Manufacturing of cast in situ ultra high performance fibre reinforced concrete (uhpfrc) - Workability, Tensile and Compressive Strength

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Abstract: The aim of this article is to share on the manufacturing process of Ultra High Performance Fibre Reinforced Concrete (UHPFRC) without heat curing or steam curing, hence, it makes UHPFRC possible to be used for in situ application. The common materials used in numerous previous studies were used in this work to produce UHPFRC: Cement type CEM I, fine sand, silica fume, water and third generation high range water reducer. Three tests were conducted, i.e. Compression test and slump flow test and tensile test. The targeted slump flow is in the range of 600 mm to 750 mm, minimum targeted compressive strength and tensile strength test is 115 MPa and 10 MPa, respectively. In addition, the UHPFRC must exhibit strain hardening properties. As a result, this study proposes the mix proportion of the above mentioned material used to produce UHPFRC which is suitable to be utilized for in situ application.

1. Introduction
Ultra High Performance Fibre Reinforced Concrete (UHPFRC) is relatively a new cementitious material. Its main features are flowable, high compressive strength (> 150 MPa), high tensile strength (> 10 MPa), high durability and exhibits strain hardening properties [1,2]. Basically, it consist of high content of cement, fine aggregate, superplasticizer, very low water content (water to cement ratio less than 2) and steel fibre. Initially it is used in manufacturing precast member, however, recently there is an attempt to use it repair and rehabilitation works [3,4,5,6,7,8]. When it comes to the in situ application like repair works, it is uneconomical to adopt heat or steam curing process and moreover, in producing UHPFRC, it is extremely difficult to obtain above mentioned UHPFRC feature just by replacing locally available material with the one established mixture proportions [8]. Therefore, this current study attempts to
determine the most optimum UHPFRC mixture which has above mentioned properties without heat or steam curing process.

2. Material and method

In order to obtain appropriate UHPFRC mixture, the mixture optimization process was carried out in two stages as shown in Figure 1. In the first stage, several concrete mixtures without fibres were prepared and tested to find the best constituents combination with respect to the maximum compressive strength and targeted workability. This stage began with the thorough review work on the existing UHPFRC mixture and mixing procedures. Based on the various mix proportions from previous studies [8-14] there were a numbers of UHPFRC mix proportions have been prepared and tested. The key mix variables considered were: 1) Silica fume-cement ratio 2) Water-cement ratio 3) Paste content 4) Type and content of superplasticizer 5) Aggregate size 6) Cement content.

There were various mixing procedures of UHPFRC adopted in previous studies. It is undeniable that mixing procedure greatly influences the quality of concrete to be produced. After a numbers of trials, this study found that the following mixing procedure of UHPFRC is suitable to be adopted: 1) Place the dry material (except for steel fibre) in the mixing pan 2) Mix slowly for at least 2 minutes 3) Gradually add about 80% of water while mixing 4) Gradually introduce superplasticizer into the mixer while mixing. Continue until it shows dark in colour and moist 5) Add the remaining water and thoroughly mix with high speed for about 3 minutes 6) Reduce the speed of the mixer and gradually add 6 mm steel fibre and followed by 14 mm steel fibre 7) Thoroughly mix with high speed for about 2 minutes.

It is worth to mention that, the speed of the mixer plays a vital role to obtain high compressive strength concrete at 28th day (> 115 MPa) with self-compacting property. Low speed mixture requires more superplasticizer content to achieve targeted slump flow and this will affect the setting time as well as compressive strength of concrete. Therefore, it is strongly recommended that UHPFRC mixture to be mixed in mixer with various speeds. Moreover, based on various trial mix done in this study, it is also proposed that steel fibre to be introduced at the end or after all water and superplastizer were added and it must be added in gradually manner as it is greatly help to avoid coagulated of steel fibre in the mixture which will create more void in the mixture and eventually impair the compressive strength of concrete.

Note that, in an attempt to obtain the suitable UHPFRC mixture, this study has used cement from three different brands, namely Blue Lion, Blue Panda and Tasek as well as three different superplasticizers, namely MasterRheobuild 1100, Glenium, MasterGlenium 8589 and MasterGlenium Ace 8109 produced by BASF company. MasterGlenium 8589 and MasterGlenium Ace 8109 give almost similar performance in terms of rheology property and compressive strength, however, the retention time for MasterGlenium Ace 8109 is longer which is about 6 hours compared to 2 hours for MasterGlenium 8589, therefore, it is suggested to use MasterGlenium Ace 8109 for onsite application particularly for repair works. The combination of Blue Panda cement and MasterGlenium Ace 8109 was found to have the best rheology properties and compressive strength. The results of workability, compressive strength and tensile strength of trial samples will be discussed in chapter 4. Therefore, this study utilized Portland cement type CEM I 52.5 N, Blue Panda brand from Hume. This type of cement was recommended for UHPFRC as it has low C3A content which result in better compatibility with superplasticizer (Denarie, 2009) and widely used by other researchers i.e. Choe et al.,[9], M Maca et al [10], Hassan and Jones [15], Habel et al., [16] and among others.

