Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.111

POSSIBLITIES OF USING UHPC AS A REPAIR MATERIAL

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Abstract

More and more buildings need to be repaired and strengthened, both for durability and for the effects of natural disasters such as earthquakes. The repair material should ensure compatibility with the substructure materials and contribute to their improvement. The continuous development of materials has led to their excellent properties and application possibilities. In addition, the new generation of materials offers more environmentally friendly solutions, which is certainly in line with repair as part of sustainable development. In an effort to meet all these requirements, the use of mortars with exceptional properties and environmental efficiency can be the key to solving repair works.

Materials such as ultra-high performance concrete (UHPC) are characterised by exceptional mechanical and durability properties. In its usual composition, it contains large amounts of cement, which can be reduced by using waste materials to improve its environmental performance. One of the properties of UHPC worth highlighting is its toughness, which is achieved through the use of fibres that ensure a cement composite with ductile behaviour. Therefore, this paper presents a general overview of UHPC and the possibility of its application as a repair material. The evaluation of UHPC as a repair material is based on the studies carried out. These are divided into tests of interfacial properties, which include bond strength, microstructure, and permeability. The influence of additional cementitious materials on the interfacial microstructure is presented. Finally, the importance of fibres and the potential self-healing effect of UHPC in repair are highlighted and opportunities for new studies are identified.

Keywords: repair, ultra-high performance concrete, waste materials, fibres, self-healing, interface microstructure

1. Introduction

There is an increasing need for the repair of concrete structures built in the 20th century, as well as newly constructed structures that are deteriorating rapidly due to adverse effects of weathering and mechanical loads [1]. These negative influences include freeze-thaw cycles, de-icing salts, marine influences, and increased live loads, all of which cause serious deterioration of concrete structures [2]. This raises the question for civil engineers of how to rehabilitate, retrofit, and maintain these structures in an efficient and cost-effective manner [2]. Although many repair materials have been developed, such as high flow concrete, resin-based repair mortar and concrete, polymer-modified mortar and concrete, etc., and many different repair techniques, such as patching, overlaying, spraying, and pressure grouting, it is devastating that nearly half of all concrete repair systems fail in use [3]. However, to ensure a successful repair, two factors must be considered: a suitable repair material and good adhesion of the repair interface [4]. The weakest zone in the repair system is the interface between the repair material and the concrete substrate [1], [4], [5]. It is important to mention that this bond, i.e. the bond between the substrate and the repair material, depends on some factors that can be divided into the surface condition of the substrate, the curing process, the compaction method, the use of binders, the age of the chemical bonds and the mechanical properties of the material [6].

As mentioned earlier, the challenge in repair systems is to find a durable and efficient repair material. One possible solution to this challenge lies in ultra-high performance concrete (UHPC). With its excellent mechanical and durability properties, UHPC offers many advantages in the rehabilitation of concrete structures. These advantages include shorter rehabilitation times and longer service life and durability of the structures, so that sustainable construction can be achieved with a minimum of intervention and maintenance [7]. On the other hand, there are also some challenges in using UHPC as a rehabilitation material, such as interfacial adhesion and interaction with the subgrade [8]. Therefore, most of the studies [1]–[4], [6], [8]–[24] on the use of UHPC in repair works are concerned with the interfacial properties and adhesion.

In this paper, the possibilities of using UHPC are presented based on a brief general overview of UHPC and the studies found evaluating UHPC as a repair material in cementitious composites.

2. UHPC in general

UHPC represents a new generation of cementitious materials with improved strength, ductility, and durability [25], with compressive strength greater than 100 MPa and tensile strength greater than 15 MPa [26]. Due to its durability, it is resistant to acids and alkalis [27]. As for the name, it is important to point out that it is not concrete but mortar, since it does not contain large aggregates and the name concrete is due to the presence of steel fibres in the usual composition [25]. The main principles for the production of ultra-high performance concrete are to reduce porosity, improve microstructure, improve homogeneity, and increase toughness [28]. Thus, the reduction of porosity is the reason for the high durable properties of UHPC [29] and is achieved by compacted composition and reduction of water-cement ratio (0,15-0,25) [30] using superplasticizers [28], [31]. Reducing the size of the aggregate leads to a homogeneous microstructure, i.e. a reduction in the size of the cracks and a more similar zone of the interface and the cement matrix [28], [31], [32]. To improve the toughness properties, fibres are added, which also increase the impact strength [28], [32]. Since the usual composition of UHPC contains large amounts of cement (800-1000 kg/m^3), the unfavorable environmental impact of UHPC production is highlighted, as the estimated CO_2 emissions from cement account for 7% of global CO_2 emissions [33]. Therefore, the use of supplementary cementitous materials, i.e. industrial by-products, is emphasised [33], [34]. UHPC can be used in structural and non-structural applications. In the structural field it allows the production of smaller, lighter and thinner elements, while the non-structural application is in the field of repairs, improving the properties of the repaired parts with less maintenance [25].

