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Procedia Engineering 54 (2013) 525 – 538

Procedia Engineering

www.elsevier.com/locate/procedia

The 2nd International Conference on Rehabilitation and Maintenance in Civil Engineering

Utilization of Ultra-High Performance Fibre Concrete (UHPFC) for Rehabilitation – *a Review*

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Abstract

Under normal circumstances, reinforced concrete structures (RCS) show excellent performance in terms of durability and structural behaviour except for the zones that are subjected to severe mechanical or cyclic loading and aggressive environmental conditions. Therefore the methods of rehabilitation or strengthening of these zones should be reliable, effective and economical. Today, many scientists, academics and engineers understood the extremely low porosity and low permeability characteristics of ultra high performance fibre concrete (UHPFC) giving its enhanced durability over high performance concrete (HPC), thus making it potentially suitable for rehabilitation and retrofitting problematic RCS. The advantages of utilising the technology of UHPFC in repairing works includes (i) decrease the working time needed for the rehabilitation works; and (ii) increase the serviceability and durability to an extent where the repaired structures can meet the expected design life of the structures, with minor preventative measure. This paper discusses and reviewing some of the most recent issues and findings using UHPFC as a repair material. The results of the findings will also be presented to prove that the UHPFC displays excellent repair and retrofit potentials in compressive and flexure strengthening and possesses high bonding strength and bond durability as compared with other types concrete.

Selection and peer-review under responsibility of Department of Civil Engineering, Sebelas Maret University

Keywords: Rehabilitation; Retrofit; Strengthening; Repair material; UHPFC.

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doi:10.1016/j.proeng.2013.03.048

1. Introduction

In the recent age, a highly developed infrastructure is vital for economic growth and prosperity. Many structures necessary to this infrastructure, especially those made of reinforced concrete, have suffered severe degradation since their construction due to the combined effects of freeze–thaw cycles, aggressive environments, de-icing salts, and significantly increased live loads. One of the most important problems faced by the civil engineers of today is to save, retrofit, and maintain these deteriorating structures. Implementation and development of new, cost-effective repair methods are required to extend the service life of these RCS (Emmons 1993, Emmons 1994, Green 200).

Industrialized countries have invested substantially in their RCS. These RCS were primarily designed to withstand the mechanical loadings, but it has also learned that these structures were also constantly subjected to physio-chemical phenomena that result in early deterioration and subsequently reducing its reliability to perform adequately (SAMMARIS 2005, SAMMARIS 2006). The early deterioration of RCS is a serious issue for any society, as it will put the public safety in jeopardy and the escalator repair cost will directly burden the future economy. In order to reduce this problem to the minimum and at the same time maintain most of functionality of these RCS, the frequency and extent of repair interventions have to be kept to the lowest probable level (Brühwiler 2005, Denariė 2005).

According to Denarié (2005) the example of using UHPFC to repair existing old RCS is increasing due to this material can be easily placed on-site. In general, UHPFC has extremely low porosity which results to an extremely low permeability and high durability, making it potentially suitable for rehabilitation and retrofitting reinforced concrete structures or for use as a new construction material (Alaee 2003, Farhat 2007, Farhat 2010).

The extremely low permeability of UHPFC associated with their outstanding mechanical properties made up the idea to use UHPFC to rehabilitate and strengthen those zones where the structure is exposed to high mechanical orcyclic loading and severe environmental condition. All other parts of the structures remain in normal structural concrete as these parts are subjected to relatively low critical exposure. Therefore, when this conceptual idea combine, it will greatly improves the serviceability and life-cycle costs reduction of the rehabilitated concrete structures (Brühwiler 2008, Denariė 2006, Rossi 2002). In term of structural applications, UHPFC contributes significantly towards increasing the stiffness and strength of the composite elements and thus the structural behaviour appreciation to its hardening behaviour under tension (Habel 2004).

