE PERFORMANCE AND RELIABILITY OF REPAIR

Concrete repair implies integration of the new material with old concrete in order to form a composite system capable of enduring exposure to service loads, environment and time. Successful repair should enable uniform behavior and performance of multi-layer system as a monolithic one. What makes this goal difficult are differences in age, properties and performance of two materials.

After placing the repair material, the bond starts to develop in the contact area between two materials. This results in gradual building up restraint of the overlay in the contact zone. On the other hand, as a consequence of hydration and drying, repair material tends to shrink. Since the movement is restrained by already hardened concrete substrate, stresses start to increase in the repair material. These stresses, induced by differential shrinkage between drying repair material and old concrete substrate, are considered to be main cause of premature failure of repair (Martinola, Sadouki et al. 2001; Li 2009; Zhou 2010; Heinemann 2012). Differential shrinkage damage depends on many factors, some of which are the age of concrete, temperature gradients, moisture variations, matching properties of repair and substrate, boundary conditions (restraints), magnitude of induced stresses, strain capacity, etc. A number of analytical models for bonded overlays subjected to differential shrinkage have been developed (Beushausen and Alexander 2007; Beushausen and Alexander 2007; Zhou, Ye et al. 2008; Denarié, Silfwerbrand et al. 2011). By experimental examination (Denarié, Silfwerbrand et al. 2011), relaxation was found to be very important as it releases approximately 40-50% of tensile overlays stresses induced by shrinkage.

Depending on the achieved properties and mutual interaction between two materials, stresses can be differently distributed and give different outcome in overall repair system (Figure 1). If the repair material is too strong compared to the original concrete, there is higher probability of debonding. Additionally, by increasing the bond strength, the debonding mechanism is delayed, but the level of constrain and therefore cracking tendency in repair material is enhanced.

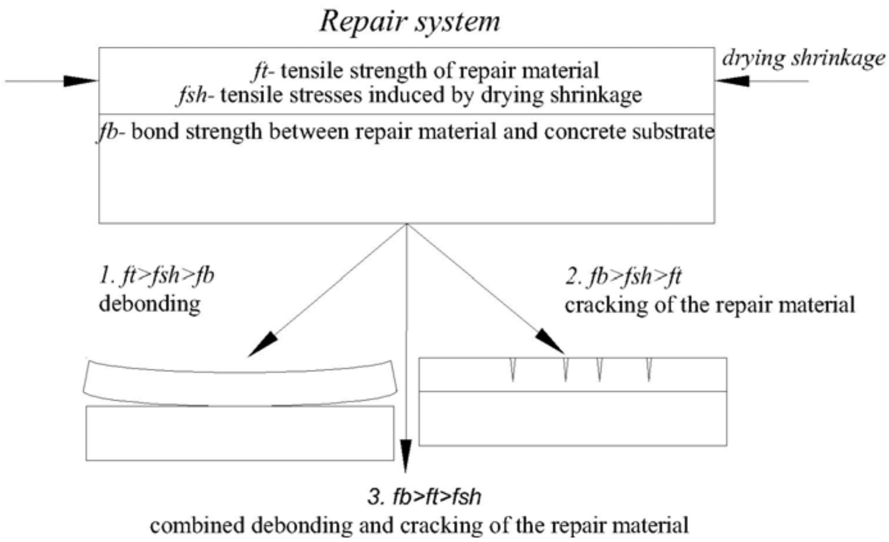

Figure 1: Damage mechanisms in repair systems

Repair patch dimensions, such as area and thickness, can also have an influence on the performance of repair (Zhou 2010; Bissonnette, Courard et al. 2011). Large repairs tend to crack more easily than smaller repairs. Thickness is also likely to influence the bond stress by thickness dependent shrinkage (Courard et al. 2011). According to an analytical model for shrinkage induced stresses developed by (Zhou, Ye et al. 2008), a thinner overlayer of the repair material is more prone to cracking, while the thicker one has more pronounced probability of interface delamination. What has to be determined and examined is how large the influence is of each of these two different mechanisms of damage on the likelihood of a bond failure. In other words, if a certain amount of damage is inevitable, which mechanism is more dangerous regarding overall performance of the repair.

Considering all stated, crucial parameters for achieving reliable performance and durability of the repair are:

- compatibility of properties of repair material and concrete substrate
- sufficient bonding mechanism and bond properties at the interface.