3. Evaluation of UHPC as a repair material

3.1 Application of UHPC in repair

With its excellent properties mentioned above, UHPC is particularly suitable for the rehabilitation or repair of concrete structures in the form of an overlay [19], [24] and offers the possibility of thinner surface layers, which reduce the self-weight of the structure and improve structural efficiency [16], [17]. Due to its resistance to weathering, chemical treatment and mechanical loads typical for bridge decks, it is a particularly suitable material for bridge decks [13], [17], but also for the lateral and lower bridge elements [13]. In addition to rehabilitation, the application of a UHPC overlay to existing or new structures represents a potential for modification [2]. In the study [35], UHPC was used as a repair material for repairing lock walls because they need frequent repair due to their exposure to ship impact and UHPC is a material that can dissipate more energy during impact loads compared to normal strength concrete (NSC) [29].

To ensure monolithic behavior of the repaired system, a strong and durable bond is required [19]. Although there is a major modulus mismatch between UHPC and NSC that can cause local stress concentrations at the interface, leading to a reduction in strength, the bond properties also depend on the microstructure of the interface, creep and shrinkage of the repair materials, etc [4]. The incompatibility of two materials, i.e., non-uniform expansion and shrinkage, cause stress concentrations at the interface and thus delamination of the interface (Figure 1) [5]. Therefore, UHPC has a denser microstructure at the interface between UHPC and substrate and lower creep and drying shrinkage, which makes it a promising material for improving bond strength [4].

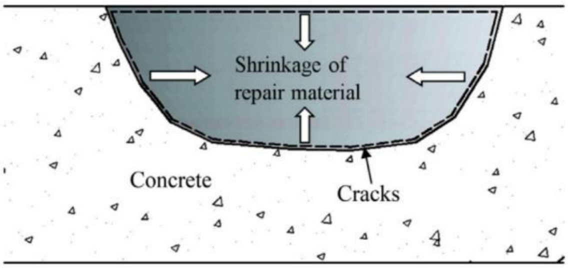

Figure 1 Schematic representation of the shrinkage of repair materials in patch repair [5]

3.2 Testing interface properties

Various test methods are available to evaluate the bond strength between two concrete materials, which can be divided into three categories depending on the stress state: Tension (splitting, direct tension, pull-off), shear (L-shaped shear, direct shear, bi-surface shear), combined shear and compression (slant shear) [4]. Of the test methods listed, only the pull-off test is the standard test for evaluating adhesion strength [8]. Adhesive bond evaluation is also the main study in the found papers/articles on UHPC for rehabilitation works, as shown in Table 1, where the substrate material was normal strength concrete (NSC). It can be seen that the most commonly performed tests are pull-off, splitting tensile and slant shear tests. The reason for the pull-off test, apart from being the only standard test, is that it can be done in situ [20]. However, some studies [8], [22] have highlighted the unsuitability of these test methods for evaluating the bond strength of interface. In [22], a new test method has been developed, namely the debonding test, which ensures debonding failure at the interface and has been shown to be a suitable solution to the problems of other test methods, such as user influences and sensitivity to eccentricity. On the other hand, [8] has pointed out that the slant-shear test is the most suitable of all test methods to evaluate bond performance, since complex loading conditions occur in the actual overlay application of UHPC material.