UHPFC materials can be applied on both newly built concrete structures, or on existing ones for rehabilitation (Denariė 2006). Composite elements consist of UHPFC and normal concrete (NC) have a very high potential in the rehabilitation and modification of existing structures. In these elements, an UHPFC layer is cast on an existing concrete member in order to rehabilitate or adjust the structure. In brief, UHPFC is an advanced cementitious based materials with specifically modified properties, where its mechanical behaviour is outstanding with compressive strength more than 170MPa; uniaxial tensile strength more than 8MPa; flexural strength over 30MPa (Voo 2010, Voo 2011, Wuest 2006) recommended that the use of UHPFC in composite elements provides an increased stiffness under service condition and the high tensile strength of UHPFC produces a significant increase in ultimate force of the tested composite elements as compared to conventional normal concrete elements. The composite UHPFC-NC structures guarantee a long-term durability which helps to avoid multiple rehabilitation interventions on concrete structures during their service life (SAMMARIS 2005). Structural elements combining UHPFC and NC offer a high potential in view of rehabilitation and adjustment of existing concrete structures (Habel 2007). The main purpose of this paper is to give an overview on the most recent studies using UHPFC as a repair material

2. Ultra High Performance Fiber Concrete (UHPFC)

UHPFC is one of the breakthroughs in the 21st century in the field of concrete technology where this composite material providing an important improvement in strength, workability, ductility and durability when compared with normal concrete. According to (Uchida 2006), UHPFC can be defines as follow:

"The UFC is a type of cementitious composites reinforced by fiber with characteristic values in excess of 150 N/mm^2 in compressive strength, 5 N/mm^2 in tensile strength, and 4 N/mm^2 in first cracking strength. The matrix of the UFC is as follows: it should be composed of aggregates, whose maximum particle sizes are less than 2.5 mm, cement, and pozzolans and the water-cement ratio is less than 0.24. It contains reinforcing fibers of more than 2% by volume, whose tensile strength exceeds 2000 N/mm^2 , ranging 10 to 20 mm in length and 0.1 to 0.25 mm in diameter."

The improved characteristics of UHPFC is founded on the principle of (i) reducing the amount of free water in concrete matrix thus lead to less and smaller air voids, (ii) improved the concrete matrix homogeneity by removing all the coarse aggregate and replacing it with well graded fine sand and adding highly active pozzolanic material such as silica fume and (iii) introducing very high strength ductile steel fibers in the formulation (Emmons 1993,Rossi 2002, Voo 2010,Graybeal 2005, Parra-Montesinos 2005, Graybeal 2007a, Graybeal 2007b, Voort 2008).

2.2 Typical Mix of UHPFC

The properties of UHPFC are mainly achieved by the improvement of homogeneity of the mix, compare to normal concrete, through elimination of all coarse aggregates (Graybeal 2005). It is noted that the grain size distributions of cement, silica fume and sand have to be optimized in order to obtain high capacity and thus, a dense matrix with a very low permeability (Richard 1995). Very fine graded sand with a size ranging from 150 to 600 micrometers is dimensionally the largest granular material in the mix. The second largest particle is cement with an average diameter of 15 micrometers. Silica fume is the smallest particle used in the UHPFC, which is approximately one hundredth the size of a cement particle. The main function of the silica fume particles is to fill the interstitial voids between the cement and crushed quartz particles. Another fine particle is crushed quartz which has an average diameter of 10 micrometers. Steel fibers are dimensionally the largest components in the mix. The inclusion of steel fiber will improve the ductility of the mix (Graybeal 2005).

A typical mix design of UHPFC contains fine sand, Portland cement, silica fume, crushed quartz, steel fibers, superplasticizer, and water is presented in Table 1 (Voort 2008).

Table 1. UHPFC mix design components (Voort 2008)

Component	Typical Range by Weight (kg/m^3)
Sand	490 – 1390
Cement	610 – 1080
Silica Fume	50 – 334
Crushed Quartz	0 – 410
Fibers	40 – 250
Superplasticizer	9 – 71
Water	126 – 261

2.3 Properties of Ultra High Performance Fiber Concrete (UHPFC)

2.3.1 Tensile behaviour

UHPFC belongs to the group of high performance fiber reinforced cementitious composites (HPFRCC), but offers additional advantage of a very dense low-permeable matrix. Figure 1 shows the example on the uniaxial tensile test results for an UHPFC specimen, conventional steel fiber-reinforced concrete (SFRC), and conventional concrete. The UHPFRC exhibits a significantly increased tensile strength and strain-hardening behaviour as compared to other cementitious materials (Habel 2004).

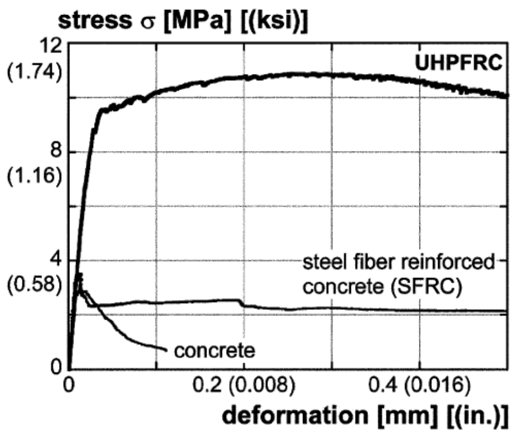

Figure 1. Uniaxial tensile behavior: comparing UHPFRC, conventional SFRC and conventional concrete (Habel 2004).