Compatibility

Compatibility is a balance between deformational, physical, chemical, electrochemical and aesthetic properties between a repair material and existing substrate which needs to ensure that repair system withstands stresses induced by restrained volume change, chemical and electrochemical effects without premature deterioration (Vaysburd and Emmons 2006).

Otherwise, incompatibility may result in initial tensile stresses that either crack the repair material or cause debonding at the interface. Dimensional compatibility, which includes drying shrinkage, thermal expansion, creep, and modulus of elasticity, is the most significant component. Important matching properties of concrete substrate and repair material are stated (table 3).

Table 3: General requirements of patch repair materials for structural compatibility (Emberson and Mays ; Vaysburd, Emmons et al. 2004; Li 2009)

Property	Relationship of repair mortar (R) to concrete substrate (S)
Strength in compression, tension and flexure	$R \geq C$
Modulus in compression, tension and flexure	$R \approx C$
Poisson's ratio	Dependant on modulus and type of repair
Coefficient of thermal expansion	$R \approx C$
Adhesion in tension and shear	$R \geq C$
Curing and long-term shrinkage	$R \leq C$
Strain capacity	$R \geq C$
Creep	Dependent on whether creep causes desirable or undesirable effects
Fatigue performance	$R \geq C$
Chemical reactivity	Should not promote alkali-aggregate reaction, sulfate attack, or corrosion of reinforcement in the S
Electrochemical stability	Dependant on permeability of R.and chloride ion content of S

Lower modulus of elasticity in the repair material compared to the concrete substrate is desirable in case of non-structural repairs, but not in case of structural repairs. When the repair material is intended to share load with the existing structure, elastic modulus should be equal.

Here it has to be emphasized that compatibility is not the same as the similarity in properties. Rule of repairing “like with like”, is wrong (Vaysburd and Emmons 2006). Bad concrete should not be repaired with similar one. Also, considering different exposure conditions and loading history which had great influence on developing properties (mechanical, chemical, electrochemical), making concrete with similar properties is practically impossible. Therefore, compatibility is rather the capacity of mutual tolerance between two materials in order to achieve unique action, than similarity in properties which enables the same response of the components in a system.

Bond strength and bonding mechanism in transition zone

Parameters that affect bond strength and bond development at the interface between concrete substrate and repair material are:

- Adhesion force
- Moisture transport

Adhesion

According to the European Standard (EN1504-10:2004), bond is defined as the adhesion of the applied product or system to the concrete substrate. In that aspect, adhesion can be considered as a fundamental issue in repair of concrete structures(Czarnecki 2008). In the European Standard for repair (EN1504-3:2005), it is stated that tensile bond strength should be at least 2 MPa for structural and 1 MPa for non-structural repairs. Properties of both repair material and concrete substrate, as well as exposure conditions, have an influence on achieved adhesive strength in repair system (Table 4) (Czarnecki 2008).

Table 4: Factors affecting adhesion between concrete substrate and repair material

Concrete substrate	Surface preparation	Mechanical strength, surface roughness, microcracs, porosity, saturation level, impurities, etc.
Repair materials	Workability, setting shrinkage, thermal expansion, elastic modulus, creep, etc.	
Environmental impact	Temperature level and change in temperature, humidity level and change in humidity, curing time, mechanical loading, degradation (ageing, carbonation,	

Very important step in achieving sufficient level of adhesion is appropriate surface preparation of concrete substrate. The first step should be identification of unsound/contaminated concrete, and its removal. After that different surface treatment are applied in order to clean the surface and accomplish appropriate roughness of concrete substrate: hammering, sandblasting, hydrojetting, scarifying, acid-etching, shotblasting (Behfarnia, Jon-nesari et al. 2005; Bissonnette, Nuta et al. 2008; Perez, Bissonnette et al. 2009). It has to be noted that some of the impacting methods such as jack hammering can induce microcracking and surface damage which "easily outweighs the benefits of an increased roughness" (Courard 2000; Bissonnette, Nuta et al. 2008). According to (Czarnecki 2008), fundamental effects of surface roughness are mechanical interlocking and contact angle modification between concrete substrate and repair material. It affects the geometric profile of the interface, increasing the contact surface area between two materials and enhancing the adhesion in repaired structure (Zhou 2010). Therefore, the surface roughness used to be considered to have a major influence on adhesion between two materials. But, according to bond tests conducted by (Bissonnette, Courard et al. 2011), surface roughness has only a minor influence on the adhesion. Results show that average bond strength is approximately equal but interface failure was more frequent in smoother surfaces. In addition, (Perez, Morency et al. 2009) stated that increase of roughness does not enhance the adhesion but reduces the risk of debonding in repaired structures. Regarding that, they concluded that high adhesion appears to be insufficient without adequate roughness of concrete substrate to prevent debonding at the interface. (Bissonnette, Courard et al. 2011) stated that there might be a threshold value for roughness, above which further improvement of the roughness does not enhance adhesion between two materials. It seems that the influence of the surface roughness is not clarified yet as it is difficult to separate and observe its influence independently from other parameters that affect bonding mechanism. Therefore, further research on this factor is still needed.

