ULTRA-HIGH-PERFORMANCE FIBER-REINFORCED CONCRETE AN ALTERNATIVE MATERIAL FOR REHABILITATION AND STRENGTHENING OF CONCRETE STRUCTURES: A REVIEW

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Abstract. Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC) is a more powerful concrete material compared to the conventional concrete. With its low permeability level, UHPFRC possesses an exceptional durability. Therefore, it is strongly recommended as a material for rehabilitation and strengthening for concrete structures. In addition to its performances, UHPFRC also holds superior mechanical properties, including compressive strength, split tensile strength, ductility and workability. In general, UHPFRC dimensions are categorized to be thinner than the conventional concrete, making it as an advantage of UHPFRC application. However, since all fine and coarse aggregates in the conventional concrete are replaced with very fine aggregates, UHPFRC is unable to be fabricated considering its availability in certain location. To date, researches on UHPFRC as a reinforced material have developed significantly, covering the discovery to increase the compressive strength, flexural strength, high bonding strength, durability and thickness. The aim of this paper is to review previous findings of UHPFRC to be utilized as conventional concrete repair material.

1. Introduction

UHPFRC is one of the breakthroughs in concrete technology, proven by more significant improvement in strength, workability, and durability compared to those in conventional-fabrication of concrete. The improvements occurred due to the reduced use of water and aggregates in certain volumes and sizes, the use of high quality of silica fume, and the utilization of steel fibers [1]. The difference between UHPFRC and conventional concrete in missing designs is the amount and sizes of binding materials, such as fibers and highly-amount of superplasticizer. By using finer aggregate grain size, the UHPFRC material arrangement tends to be much denser than those from conventional methods. The reduction of water usage during the process is replaced by the highly-amounts of superplasticizer which improves its workability, in which forming superplasticizer property as the characteristics of UHPFRC [2]. The UHPFRC is composed of a very fine nano-size substances, allowing it to be tightly arranged due the very low amounts of water in producing steel-like strength property [3]. The ultra-high-performance concrete (UHPC) is a hydraulic cement based concrete with a compressive strength at least to be equal to 150 MPa, while the UHPFRC is a UHPC reinforced by adding fibrous materials in order
to significantly improve a particular mechanical properties [4].

In general, the characteristics produced by UHPFRC show an increase in the quality of permeability, heat resistance, and impact strength. Obtained flexural strength is much higher than its tensile strength, whereas the addition of fibres improves the tensile strength significantly. On the other hand, the compressive strength owned by the UHPFRC has higher level than that in normal concretes although it has not been considered as the main standard in determining the UHPFRC quality. However, the other tensile and flexure strengths become a very important indicators [2]. The UHPFRC also can bind effectively, so it can be use as alternative materials for concrete structural improvements based on the results of rapid chloride permeability tests as well as electron microscope image characterizations [5]. The UHPFRC has excellent workability which allows it to be as an easily repairing material to be applied in the field works for replacement material [6].

2. Current application of UHPFRC

To date, the development of UHPFRC has been widely implemented in bridge structure [7], [8]. Further application of UHPFRC as a material for repairing concrete structures in particular for rehabilitation and strengthening process of concrete structures has started to develop to several occurrences, including for the improvement of beam structure concrete has been carried by Tanarslam et al [9], Al-Osta et al [10], Brühwiler et al [11], Lampropoulos et al [12], Jasim et al [13] and Spyridon [14]. Meanwhile, experimental investigations of slab behavior in concrete structures reinforced with UHPFRC have been studied by Yin et al [15] and Sanz et al [16]. Current applications of UHPFRC in bridges, beam or slab structures are generally implemented using the precast or jacket layer methods.

3. Mix proportion

Several studies related the mixing designs of Ultra-High-Performance Concrete are displayed by the following Table 1 below.