2.3.2 Flexural Strength

UHPFC has a remarkable flexural strength and very high ductility. According to Richard and Cheyrezy (Richard 1995) the ductility of UHPFC is 250 times greater than that of conventional concrete. The behaviour of UHPFC under flexure loading can be characterized by three phases that is (i) the linear elastic behaviour up to the first cracking strength of the material, (ii) a displacement-hardening phase up to the maximum load, and (iii) a deflection-softening phase after the maximum load is reached. Figure 2 shows a typical load-deflection diagram for UHPFC in bending with the typical phases labelled.

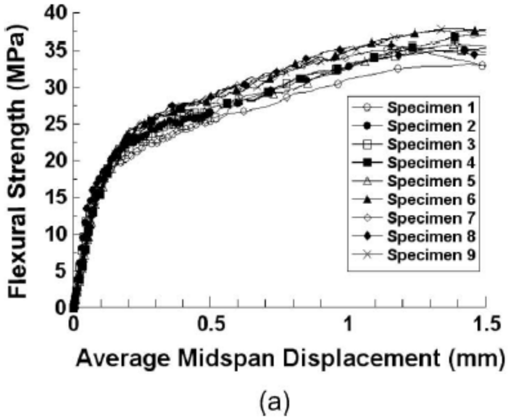

Figure 2. Flexural strength versus midspan displacement (Voo 2004), (a) for w up to 1.5mm and (b) full experimental curves.

2.3.3 Durability

The greatly improved microstructure of UHPFC not only results in higher mechanical strength but also leads to greater durability properties. This makes UHPFC both a high strength and a high performance material. The very low porosity of UHPFC, particularly capillary porosity, leads to great improvements in the durability properties of UHPFC (Voort 2008). From some previous researches, (Voort 2008) show in Figure 3 the various durability properties for UHPC are compared to HPC and normal concrete. The great durability of UHPC may lead to reduce maintenance costs for the material and a possible reduction in the cover concrete required to resist weathering effects compared to normal concrete.

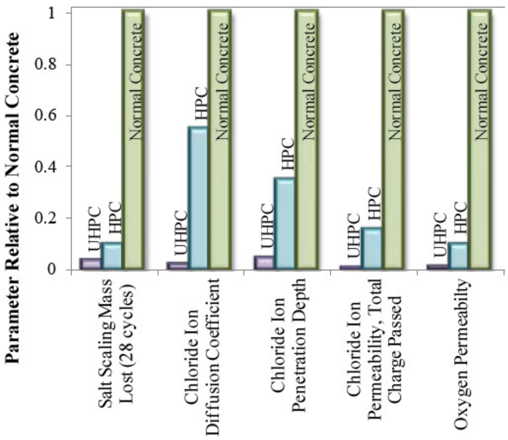

Figure 3. Durability properties of UHPC and HPC with respect to normal concrete (lowest values identify the most favorable material) (Voort 2008).

3. UHPFC in Rehabilitations

3.1 Introduction

For the last 30 years, most of the concrete structures expose to severe environmental conditions are required for strengthening or rehabilitation. Many of these severe environmental conditions are the result of cold climate conditions such as low temperature, freeze–thaw action and exposure to deicing salts etc. Because of this, the environmental durability of the repair materials and methods used in strengthening or rehabilitation applications are of greatest importance, especially in aggressive climates (Emmons 1993).

Rehabilitation and strengthening of deteriorated concrete structures is a heavy burden from the socio-economic viewpoint since it also leads to significant user costs. As a result, novel concepts for the rehabilitation of concrete structures must be developed. Sustainable concrete structures of the future will be those where the interventions will be kept to the lowest possible minimum of only preventative maintenance with no or only little service disruptions (Brühwiler 2008). Hypothetically this can be achieved when UHPFC is being used in rehabilitation works, where the outstanding UHPFC properties in terms of durability and strength are fully exploited. During this rehabilitation works, UHPRC can be used to stiffen and strengthen the zones where the concrete structures are exposed to severe environmental conditions such as deicing salts, marine environment; and high mechanical loading such as regions subject to impact loading, concentrated loads and fatigue loads. All other parts of the concrete structure remain in ordinary structural concrete as these parts are subjected to relatively moderate exposure. This concept may also applicable to new construction, necessarily leads to composite structural elements combining conventional reinforced concrete and UHPFC (Brühwiler 2008).