Adequate fluidity and workability are paramount properties of the repair material which influence the developing adhesion force. Lower viscosity, lower contact angle and higher superficial tension of the repair material enable faster spreading, penetration into the waviness profile of the concrete substrate and higher interaction area between two materials (Courard 2000; Garbacz, Górka et al. 2005). As a viscosity of repair material increases in time, it is very important to enable contact between repair material and original concrete as soon as possible (Bissonnette, Courard et al. 2011).

Adhesion and, therefore, strength and integrity of the bond depend not only on physical and chemical characteristics of the repair material and concrete substrate, but also on the environmental conditions that the repaired structure is exposed to. Temperature and relative humidity of the environment have great influence on initial saturation level of concrete substrate. There is a widespread agreement to promote the “saturated substrate with dry surface” as one of the best compromises for achieving good surface preparation (Bissonnette, Courard et al. 2011). Curing period of repair patches, which has not been thoroughly examined and usually is neglected, is very important for achieving good adhesion. In practical situations it is suggested that curing period for cement based materials should last at least 3 days (Behfarnia, Jon-nesari et al. 2005). For the bridge deck overlays, this demand is even stricter, as (Silfwerbrand and Paulsson 1998) recommended a minimum of five days water curing.

In order to gain higher adhesion, Portland cement grout, latex modified Portland cement grout, and epoxy resins are sometimes used as a bonding agents (Bissonnette, Courard et al. 2011). But this implies than sometimes instead of one potential weak zone, two interfaces might be created. That is why (Bissonnette, Courard et al. 2011) stated that the use of bonding agents should normally be avoided. In addition, it has to be noted that application of different chemical substances cannot be the substitution for poor and inadequate workmanship.

Although all the factors discussed above can improve the adhesion, the highest bond strength does not mean the optimal behavior of a repair. What is more, defect sometimes has a positive effect in a way that it helps partially relieving stresses at the interface and reduces the level of constrains. Therefore, what is more important than achieving maximum adhesion between overlays and concrete substrate, is reaching monolithic behavior which should ensure an even distribution of stresses in repaired structure. To understand this, it is important to address development of the microstructure and mechanical properties at the interface between concrete substrate and repair material. The main parameter influencing this is moisture content and moisture flux between the repair material and original concrete.

Moisture transport

(Ye 2003; Sun, Ye et al. 2005) stated that microstructure of cement based materials could be described by the following parameters: degree of hydration, volume fraction and distribution of the total solid phase and the pore phase. These microstructural properties dominate further development of mechanical properties of cement based materials (Sun, Ye et al. 2005).

Interface zone presents a weak link in a repaired structure. (Pigeon and Saucier 1992) reported that the interface between old and new concrete is very similar to bond between aggregates and cement paste. Therefore, well known phenomenon called the “wall effect” could be expected at the interfacial zone between repair material and concrete substrate. One of the reasons for existence of this layer with high porosity can be explained by the loose packing of cement particles. Also, the concentration of small particles in the interfacial zone makes it possible that the degree of hydration in this zone is higher than in the bulk paste (Van Breugel 1991). The addition of ultra fines like silica fume and fly ash was found to be beneficial in a way of reducing porosity and therefore increasing microhardness in this weak zone. But, what makes the interface between the repair material and the concrete substrate more complex than interfacial zone between aggregate and cement paste, is the sorptivity of unsaturated concrete substrate. In other words, aggregates are usually impermeable, whereas concrete substrate is porous material which absorbs water from initially fully saturated repair material. Consequently, development of microstructure and mechanical properties in repaired systems is additionally affected by moisture transport between the two materials.