Table 1 Studies on the bond propertis of UHPC as a repair material

Studied interface properties			**Bond parameters**
Mechanical	**Durability**	**Microstructure**	
Pull-off [8], [12], [15], [20]–[22] Spiltting tensile [2]–[4], [8], [10], [12], [17], [19]–[21] Slant-shear [2]–[4], [6], [8], [10], [12], [17], [19], [21] Indirect tensile [22] Direct tensile [19] Push-off [16] Modified pull-off [22] Third-point flexure [6] Direct shear [6] Bi-surface shear [8], [13] Double-sided shear [11] Single-side shear [24]	Gas permeability [3] Rapid chloride permeability [2], [3] Water permeability [3]	SEM-EDS [15], [20] SEM [2], [3] BSE-EDX [4] BSE [24]	Surface roughness [8], [10]–[13], [16]–[21] Moisture degree [11], [12], [19] UHPC age [11], [19] Curing conditions [11], [19] Substrate strength [4], [11], [19] Bonding agent [13], [19] Expansive agent [11], [19] Age of composite [12] Stress state of the interface [11] Interface shear reinforcement [16] Mechanical connector [13] Formwork influence [15]

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As shown in Table 1, some studies have also investigated durability properties and interface microstructure, and some have included bonding parameters to evaluate all of these bonding properties. Testing permeability properties is especially important for repaired concretes, as the presence of degraded chemicals through the adhesive joints can cause irreversible damage to the structure [1]. The bond parameters considered in most studies are substrate properties: surface roughness, moisture degree, and strength. This was to be expected, since surface preparation is the key to effective adhesion [9] and the properties of the repair are highly dependent on the nature of the substrate surface [17]. Also in [19], the test results have shown that the surface roughness, the degree of moisture and the strength of the substrate are the most important factors affecting the interfacial adhesion, with higher strength, suitable roughness preparation and complete moisture of the substrate ensuring reliable bond performance. This was also confirmed in [22], where the test results showed excellent adhesion between UHPC and substrate with proper surface preparation and no binder. On the other hand, UHPC has shown good bond with old concrete in [20], regardless of surface roughness. This can be partially confirmed in [12], where the importance of adequate wetting of the substrate is emphasized, since then the roughness of the surface of the substrate is not decisive in ensuring a good bond. The influence of the saturated surface of the substrate on the improvement of bond strength described in [12] can be explained by the fact that UHPC is a material with a low w/c ratio, containing a large amount of non-hydrated particles that can be hydrated by the substrate and generate hydration products in the transition zone, creating cohesion between the two materials during the curing time. The addition of binders has been shown to increase adhesion on smooth substrate surfaces, while weakening it on rough substrate surfaces [13], [19]. It is worth noting that these bond parameters, such as surface roughness, depend on the test methods used, i.e. it has no influence in the case of the pull-off test, while in other test methods, such as the split tensile and shear tests, surface preparation plays a role [21]. In the case of the pull-off test , the insensitivity of the test to the surface preparation parameters can be explained by the effect of a stronger chemical bond than the effect of the mechanical bond on interfacial adhesion [21].

The adequate bond performance of UHPC for a wide range of surface conditions was demonstrated by test results in [17], while also in [3], [10] UHPC overlays showed excellent bond quality in split tensile test, with most of the failure modes caused by the NSC substrate, indicating a higher bond strength between UHPC and NSC substrate than the strength of NSC. Concrete repaired with UHPC is stronger by a factor of two compared to concrete substrate repaired with NSC [13]. The slant shear test results also showed a strong bond between UHPC and NSC substrate, as the failure of the interface occurred after the substrate was damaged [3]. In terms of permeability properties, UHPC shows high resistance to degradation processes such as the penetration of carbon dioxide, chloride, sulfate, etc., which was also confirmed when UHPC was used as an overlay in [23]. The durability tests (capillary absorption, air/gas permeability, freeze-thaw resistance, chloride penetration) have shown that the quality of the interfacial composite can withstand severe environmental conditions [23]. This was also proved in [2], where the results of the rapid chloride test confirmed the low permeability of UHPC, resulting in higher chloride resistance of the composite, so the better mechanical bond between UHPC and NSC substrate could improve the chloride resistance of the composite, resulting in longer service life of the repaired structures (Figure 2). As for the interface microstructure, the SEM /EDS results showed that UHPC improves the microstructure by forming a C-S-H gel that fills the voids, resulting in a dense, strong and uniform composite bond [20].