3.2 UHPFC as a repair material

Selecting repair materials for concrete structures requires an understanding of material behaviour in the uncured and cured states in the anticipated service and exposure conditions. One of the greatest challenges faced by a successful performance of repair materials istheir dimensional behaviour relative to the substrate. Relative dimensional changes cause internal stresses within the repair material and within the substrate. High internal stresses may result in tension cracks, loss of load carrying capability, delimitation or deterioration. Particular attention is required to minimize these stresses and to select materials that properly address relative dimensional behaviour (Neville 1995).

Over the last two decades, significant efforts to improve the behaviour of cementitious materials by incorporating fibers have led to the appearance of UHPFC. These novel building materials give the structural engineer with an unique combination of (i) very high mechanical strength; (ii) extremely low permeability which mostly prevents the ingress of detrimental substances such as water and chlorides and in addition. UHPFC have excellent rheological properties in the fresh state allowing for easy casting of the self-compacting fresh material with normal concreting equipment. Consequently, UHPFC have clearly improved resistance against severe environmental and mechanical loading and offer high potential for concrete structures with significantly improved structural resistance and durability (Oesterlee 2007). UHPFRC is a promising material for the rehabilitation of existing concrete elements. The advantage offered by UHPFRC is their low permeability that prevents the ingress of detrimental substances and should therefore significantly improve the durability of composite members when compared to normal concrete (Habel 2007). The rapid strength gain of UHPFC is an important characteristic for speed construction. Typically UHPFC materials are capable of gaining compressive strength of 80MPa and 100MPa after 1 day and 2 days respectively, of ambient air curing (Voo 2011), which significantly surpasses conventional overlay materials, which is also far greater than conventional concrete and high performance concrete strength. Lee et al. (2007) reported from there experimental findings that reactive powder concrete (RPC) displays excellent repair and retrofit potentials on both compressive and flexure strengthening due to its possesses high dynamic modulus value, high bond strength capacity and outstanding bond durability as compared with other types of concrete. The adhesion strength between the RPC and the steel reinforcement is also much higher than that for the other types of concrete.

3.3 Suitability of UHPFRC for rehabilitation

A well established principle for the application of a rehabilitation layer on an existing substrate is to try as far as possible to select a new material with mechanical properties close to those of the substrate. With this respect, UHPFC with a high elastic modulus up to 55GPa might appear to be inappropriate. This argument may not be irrelevant, however wrong for several reasons (SAMMARIS 2006).

- First of all, in the elastic domain, the elastic modulus of UHPFC is around 60% larger than that of normal concretes (55GPa /35GPa = 1.57). This difference is however largely compensated by the improved tensile strength of the UHPFC (10 MPa for the matrix and up to 14 for the composite compared to 3 to 4 MPa for normal concrete, (SAMMARIS 2006).
- Secondly, UHPFC exhibit a significant strain hardening, several times larger than its maximum elastic elongation, which is not the case for normal concrete.
- Finally, UHPFRC exhibit significant visco-elasticity at early age, compared to high performance concretes (Habel 2004). Restrained shrinkage tests on UHPFRC specimens at an early age show that the development of stresses under full restraint remain moderate (45% of the tensile first crack strength) with respect to the uniaxial tensile characteristics of the UHPFC (Kamen 2005). The ultimate shrinkage of UHPFC is less than normal concretes (in the range of 600 μm/m = 0.0006 at 6 month) and the driving force for this shrinkage is also lower. In UHPFC, with a very low water/binder ratio, drying shrinkage is negligible after 8 days of moist curing. Therefore, the main source of deformations in UHPFC is autogenous shrinkage, instead of drying processes in usual concrete. In addition, strain hardening UHPFC turn out to be an excellent compromise of density, high tensile strength and significant deformation capability, perfectly suited for combination with normal concretes, in existing or new structures.