Mechanism of moisture transport in repair system consists of:

- Water loss due to drying of repair material
- Water loss due to ongoing hydration process in repair material
- Capillary absorption by concrete substrate

After placing of the repair material, it starts hardening. Its microstructure starts forming and process is driven by hydration. This causes continuous changes in phases present in the repair material (Koenders 1997). Due to a continuous change of pore structure with age and wide range of pore sizes present in cement paste, migration of moisture within concrete is more complex than in most other porous media (Xi, Bazant et al. 1994). Moisture transport is driven by difference in moisture content between repair material and surface, and between repair material and concrete substrate. Water will move from areas with higher to areas with lower water concentrations (Figure 2). What complicates the problem is that the diffusion coefficient, which determines the rate of transport, is dependent on moisture content in pore structure. In the literature, it is found that the diffusion coefficient decreases by about 10 to 20 times when passing from 90% to 60% pore humidity (Bažant and Najjar 1972). This makes the issue of moisture transport strongly non-linear. The diffusion coefficient of a concrete substrate is, therefore, dependent on the moisture content and the already formed pore structure of the hardened concrete, while the diffusion coefficient of the repair material is dependent on the moisture content and ongoing hydration which causes continuous change of the pore structure. On the other hand, diffusion affects the rate of cement hydration as it decreases the water amount available for further hydration process and slows down reaction. Initial water cement ratio in bulk repair material also decreases. Although, this can be beneficial, as the bond strength may increase (Zhou 2010), for low water to cement mixtures, there might not be enough water for further hydration. This may significantly affect the quality of the repair.

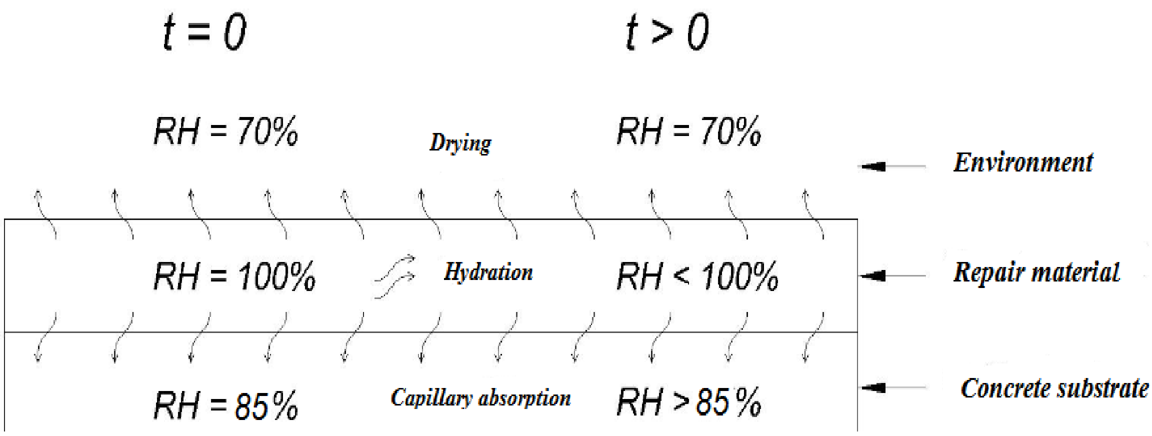

Figure 2: Moisture transport in concrete

In case the repair system is properly cured, the water loss by drying will be compensated and moisture transport will be driven just by capillary absorption of the concrete substrate. The absorption rate of the concrete substrate is influenced by its initial moisture content and concrete surface porosity. According to some experimental results (Courard and Degeimbre 2003), the rate of capillary absorption of the concrete substrate is also influenced by surface roughness of concrete substrate. It was observed that, due to higher penetration into cavities of concrete substrate, smoother surface enables better development of mechanical and chemical anchorage between concrete substrate (Courard and Degeimbre 2003. Further on, they concluded that higher roughness of concrete substrate demands better workability and fluidity of repair materials in order to achieve sufficient interlocking with concrete substrate.

By resolving moisture movement through new and old concrete, degree of hydration, local water-cement ration and pore structure at the interface can be determined. This way the key factor regarding bonding mechanism between concrete substrate and repair material would be obtained, giving useful information regarding quality and development of the bond. According to present literature review, microstructure properties and development at the interface are not investigated thoroughly (Zhou 2010).