| Component       | Mix Proportions | Ratio | kg/m³ |
|-----------------|-----------------|-------|-------|
|                 |                 | [2]   | [17]  | [18]  | [19]  | [20]  | [21]  | [5] |
| Cement          | 1               | 1     | 1     | 1     | 800   | 875   | -     | 768 |
| Water           | 0,2             | 0,22  | -     | 176   | 202,1 | 46,2  | 144   |
| HRWR            | 0,0108          | 0,05  | 3,5 % | 40    | 45,9  | -     | 40    |
| Silica Fume     | 0,25            | 0,25  | 0,25  | 200   | 44    | 21 %  | 192   |
| (0,2mm)         | (0,1/0,66 mm)   |       |       |       |       |       |       |
|                 | 0,28            | 0,42  | 0,3/0,88 mm | 0,8 | 1,32  |       |       |       |
| Glass Powder    | 0,25            | 0,25  | -     | 200   | -     | -     | -     |
| Fibers          | 0,22            | 0,2   | 0,21  | 160   | 2,5 % | 3 %   | 157   |
| Quartz Sand     | -               | -     | 0,3   | -     | 175   | -     | -     |
| Sieve Sand      | -               | -     | -     | -     | -     | -     | -     |
| Marble Powder   | -               | -     | -     | -     | -     | -     | -     |
| w/b             | -               | -     | -     | -     | -     | 0,2   | -     |
| Binder          | -               | -     | -     | -     | -     | 1363  | -     |
4. Flexural Performance
The addition of 3% steel fiber to UHPFRC has been reported to contribute for 47.5 MPa of flexural strength [17]. Tanarslan et al [9] has suggested that reinforcement using UHPFRC layers followed by the addition of longitudinal reinforcement bars in particular by performing mechanical anchoring is an effective method for increasing the flexural capacity of concrete beam, and the reinforcement without this longitudinal addition can increase stiffness capacity as well as a reduction in deflection features. Subsequently, damages caused by flexural loads can be repaired effectively by coating them with layers of UHPFRC, and these prevent the beam against crack propagation, stiffness, and loading failures that occur [10].

The evenly distribution of fibres provide a much higher fatigue resistance against occurred static flexural strength which is up to 80% compared to that in non-uniform fiber distribution [22]. Common concrete that uses UHPFRC as reinforcement can produce flexural tensile strengths on the beams structure up to 30 MPa without bond slip characteristics [23]. As a result, the addition of 1.5% steel fiber into UHPFRC mixture has been reported to increase flexural strength to 200% by changing the specimen sizes, casting method, and support system [24].

5. Tensile Strength
The addition of micro-fibers into UHPFRC mixture which has been reinforced by macro-fibers can increase the tensile strength. A study conducted by Park et al., [25] has reported that the addition varied micro fibres into UHPFRC reinforced by macro-fibers such as hooked fiber A (HA), hooked fiber B (HB), twisted steel fiber (T), and long smooth steel fiber (LS) provided an increase for all of the tensile stress as it is displayed by the following Figure 1.

![Figure 1. Comparison of tensile response of UHP-HFRCs with 1.5% micro fibers and 1.0% macro-fibers according to the types of macro-fiber. [25]](image)

The tensile strength generated by UHPFRC varies in between 6.22 MPa to 24.1 Mpa [26]–[34]. UHPFRC with heat curing has been reported to have higher tensile strength than that from normal curing treatment [27].

6. Durability
The improvement of mechanical performance and durability of UHPC by adding fiber has been reported to be successfully carried out, and its improvements were higher than those in ordinary-high-strength concrete [35]. Graybeal [26] conducted a study that showed excellent UHPFRC durability against a very low chloride penetration rates and a very high freezing resistance results. Another study
conducted by Spiesz [36] and Alkaysi [37] by performing porosity measurement tests, freeze-thaw resistance tests, carbonation and chloride diffusion tests, migration tests, the presence and distribution of air cavities, have shown that UHPC had a very dense and durable characteristics in which allows it to have longer service life, lower maintenance and repair costs; compared to those structures made of conventional concrete. A previous research conducted by Abbas [38] has concluded that the addition of steel fibers with various sizes in the composition of UHPC provided relatively greater mechanical dan durability properties, in line with the addition of shorter fiber sizes and compositions.