3.4 Strategy of Conservation

Figure 4 presents the two different strategies of conservation from the end user's or owner's point of view. The traffic demand is continuously increasing in all cases. Strategy B usually induced during the planned service life of the structures, multiple periods of traffic disruptions, shown as shaded areas. Depending on the size of the structure and the extent of the interventions to be realized, these periods of traffic disruption can extend up to several years with dramatic consequences in terms of traffic disturbance, and end users and environmental costs. On the contrary, Strategy A aims at both: decreasing the time spent for the rehabilitation works, and increasing the durability to an extent that will make the rehabilitated structures fulfil all requirements of functionality, serviceability and resistance, for the planned service life, with only minor preventative maintenance. Strategy A is thus highly desirable (Denariė 2006).

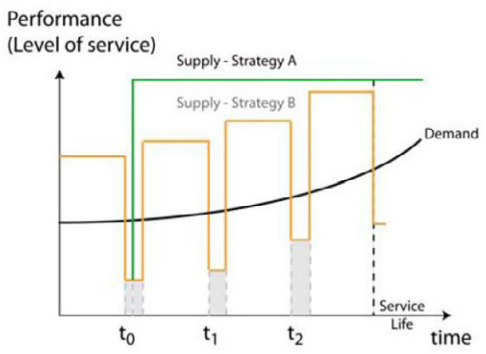

Figure 4. Evolution with time of the demand and supply for two conservation strategies.

4. Review on Previous Works using UHPFC in Rehabilitation

Krstulov and Toutanj (Krstulov1c-opara 1996) used a layer of thin high-performance fiber-reinforced cementitious composites (HPFRCC) overlays, between 10 and 50 mm to repair deteriorated cementitious structures such as cracked pavements and bridge decks. It was found out this thin overlay tensile strain-hardening behaviour improves the original structure's deformation and energy dissipation capacity. Thus, HPFRCC overlays are able to bridge existing cracks in the concrete substrate. The cracks in the HPFRCC layer remain small, between 30μm and 50μm and are closely distributed.

In the recent years, an experimental pilot-scale test on the flexure behaviour of various composite UHPFRC and conventional reinforced concrete (RC) beams have been studied by (Denariė 2003). In their tests, the composite beams were comprised of an UHPFRC overlay to replace the standard tensile reinforcing bar in an RC beam and exhibited an ultimate force compared to the standard RC beams. The composite beams exhibited an increased stiffness until the ultimate force was reached and, thereafter, a pronounced softening behaviour, while the RC beams showed a slight hardening behaviour commonly observed in concrete flexural members.

Another method is using the CARDIFRC (a new class of high performance fibre-reinforced cementitious composite). It that had been used as bonded strips applied to the tensile face to rehabilitate and improve existing reinforced concrete beams by (Habel 2007). All beams were tested in four-point bending. The results demonstrated the followings:

- The rehabilitated composite beams behaved monolithically until fracture. The composite beam ultimate force was equal to or higher than the reference concrete member, but experienced as oftening phase after reaching the ultimate force.
- High tensile/flexural strength and high energy-absorption capacity (i.e.ductility). The special characteristics of CARDIFRC make them particularly suitable for rehabilitation.
- The damaged reinforced concrete beams can be effectively rehabilitating and strengthening in a variety of different retrofit configurations using CARDIFRC strips adhesively bonded to the prepared surfaces of the damaged beams.

Habel (2004) evaluated the performance of (UHPFC) overlay material above ordinary reinforced concrete element subjected to impact loading. The application of a UHPFC overlay significantly improved the structural response of the member subjected to impact loading, with none of the spalling, crushing, or cracking that are typically common for normal concrete overlay, and the results confirmed that applying a UHPFRC layer to form a composite UHPFRC and NC element increases the service condition stiffness, minimizes deformations for given imposed forces, reduces crack widths and crack spacing, and delays the formation of localized macro-cracks as compared to the original conventionally reinforced concrete element. This improved performance is attributed by the UHPFRC layer high tensile strength and strain-hardening properties.

In the mid 2000, (Denariė 2003), (Lee 2006) and (Chui 2005) performed a preliminary study on reactive powder concrete (RPC) as a new repair material. Samples were evaluated for compressive strength, bond strength by slant shear test measured at an inclined angle of 45°, steel pull-out strength test and relative dynamic modulus test. The test results shown that the effect of compressive strength and flexural strength with bonding RPC 10 mm thick were between 150-200% more than those of normal strength concrete. The abrasion coefficient of the RPC was shown to be about eight times greater than that of normal strength concrete and about four times higher than that of high strength mortar. The test results also shown that the using of RPC as a repair material improved bond strength as shown in Table 2.