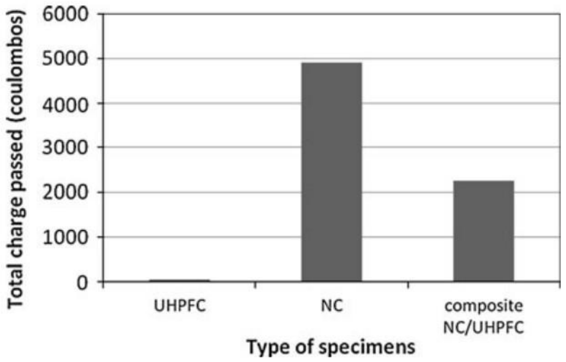

Figure 2 Comparison of the rapid chloride permeability [2]

3.2 Economic aspects

In addition to bond strength, service life and economic aspects are also decisive in assessing the suitability of repair systems for concrete rehabilitation. For example, in [36], the service life of concrete structures in chloride-stressed environments repaired with UHPC was calculated. The results show that the service life increases by 7 to 9 times when a UHPC layer is applied [36]. In another study [14], the effect of UHPC as a repair material on the service life of the repaired system was investigated based on the time required for chloride ions to reach the surface of the reinforcement. In this case, the service life was also extended, by 5 to 10 times, depending on the environment (Table 2).

Table 2 Comparison of the protective layer of UHPC and NSC based on service life [14]

Chloride Concentration (C_0) (kg/m^3)	Protective Layer Material	Protective Layer Thickness (cm)	$t_{critical}$ (years)
10	UHPC	2	31
		5	140
	NSC	2	6
		5	19
20	UHPC	2	21
		5	95
	NSC	2	4
		5	13
30	UHPC	2	17
		5	80
	NSC	2	3
		5	11

3.3 Fibre influence

Steel fibres have been shown to increase the bond strength of the repaired system through a "dowel effect" [5], [24]. On the other hand, repair materials with steel fibres ensure the toughness properties of the repaired system compared to ordinary cement-based repair materials. However, other types of fibres, such as polypropylene fibres, have been shown to improve the bond strength and contribute to the anti-cracking effect [5]. Another study [35], in which a lock wall was repaired with UHPC and the behaviour of the repaired system after one year showed that UHPC was firmly bonded to the structure due to the

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.111

anchoring effect of the fibres (Figure 3). In this case, the fibres were metal fibres with a diameter of 0.2 mm and a length of 13 mm.

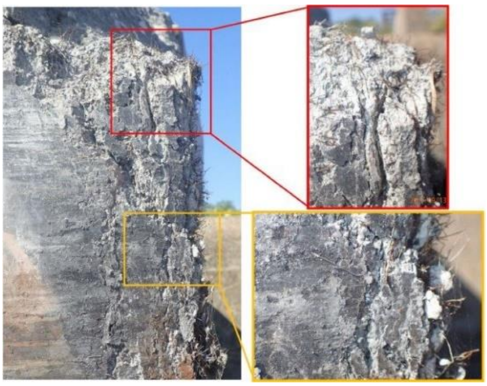

Figure 3 UHPC repair layer after one year [35]

In general, fibre-reinforced cementitious composites meet all the requirements demanded of a repair material, i.e. impermeability to aggressive liquids and gases, adequate bonding to the substrate and ensuring structural integrity, durability and resistance to severe environmental conditions, and compatibility with the substrate concrete [37]. Apart from these few studies, the exact influence of fibres on the properties of the repair interface when using UHPC repair material has not yet been found, so this is a potential that needs to be investigated.