7. Bonding Strength
In order to achieve a good repairing material, the bonding power between the repairing material and its substrate is very important in reconstructing structural concretes. As a repair material, at an early stage of UHPFRC provides high bond strengths and strong interactions on the surface of the substrates, which have been observed mostly on the substrate itself [1]. The flexural strength test results also prove and confirm that the UHPFRC can be connected and strongly bound with substrates (media). The strength of the bonds between the normal concrete substrate and UHPFRC has been reported to be stronger in UHPFRC regarding to substrate roughness, which was indicated by the absence of bonding damage within the bonds on the surface of substrates [39]. As it has been investigated by Munoz et al., [40], the bond performance between UHPFRC and normal concrete as the substrate contributed promising investigation results in accordance to ACI 546.3R-06. The following Figure 2 displays the bonding capacities of substrates

![Bond Capacities](image)

Figure 2. Bond strength per case study obtained in the splitting tensile test [40]
Figure 3. Average split tensile strength values ($T_{av}$) for each type of substrate surface [41]

| Type of substrate surface | Split tensile strength (MPa) |
|---------------------------|-----------------------------|
| As cast                   | 1.82                        |
| Drill Holes               | 2.5                         |
| Wire Brush                | 2.77                        |
| Grooved                   | 3.11                        |
| Sand Blast                | 3.68                        |

Table 2. Pull Out Test Results [42]

| Curing used                        | Load (KN) | Failure mode               |
|------------------------------------|-----------|----------------------------|
| Fog room                           | 48.72     | Bar Rapture Failure        |
| Immersing specimens in water       | 48.44     | Bar Rapture Failure        |
| Normal curing                      | 49.5      | Bar Rapture Failure        |
| Boiling water curing               | 50.11     | Bar Rapture Failure        |
| Steam cured after one day casting  | 50.59     | Bar Rapture Failure        |
| Steam cured after two days casting | 50.84     | Bar Rapture Failure        |

8. Conclusion

The UHPFRC has excellent properties, based on several studies due to the compressive strengths up to 150 MPa. The addition of fibrous materials contributes an increase in mechanical performance, including flexural strength of 47.5 MPa and tensile strength that reaches to 24 MPa. Regarding to the bond strength, the UHPFRC and NC as substrates, provides a promising strategy as it is seen from the absence of damage on the surface. With these exceptional mechanical, durability and simplicity to be applied [16], the UHPFRC can be utilizes as alternative material for reinforcement and repairing materials for normal concrete structures based on the results obtained [43]. Likewise, the numerical analysis of UHPFRC as reinforcement and improvement material for concrete structures contributes promising results [44], so that it can be applied for strengthening and repairing strategy throughout layers coating on normal concrete beam.

References

[1] B. A. Tayeh, B. H. Abu Bakar, and M. A. Megat Johari, “Mechanical properties of old concrete- UHPFRC interface,” Concr. Repair, Rehabil. Retrofit. III - Proc. 3rd Int. Conf. Concr. Repair, Rehabil. Retrofit. ICCRRR 2012, no. September, 2012.
[2] M. B. Eide and J. M. Hisdal, Ultra High Performance Fibre Reinforced Concrete (UHPFRC) – State of Art. COIN Project report 44. 2012.
[3] M. Schmidt, “Sustainable Building with Ultra-High-Performance Concrete (UPHC) - Coordinated Research Program in Germany,” 2012, pp. 17–25.
[4] A. E. Naaman and K. Wille, “The Path to Ultra-High Performance Fiber Reinforced Concrete (UHP-FRC): Five Decades of Progress,” in Proceedings of HiperMat 2012 (Kassel, March 7-9, 2012), 2012, pp. 3–15.
[5] 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.

[6] M. Z. A. Mohd Zahid, M. A. H. Abdullah, B. H. Abu Bakar, F. M. Nazri, and A. Ayob,  
“UHPFRC as Repair Material for Fire-Damaged Reinforced Concrete Structure – A Review,”  
*Appl. Mech. Mater.*, vol. 802, pp. 283–289, 2015.

[7] Y. L. Voo, S. J. Foster, and C. C. Voo, “Ultrahigh-Performance Concrete Segmental Bridge Technology: Toward Sustainable Bridge Construction,”  
*J. Bridg. Eng.*, vol. 20, no. 8, p. B5014001, 2014.

[8] G. C. Marano *et al.*, “Ultra-High-Performance Fiber-Reinforced Concrete Jacket for the Repair and the Seismic Retrofitting of Italian and Chinese Re Bridges,” pp. 2149–2160, 2017.

[9] H. M. Tanarslan, N. Alver, R. Jahangiri, Yağcınkaya, and H. Yazıcı, “Flexural strengthening of RC beams using UHPFRC laminates: Bonding techniques and rebar addition,”  
*Constr. Build. Mater.*, vol. 155, pp. 45–55, 2017.