Table 2. Slant shear strength and failure type of RPC in comparison with RC and HSM (Lee 2007)

Upper/LowMaterials	NC/NC f'c = 34.1	HSM/NC f'c = 34.1	UFC/NC f'c = 34.1	UFC/UFC f'c = 181.6
28 Days shear strength, τ (MPa)	12.4 Interface failure	12.6 Failure in lower	13.7 Failure in lower	59.6 Failure in lower & upper
Normalized Shear Strength τ /√ f'c	2.12	21.6	2.35	58.9 4.42
28 Days+ 300 Cycles, Shear Strength (MPa)	9.6 Interface failure	12.4 Failure in lower	12.8 Failure in lower	59.0 Failure in lower & upper
28 Days+ 600 Cycles, Shear Strength (MPa)	5.9 Interface failure	9.2 Interface Failure	11.3 Failure in lower	57.6 Failure in lower & upper
28 Days+ 1000 Cycles, Shear Strength (MPa)	3.8 Interface failure	7.0 Interface failure	9.1 Interface failure	Failure in lower & upper

In year 2007, Wang and Lee (2007) used UHPFC for strengthening of ordinary reinforced concrete frames. Prior to the structural frame testing, the mechanical properties of the UHPFC were examined. In their material strength tests programme, the compressive strength, flexure strength, rebar bonding, and slant shear strengths, and durability are reported. The material test results indicated that the UHPFC displays excellent performance in terms of mechanical and durable behaviour. From there structural frame test, the experimental results show the UHPFC replaced joint frame behaves very well in seismic resistance. Its performance is even much better than the frame strengthened with RC jacketing as normally seen in the traditional retrofit schemes.

In year 2008, Brühwiler and Denarié (2008) used 30 mm thick UHPFC overlay for the rehabilitation of short span road bridge with heavy traffic. The protective function of the UHPFRC overlay was verified by air permeability tests which confirmed the extremely low permeability; approximately 30 times lower than normal concrete. The study of the construction costs showed that the rehabilitation with UHPFRC was 12% more expensive that a more traditional solution with waterproofing membrane and rehabilitation mortar and providing lower quality in terms of durability and life-cycle costs. However, in the latter case the duration of the site would have been largely increased by the drying period of the rehabilitation mortar, prior to the application of the waterproofing membrane (up to 3 weeks). In conclusion this technique will become cheaper than traditional methods in terms of time and future repair cost saving, hassle and convenience for the repair team and public and not to mention its outstanding advantages of long term durability and reduction of traffic disruptions (and subsequent user costs) due to multiple interventions.

Recently an experimental study was performed by (Sarkar 2010) and (Harris 2011) to evaluate the bond strength between UHPFC overlay and a normal concrete substrate with different types of surface textures including, smooth, low roughness (0.04 in. – 0.09 in.) where a very stiff steel wire brush was used to prepare 'low rough surface condition' , and high roughness (0.25 in.) deep transverse grooves surface made by using hand held metal grinder. Slant shear test according to (ASTM 1999) and splitting prism test were performed to quantify the bond strength in compression and shear, and in tension. Additionally, third point loading tests according to (ASTM 1997) were conducted to evaluate the performance of a bi-layer member in flexure, all tests done at 10 days after UHPFC casting. The study demonstrated that under slant shear test, the bond strength is greater than the strength of mortar substrate, provided that a proper surface roughness is used on the other hand. While in the case of no surface preparation, failure consistently occurs at the interface. Meanwhile, for the bond strength under splitting test, results were not very sensitive to the surface roughness. Failure at the interface included corner breaks or chunk breaks in the concrete with no failure within the UHPFC section.

5. Conclusion

The extremely low permeability, very high strength and outstanding mechanical properties of UHPFC appear to make it suitable for use as a standard overlay material that is capable of resisting mechanical loading and severe environment. The improved durability characteristics and the high compressive strength suggest that (UHPFC) could be used as an attractive choice to conventional overlay materials and solutions. Composite UHPFRC – normal concrete structures is able to guarantee a long-term durability which helps avoid multiple rehabilitation interventions on concrete structures during their service life.

The results of slant shear tests show that the bond strength between UHPFC and normal concrete possesses high bond strength and bond durability as compared with other concretes. There may be more experimental tests to be carried for the bond strength between UHPFC and normal concrete for example split test and pull off test to further proven that this material is one of the most compatible and advisable material to be used as a concrete structures repair material. In addition, long-term test for bond strength should also be carried out to collect statistics and to review the performance of UHPFC against time effects.

Acknowlegement

This study was made possible by the support of the School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia.

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