3.4 Cementitous materials influence

As mentioned earlier, it is not only the mechanical properties that affect the bonding between two materials, but also the chemical properties. Therefore, some studies [2]–[4], [15], [20], [24] have investigated the microstructure of the UHPC/substrate interface. The usual composition of UHPC contains silica fume, which refines the pore system of the transition zone, making it dense and uniform. It alsoprovides stronger bonding through the reaction of the contained silica (SiO_2) with the $Ca(OH)_2$ of the substrate, forming a C-S-H gel [21]. This was confirmed by SEM-EDS test results showing the influence of silica fume from UHPC in generating C-S-H gel products at the interface reacting with $Ca(OH)_2$, but also the possibility of a secondary reaction with the $Ca(OH)_2$ to further improve the microstructure of the transition zone and thus increase the bond strength [4]. The reaction of silica fume in UHPC with the $Ca(OH)_2$ in the substrate in the formation of C-S-H gel was also confirmed in [24], due to the lower Ca/Si ratio of the UHPC-NSC interface, as shown in the results of EDS. SEM Images of UHPC-NSC interface have shown very good interlocking of UHPC with NSC, leading to strong bonding and consequently efficient repair [2], [3]. Since UHPC contains a large amount of unhydrated particles, exposure to freeze-thaw cycles could favour the hydration of these particles at the interface and in this way also improve cohesion [12]. When using UHPC, there is always the possibility of creating an eco-UHPC that is also suitable for use as a repair material. This was done in the study [15], where 50% limestone filler was used for UHPC repair material. In this way, the use of supplementary cementitious materials in repair UHPC materials reduces CO_2 emissions and production costs. However, with the exception of [15], no studies on UHPC with waste materials, i.e. cementitious materials, were found. This opens new possibilities in the study of UHPC in repair works.

3.5 Self-healing effect

In the study [15], another important property of UHPC materials was briefly investigated. This is autogenous self-healing, which is defined as the process that occurs when materials recover themselves after damage [38], [39]. In the case of UHPCs, which contain a significant amount of unhydrated cementitious materials, self-healing is expected to be an efficient process for autogenous self-healing when continued hydration is considered [38]. In [15], among other tests conducted to test UHPC as a repair material, self-healing effectiveness was also investigated, which showed limited healing, with only cracks smaller than 50 µm being completely healed. However, the potential for self-healing was highlighted due to the high content of unhydrated cement and limestone particles, which could be further improved by a more efficient curing process [15].

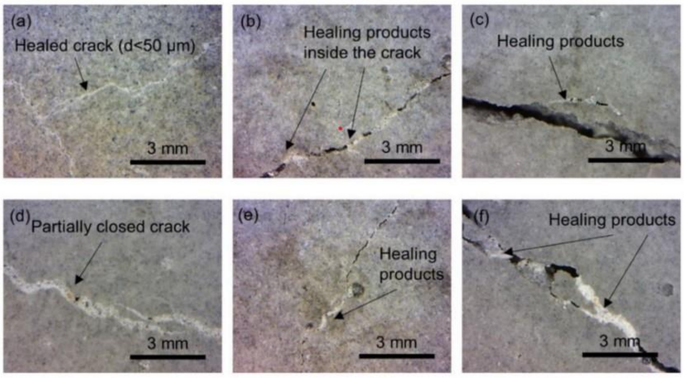

Figure 4 Self-healing of surface cracks on the UHPC layer: a) completely healed cracks; b)-f) partially healed cracks [15]

In this way, self-healing is a valuable property of UHPC that should also be investigated in the case of UHPC repair material, as it could further reduce the costs and improve durability and service life along with supplementary cementitious materials and fibres.

4. Conclusion

UHPC has demonstrated its potential as a material for future repair work due to its mechanical properties and permeability. In this paper, a brief overview of the most important of these properties that are and could be important for rehabilitation works is presented. Most studies investigated the bond strength when using UHPC as a repair material for NSC substrates, and the results showed very good or excellent interfacial adhesion in most cases. For better adhesion, different adhesion parameters were investigated, and different test methods were used depending on the stress of the repaired system, of which the pull-off test is a standard method. Since most failure modes occur in the substrate material, this emphasises a strong mechanical and chemical bond between UHPC and substrate. From the studies found, there is a lack of further studies to understand this chemical bond, i.e., the microstructure of the interface and the potential that the materials in UHPC offer in creating this bond. In this sense, there is also the possibility to investigate the use of other supplementary cementitious materials in the composition of UHPC repair materials. On the other hand, few studies have investigated the effect of fibres on interfacial adhesion, which also opens new opportunities for using other types of fibres and improving the microstructure of the interface, as well as providing mechanical bonds as an anchoring effect. Finally, abundant cement and supplementary cementitious materials in the composition of UHPC always provide the possibility of a self-healing effect, for which there is a lack of studies on repair materials.

Acknowledgements

The presented research is a part of the project "Development of new technologies and services in the field of special construction works" (K.K.01.2.1.02.0297), funded by the European Regional Development Fund and the project "Cement Composites Reinforced with Waste Fibers" - ReWire (UIP-2020-02-5242) funded by the Croatian Science Foundation.