[10] M. A. Al-Osta, M. N. Isa, M. H. Baluch, and M. K. Rahman, “Flexural behavior of reinforced concrete beams strengthened with ultra-high performance fiber reinforced concrete,”  
*Constr. Build. Mater.*, vol. 134, pp. 279–296, 2017.

[11] E. Brühwiler and E. Denarié, “Rehabilitation and strengthening of concrete structures using ultra-high performance fibre reinforced concrete,”  
*Struct. Eng. Int. J. Int. Assoc. Bridg. Struct. Eng.*, vol. 23, no. 4, pp. 450–457, 2013.

[12] A. P. Lampropoulos, S. A. Paschalis, O. T. Tsioulou, and S. E. Dritsos, “Strengthening of reinforced concrete beams using ultra high performance fibre reinforced concrete (UHPFRC),”  
*Eng. Struct.*, vol. 106, pp. 370–384, 2016.

[13] T. J. Mohammed, B. H. Abu Bakar, and N. Muhamad Bunnori, “Torsional improvement of reinforced concrete beams using ultra high-performance fiber reinforced concrete (UHPFRC) jackets - Experimental study,”  
*Constr. Build. Mater.*, vol. 106, pp. 533–542, 2016.

[14] S. A. Paschalis, A. P. Lampropoulos, and O. Tsioulou, “Experimental and numerical study of the performance of ultra high performance fiber reinforced concrete for the flexural strengthening of full scale reinforced concrete members,”  
*Constr. Build. Mater.*, vol. 186, pp. 351–366, 2018.

[15] H. Yin, W. Teo, and K. Shirai, “Experimental investigation on the behaviour of reinforced concrete slabs strengthened with ultra-high performance concrete,”  
*Constr. Build. Mater.*, vol. 155, pp. 463–474, 2017.

[16] H. Martin-Sanz, E. Chatzi, and E. Brühwiler, “The use of Ultra High Performance Fibre Reinforced cement-based Composites in rehabilitation projects: a review,” 2016.

[17] P. Máca, R. Sovjak, and P. Konvalinka, “Mix design of UHPFRC and its response to projectile impact,”  
*Int. J. Impact Eng.*, vol. 63, pp. 158–163, 2014.

[18] N. M. Sudarshan and T. C. Rao, “Experimental Investigation of UHPFRC Cube and Cylinder Compression Test at Elevated Temperature,” pp. 282–296, 2017.

[19] P. Máca, R. Sovjak, and T. Vavříník, “Experimental investigation of mechanical properties of UHPFRC,”  
*Procedia Eng.*, vol. 65, pp. 14–19, 2013.

[20] R. Yu, P. Spiesz, and H. J. H. Brouwers, “Mix design and properties assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC),”  
*Cem. Concr. Res.*, vol. 56, pp. 29–39, 2014.

[21] A. Alsalman, C. N. Dang, and W. Micah Hale, “Development of ultra-high performance concrete with locally available materials,”  
*Constr. Build. Mater.*, vol. 133, pp. 135–145, 2017.

[22] B. L. Karihaloo, “Flexural Fatigue Behavior of a Self-Compacting Ultrahigh Performance Fiber-Reinforced Concrete,”  
*vol. 29*, no. 11, pp. 1–9, 2017.

[23] A. K. Azad and I. Y. Hakeem, “Flexural behavior of hybrid concrete beams reinforced with ultra-high performance concrete bars,”  
*Constr. Build. Mater.*, vol. 49, pp. 128–133, 2013.

[24] K. Wille and G. J. Parra-Montesinos, “Effect of beam size, casting method, and support conditions on flexural behavior of ultra-high-performance fiber-reinforced concrete,”  
*ACI Mater. J.*, vol. 109, no. 3, pp. 379–388, 2012.
[25] S. H. Park, D. J. Kim, G. S. Ryu, and K. T. Koh, “Tensile behavior of ultra high performance hybrid fiber reinforced concrete,” Cem. Concr. Compos., vol. 34, no. 2, pp. 172–184, 2012.

[26] B. A. Graybeal and J. L. Hartmann, “STRENGTH AND DURABILITY OF ULTRA-HIGH PERFORMANCE CONCRETE Benjamin A. Graybeal, PE, PSU, Inc., McLean, VA Joseph L. Hartmann, PE, Federal Highway Administration, McLean, VA,” Concr. Bridg. Conf., 2003.