ENGINEERED CEMENTITIOUS COMPOSITES-A NEW APPROACH FOR DURABLE REPAIR

Most of the past efforts have focused on reducing damage due to drying shrinkage in order to get durable repair. That was achieved either by reducing free shrinkage of the material, by increasing compressive/tensile strength of the repair material or by increasing bond strength between the repair material and the concrete substrate (Li 2009). All of these attempts resulted in only marginal improvements as they do not address inherent concrete behavior as a brittle material (Li ; Lepech and Li 2006; Li 2008; Li 2009). What is more, brittleness is even more pronounced in high-performance concrete, as it turned to be more prone to cracking. According to (Czarnecki 2008; Turatsinze, Beushausen et al. 2011), repair material as the rule should contain microfibers for enabling microcrack bridging property. Adding fibers to the repair material can decrease fragility, reduce shrinkage, increase abrasive resistance and bond strength (Zhao and Song 2011). This is especially important as a lot of authors (Martinola, Sadouki et al. 2001; Li 2003; Beushausen and Alexander 2007; Li 2009) indicated that elastic and viscoelastic properties are the target properties of repair material in order to obtain durable repair.

In order to answer these demands, (Li, Horii et al. 2000) recently introduced ultra ductile fiber reinforced cementitious composite, named Engineered Cementitious Composite (ECC). This material has promising properties regarding long-term behavior in repair systems. ECC is characterized by microcracking behavior with tight cracks raging around 60-100 μm, strain hardening behavior and a metal-like properties (high ductility) after the first cracking. Multiple cracking is an excellent feature in a view of stress relieving properties induced by deformational incompatibility between concrete substrate and repair material. High material ductility and damage tolerant behavior appear to provide strong structural behavior of repaired structures (Li, Horii et al. 2000). Therefore, ECC repair systems are discovered to effectively suppress: cracking and interfacial delamination due to restrained volume shrinkage, reflective cracking due to stress concentration from pre-existing concrete cracks and chloride transport that initiates corrosion of embedded steel (Sahmaran, Li et al. 2007).

According to (Li 2003), ECC has capability of sustaining large imposed deformation without damage localization. This is of paramount importance as repairs showed to be susceptible to differential deformations between original concrete and repair material. Also, tight crack width control enables increased durability of repaired structures. As the crack width is related to the water flow rate, one order of magnitude in crack width reduction can decrease water penetration by three orders of magnitude.

Comparing experimental results of repaired systems subjected to differential shrinkage (Zhou 2010), ECC material showed smaller crack widths than the most widely used repair material in the Netherlands, fiber reinforced polymer-modified mortar (FRPM). On the other hand, delamination length of ECC repair material is higher and achieved bond strength lower compared to FRPM. Obviously, weakness of the ECC material lies in insufficient adhesion to the original substrate. Therefore, proper bonding turns to be crucial parameter for reliable performance of ECC repairs (Li 2009; Zhou 2010). When applying ECC as a repair material, bond should be high enough to prevent debonding before cracking mechanism in this material. That is the only way by which benefits and advantages of this material in terms of durability, designed properties and predicted performance can be achieved. In order to reach appropriate bonding, understanding of the microstructure formation in the interface between the repair material and the concrete substrate is essential.

CONCLUSIONS

Based on the above discussion, following conclusions can be drawn:

- Identification of underlying cause of damage is the essential step toward achieving successful repair
- Link between properties of materials and the performance in real exposure conditions has to be made. Ways to improve communication between all people involved in the entire repair system (from scientists and academic workers to material suppliers, engineers and workers at the construction site) has to be achieved
- Neither high bond strength nor high strength repair material is crucial for a durable repair. A balance in the performance and uniform behavior which enable monolithic action between repair material and concrete substrate are preferential in order to achieve reliable repair.

- The most important properties of the repair material are its compatibility to concrete substrate, sufficient bonding and deformational capacity to withstand huge deformation induced by differential shrinkage
- There is still a lack of knowledge regarding bonding mechanism in repaired structure. Adhesion force is not the only factor influencing it. Microstructure development at the interface plays an important role in bonding. Considering all the parameters involved, ways to improve monolithic action between repair material and concrete substrate need to be defined.
- In order to improve overall behavior of ECC repair systems, better bonding between new and old material has to be achieved

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