References

[1] W. L. Baloch, H. Siad, M. Lachemi, and M. Sahmaran, “A review on the durability of concrete-to-concrete

bond in recent rehabilitated structures," *J. Build. Eng.*, vol. 44, no. September, p. 103315, 2021, doi: 10.1016/j.jobe.2021.103315.

[2] B. A. Tayeh, B. H. Abu Bakar, and M. A. Megat Johari, "Characterization of the interfacial bond between old concrete substrate and ultra high performance fiber concrete repair composite," *Mater. Struct. Constr.*, vol. 46, no. 5, pp. 743–753, 2013, doi: 10.1617/s11527-012-9931-1.

[3] B. A. Tayeh, B. H. Abu Bakar, M. A. Megat Johari, and Y. L. Voo, "Mechanical and permeability properties of the interface between normal concrete substrate and ultra high performance fiber concrete overlay," *Constr. Build. Mater.*, vol. 36, pp. 538–548, 2012, doi: 10.1016/j.conbuildmat.2012.06.013.

[4] S. Feng, H. Xiao, and H. Li, "Comparative studies of the effect of ultrahigh-performance concrete and normal concrete as repair materials on interfacial bond properties and microstructure," *Eng. Struct.*, vol. 222, no. January, p. 111122, 2020, doi: 10.1016/j.engstruct.2020.111122.

[5] X. Song *et al.*, "Cement-Based Repair Materials and the Interface with Concrete Substrates: Characterization, Evaluation and Improvement," *Polymers (Basel).*, vol. 14, no. 7, 2022, doi: 10.3390/polym14071485.

[6] M. Farzad, M. Shafieifar, and A. Azizinamini, "Experimental and numerical study on bond strength between conventional concrete and Ultra High-Performance Concrete (UHPC)," *Eng. Struct.*, vol. 186, no. December 2018, pp. 297–305, 2019, doi: 10.1016/j.engstruct.2019.02.030.

[7] B. A. Tayeh, B. H. Abu Bakar, M. A. Megat Johari, and Y. L. Voo, "Utilization of ultra-high performance fibre concrete (UHPFC) for rehabilitation a review," *Procedia Eng.*, vol. 54, no. April 2014, pp. 525–538, 2013, doi: 10.1016/j.proeng.2013.03.048.

[8] D. K. Harris, M. A. Carbonell Muñoz, A. Gheitasi, T. M. Ahlborn, and S. V. Rush, "The challenges related to interface bond characterization of ultra-high-performance concrete with implications for bridge rehabilitation practices," *Adv. Civ. Eng. Mater.*, vol. 4, no. 2, pp. 75–101, 2015, doi: 10.1520/ACEM20140034.

[9] A. Ibrahim, B. Farouk, and S. I. Haruna, "Evaluation of Bond Strength between Ultra-High-Performance Concrete and Normal Strength Concrete: An Overview," *J. Kejuruter.*, vol. 32, no. 3, pp. 397–407, 2020, doi: 10.17576/jkukm-2020-32(3)-04.

[10] B. A. Tayeh, B. H. Abu Bakar, M. A. Megat Johari, and Y. L. Voo, "Evaluation of bond strength between normal concrete substrate and ultra high performance fiber concrete as a repair material," *Procedia Eng.*, vol. 54, no. Farhat 2010, pp. 554–563, 2013, doi: 10.1016/j.proeng.2013.03.050.

[11] Y. Zhang, C. Zhang, Y. Zhu, J. Cao, and X. Shao, "An experimental study: various influence factors affecting interfacial shear performance of UHPC-NSC," *Constr. Build. Mater.*, vol. 236, p. 117480, 2020, doi: 10.1016/j.conbuildmat.2019.117480.

[12] M. A. Carbonell Muñoz, D. K. Harris, T. M. Ahlborn, and D. C. Froster, "Bond Performance between Ultrahigh-Performance Concrete and Normal-Strength Concrete," *J. Mater. Civ. Eng.*, vol. 26, no. 8, pp. 1–10, 2014, doi: 10.1061/(asce)mt.1943-5533.0000890.