[27] D. Y. Yoo, J. J. Park, S. W. Kim, and Y. S. Yoon, “Early age setting, shrinkage and tensile characteristics of ultra high performance fiber reinforced concrete,” Constr. Build. Mater., vol. 41, pp. 427–438, 2013.

[28] K. Wille, S. El-Tawil, and A. E. Naaman, “Properties of strain hardening ultra high performance fiber reinforced concrete (UHP-FRC) under direct tensile loading,” Cem. Concr. Compos., vol. 48, pp. 53–66, 2014.

[29] S. Pyo, K. Wille, S. El-tawil, and A. E. Naaman, “Cement & Concrete Composites Strain rate dependent properties of ultra high performance fiber reinforced concrete (UHP-FRC) under tension,” Cem. Concr. Compos., vol. 56, pp. 15–24, 2015.

[30] Y. Kusumawardaningsih, E. Fehling, M. Ismail, A. Amen, and M. Aboubakr, “Tensile strength behavior of UHPC and UHPFRC,” Procedia Eng., vol. 125, pp. 1081–1086, 2015.

[31] M. Bastien-Masse, E. Denarié, and E. Brühwiler, “Effect of fiber orientation on the in-plane tensile response of UHPFRC reinforcement layers,” Cem. Concr. Compos., vol. 67, pp. 111–125, 2016.

[32] J. Liu et al., “Combined effect of coarse aggregate and fiber on tensile behavior of ultra-high performance concrete,” Constr. Build. Mater., vol. 121, pp. 310–318, 2016.

[33] A. Abrishambaf, M. Pimentel, and S. Nunes, “Influence of fibre orientation on the tensile behaviour of ultra-high performance fibre reinforced cementitious composites,” Cem. Concr. Res., vol. 97, pp. 28–40, 2017.

[34] M. A. Hafiz and E. Denarié, “Tensile viscous response of Strain Hardening UHPFRC under high restraint and isothermal conditions,” Comput. Model. Concr. Struct., pp. 903–912, 2018.

[35] C. Magureanu, I. Sosa, C. Negruțiu, and B. Hehges, “Mechanical properties and durability of ultra-high-performance concrete,” ACI Mater. J., vol. 109, no. 2, pp. 177–184, 2012.

[36] P. R. Spiesz and M. Hunger. “Durability of ultra-high performance concrete – Experiences from a real-scale application,” no. 2017, pp. 1–12, 2017.

[37] M. Alkaysi, S. El-Tawil, Z. Liu, and W. Hansen, “Effects of silica powder and cement type on durability of ultra high performance concrete (UHPC),” Cem. Concr. Compos., vol. 66, pp. 47–56, 2016.

[38] S. Abbas, A. M. Soliman, and M. L. Nehdi, “Exploring mechanical and durability properties of ultra-high-performance concrete incorporating various steel fiber lengths and dosages,” Constr. Build. Mater., vol. 75, pp. 429–441, 2015.

[39] B. A. Tayeh, B. H. A. Bakar, M. A. Megat Johari, and A. M. Zeyad, “Flexural Strength Behavior of Composite UHPFC - Existing Concrete,” Adv. Mater. Res., vol. 701, no. May, pp. 32–36, 2013.

[40] M. Á. C. Muñoz, “Compatibility of ultra high performance concrete as repair material : bond characterization with concrete under different loading scenarios,” p. 168, 2012.

[41] 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 reinforced fiber as a repair material,” Procedia Eng., vol. 54, no. Farhat 2010, pp. 554–563, 2013.

[42] L. K. Askar, B. A. Tayeh, B. H. A. Bakar, and A. M. Zeyad, “Properties of Ultra-High Performance Fiber Concrete (Uhpfc) Under Different Curing Regimes,” Int. J. Civ. Eng. Technol., vol. 8, no. 4, pp. 965–974, 2017.

[43] M. Safdar, T. Matsumoto, and K. Kakuma, “Flexural behavior of reinforced concrete beams repaired with ultra-high performance fiber reinforced concrete (UHPFRC),” Compos. Struct., vol. 157, pp. 448–460, 2016.

[44] A. P. Lampropoulos, S. A. Paschalis, O. T. Tsioulou, and S. E. Dritsos, “Strengthening of
existing reinforced concrete beams using ultra high performance fibre reinforced concrete,” in Proceedings of the 4th International Conference on Concrete Repair, Rehabilitation and Retrofitting, ICCRRR 2015, 2016, pp. 124–125.