[13] A. Valikhani, A. J. Jahromi, I. M. Mantawy, and A. Azizinamini, "Experimental evaluation of concrete-to-UHPC bond strength with correlation to surface roughness for repair application," *Constr. Build. Mater.*, vol. 238, p. 117753, 2020, doi: 10.1016/j.conbuildmat.2019.117753.

[14] M. Farzad, A. Sadeghnejad, S. Rastkar, A. Moshkforoush, and A. Azizinamini, "A theoretical analysis of mechanical and durability enhancement of circular reinforced concrete columns repaired with UHPC," *Eng. Struct.*, vol. 209, no. June, p. 109928, 2020, doi: 10.1016/j.engstruct.2019.109928.

[15] A. Kothari, M. Rajczakowska, T. Buasiri, K. Habermehl-Cwirzen, and A. Cwirzen, "Eco-uhpc as repair material—bond strength, interfacial transition zone and effects of formwork type," *Materials (Basel).*, vol. 13, no. 24, pp. 1–19, 2020, doi: 10.3390/ma13245778.

[16] S. Sharma, V. S. Ronanki, S. Aaleti, and P. Okumus, "Experimental Investigation of Surface Preparation on Normal and Ultrahigh-Performance Concrete Interface Behavior," *J. Bridg. Eng.*, vol. 26, no. 4, pp. 1–13, 2021, doi: 10.1061/(asce)be.1943-5592.0001697.

[17] D. K. Harris, J. Sarkar, and T. T. M. Ahlborn, "Characterization of interface bond of ultra-high-performance concrete bridge deck overlays," *Transp. Res. Rec.*, no. 2240, pp. 40–49, 2011, doi:

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DOI: https://doi.org/10.5592/CO/2CroCEE.2023.111

10.3141/2240-07.

[18] A. Valikhani, A. J. Jahromi, I. M. Mantawy, and A. Azizinamini, “Numerical modelling of concrete-to-UHPC bond strength,” *Materials (Basel).*, vol. 13, no. 6, pp. 26–29, 2020, doi: 10.3390/ma13061379.

[19] Y. Zhang, P. Zhu, Z. Liao, and L. Wang, “Interfacial bond properties between normal strength concrete substrate and ultra-high performance concrete as a repair material,” *Constr. Build. Mater.*, vol. 235, p. 117431, 2020, doi: 10.1016/j.conbuildmat.2019.117431.

[20] B. A. Tayeh, B. H. Abu Bakar, M. A. Megat Johari, and A. M. Zeyad, “Microstructural analysis of the adhesion mechanism between old concrete substrate and UHPFC,” *J. Adhes. Sci. Technol.*, vol. 28, no. 18, pp. 1846–1864, 2014, doi: 10.1080/01694243.2014.925386.

[21] B. A. Tayeh, B. H. A. Bakar, M. A. M. Johari, and M. M. Ratnam, “The relationship between substrate roughness parameters and bond strength of ultra high-performance fiber concrete,” *J. Adhes. Sci. Technol.*, vol. 27, no. 16, pp. 1790–1810, 2013, doi: 10.1080/01694243.2012.761543.

[22] M. Valipour and K. H. Khayat, “Debonding test method to evaluate bond strength between UHPC and concrete substrate,” *Mater. Struct. Constr.*, vol. 53, no. 1, pp. 1–10, 2020, doi: 10.1617/s11527-020-1446-6.

[23] Y. Huang, S. Grünewald, E. Schlangen, and M. Luković, “Strengthening of concrete structures with ultra high performance fiber reinforced concrete (UHPFRC): A critical review,” *Constr. Build. Mater.*, vol. 336, no. September 2021, 2022, doi: 10.1016/j.conbuildmat.2022.127398.

[24] S. Feng, H. Xiao, R. Liu, and M. Liu, “Single-Side Shear Bond Strength and OTZ Microstructure of UHPC Repair Materials with Concrete Substrate,” *J. Mater. Civ. Eng.*, vol. 34, no. 9, pp. 1–15, 2022, doi: 10.1061/(asce)mt.1943-5533.0004360.

[25] N. M. Azmee and N. Shafiq, “Ultra-high performance concrete: From fundamental to applications,” *Case Stud. Constr. Mater.*, vol. 9, 2018, doi: 10.1016/j.cscm.2018.e00197.

[26] R. Pernicova, D. Dobias, and T. Mandlík, “Mechanical properties of UHPC with different kinds of glass fibres,” *Proc. Int. Conf. FIBRE Concr.*, vol. 2015-Janua, pp. 353–359, 2015.

[27] S. R. Rosseli *et al.*, “Ultra High-Performance Concrete as Alternative Repair Method: A Review,” *J. Fail. Anal. Prev.*, vol. 21, no. 6, pp. 2072–2080, 2021, doi: 10.1007/s11668-021-01296-3.

[28] C. Shi, Z. Wu, J. Xiao, D. Wang, Z. Huang, and Z. Fang, “A review on ultra high performance concrete: Part I. Raw materials and mixture design,” *Constr. Build. Mater.*, vol. 101, pp. 741–751, 2015, doi: 10.1016/j.conbuildmat.2015.10.088.

[29] S. Abbas, M. L. Nehdi, and M. A. Saleem, “Ultra-High Performance Concrete: Mechanical Performance, Durability, Sustainability and Implementation Challenges,” *Int. J. Concr. Struct. Mater.*, vol. 10, no. 3, pp. 271–295, 2016, doi: 10.1007/s40069-016-0157-4.

[30] J. Du *et al.*, “New development of ultra-high-performance concrete (UHPC),” *Compos. Part B Eng.*, vol. 224, no. August, p. 109220, 2021, doi: 10.1016/j.compositesb.2021.109220.

[31] O. Mishra and S. P. Singh, “An overview of microstructural and material properties of ultra-high-performance concrete,” *J. Sustain. Cem. Mater.*, vol. 8, no. 2, pp. 97–143, 2019, doi: 10.1080/21650373.2018.1564398.

[32] Shweta Mishra, “Reviewing Some Properties of Ultra High Performance Concrete,” *Int. J. Eng. Res.*, vol. V9, no. 06, pp. 108–121, 2020, doi: 10.17577/ijertv9is060156.

[33] M. A. Hamad *et al.*, “Production of ultra-high-performance concrete with low energy consumption and carbon footprint using supplementary cementitious materials instead of silica fume: A review,” *Energies*, vol. 14, no. 24, pp. 1–26, 2021, doi: 10.3390/en14248291.

[34] R. Yu, Q. Song, X. Wang, Z. Zhang, Z. Shui, and H. J. H. Brouwers, “Sustainable development of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC): Towards to an optimized concrete matrix and efficient fibre application,” *J. Clean. Prod.*, vol. 162, pp. 220–233, 2017, doi: 10.1016/j.jclepro.2017.06.017.

[35] A. Maltais, N. Petrov, M. Thibault, and B. Bissonnette, “UHPFRC for concrete repair,” *MATEC Web Conf.*, vol. 199, pp. 1–8, 2018, doi: 10.1051/matecconf/201819907007.

Proceedings of the 2nd Croatian Conference on Earthquake Engineering - 2CroCEE
Zagreb, Croatia - March 22 to 24, 2023

DOI: https://doi.org/10.5592/CO/2CroCEE.2023.111

[36] C. P. Gu, W. Sun, L. P. Guo, and Q. N. Wang, "Ultrahigh performance concrete: A potential material for sustainable marine construction in view of the service life," *Appl. Mech. Mater.*, vol. 438–439, no. October, pp. 108–112, 2013, doi: 10.4028/www.scientific.net/AMM.438-439.108.

[37] N. Banthia, C. Zanotti, and M. Sappakittipakorn, "Sustainable fiber reinforced concrete for repair applications," *Constr. Build. Mater.*, vol. 67, no. PART C, pp. 405–412, 2014, doi: 10.1016/j.conbuildmat.2013.12.073.

[38] M. Rajczakowska, L. Nilsson, K. Habermehl-Cwirzen, H. Hedlund, and A. Cwirzen, "Does a high amount of unhydrated Portland cement ensure an effective autogenous self-healing of mortar?," *Materials (Basel).*, vol. 12, no. 20, 2019, doi: 10.3390/ma12203298.

[39] E. Cuenca and L. Ferrara, "Self-healing capacity of fiber reinforced cementitious composites. State of the art and perspectives," *KSCE J. Civ. Eng.*, vol. 21, no. 7, pp. 2777–2789, 2017, doi: 10.1007/s12205-017-0939-5.