Prior to cast, the inverted slump flow test was performed following ASTM C1611[17] and the targeted slump spread was 600 mm to 760 mm and flow rate (T50) should be greater than 2s following recommendation by Koehler & Fowler [18]. Noted that, in general, as slump flow increases the susceptibility to segregation also increases. In this method, a sample of freshly mixed concrete was placed in the cone in one lift without tamping or vibration. The mould was lifted and the concrete was allowed to spread. After spreading ceases, two orthogonal diameters of the concrete patty were measured as shown.
The slump flow was the average of the two diameters. This method also provides a procedure for a relative measurement of flow rate, viscosity, and stability. The flow rate, $T_{50}$ was obtained by measuring the time taken by the fresh concrete achieve 500 mm diameter of spreading. The concrete viscosity influences the flow rate. The stability can be observed by visually examining the concrete patty for evidence of segregation.

*Figure 1.* Mixing process flow of UHPFRC.

Besides inverted slump test, there were a numbers of tests conducted by previous study to quantify the workability of UHPFRC. For instance, Benson and Karihaloo [19] adopted Cone Penetration Test (CPT) which widely used for soil to determine the workability properties of UHPFRC since it consists of graded sand and smaller particles in the form of cement and microsilica which make it like a sandy soil and a rough correlation between CPT value and slump are a CPT value of 20 mm is equivalent to a slump in excess of 250 mm and CPT value of 25 mm to a slump in excess of 300mm. Slump greater than 300mm considered very flowable. Kang & Kim (2011) used flow table test in accordance to ASTM C 1437 to measure the flowability. Meanwhile, Maca et al [10] and Wille, et al. [11] used standard flow table test in accordance to EN 1015-3 [20] and ASTM C230 [21], respectively. However this study choose inverted cone flow test to quantify the workability of UHPFRC as this test adopts standard slump cone apparatus which widely used in construction site.

The UHPFRC specimens were cast in 100mm x 100mm x 100mm cube and then cured for 28 days prior to test. Curing is a crucial process and it significantly affects the mechanical performance of cementitious material. Various curing method have been used by previous researchers in producing UHPFRC. For example Wu et al., [22] cured their sample in lime saturated water and the minimum
compressive strength of UHPFRC was about 110 MPa at 28th day. According to Voo [23] and Voo & Foster [24] the specimens or members made of UHPFRC must be heat cured for 48 hours at a temperature of 90ºC. Heat cure and steam cure are the most popular method and widely applied in producing UHPFRC as it may minimize the creep and long term shrinkage as well as smooth and good finishing [25]. A few studies have investigated the effect of curing process on the compressive strength of concrete. For instance, Persson [26] found that the compressive strength of water-cured, sealed and air-cured specimens were 110 MPa, 112 MPa and 119 MPa, respectively, after 28 days. Moreover, Lutfi Ay [14] showed that UHPC should not be water cured as it may create a partially open system which may harm the balance between inner and the outer part of the concrete. This can result in pre-stressing in the body and on the fibres. However, since this UHPFRC material to be used as repair material, neither heat nor steam curing method will be used as it is impractical to apply steam curing process at construction site for repair work, hence, only normal curing method was adopted in preparation of UHPFRC in this study. Furthermore, there were few studies have proved that the UHPFRC with high compressive strength of greater than 120 MPa were able to be attained with minimal curing i.e. ambient environment curing or air curing [9-14].

In this current study the UHPFRC specimens were cast in the 100mm x 100mm x 100mm cube and cured for twenty eight days in ambient environment prior to test. The compressive strength test was conducted with the loading rate of 2 kN/s in accordance to BS EN 12390 Part 3 [27]. Note that, BS EN 12390 Part 3 [27] suggested to apply compression load with loading rate ranging from 0.2 MPa/s up to 1.0 MPa/s which is equivalent to 2 kN/s up to 10kN/s for 100mm x 100mm x 100mm cube sample. The mix proportion by means of the best constituent combination with respect to the minimum compressive strength of 115 MPa and within the targeted workability (600 - 760mm) was chosen for the stage two. In the stage two, the optimum UHPC mixture was added with steel fibre from 1% up to 2% by volume. Two different sizes were used (i.e. 6 mm and 14 mm long) and its mechanical properties based on supplier technical data sheet. According to Denarie [8], the typical fibre dosage in UHPFRC to exhibit the strain hardening characteristic is about 0.5% to 3%. Recently, Hoang et al. [28] reported that there were fibre balling appeared in UHPFRC paste with 3% (vol) of steel fibre and it degraded the compressive strength of UHPFRC. Therefore this current study utilized steel fibre content from 1% to maximum of 2% by volume. Then, the UHPFRC samples underwent similar process as stage one (i.e. slump flow test, curing and compressive strength test) in addition with uniaxial tensile strength test to examine the strain hardening behaviour of UHPFRC. According to Wille, et al., tensile testing of materials with strain hardening behaviour accompanied by multiple cracking is particularly challenging. Currently, there are no testing standards available that define the test conditions, specimen geometry, and analytical procedures necessary to fully characterize the tensile properties of strain-hardening cementitious material. Predetermination of crack development by notching the specimen in bending or direct tension is commonly utilized to simplify the test setup, deformation control, measurement system and data analysis. However, doing so may not be appropriate for capturing the strain hardening behaviour of UHPFRC. Difficulties in obtaining evenly distributed stresses throughout the cross section and controlling a stable load versus displacement/crack opening response has limited the number of researchers performing direct tensile tests on cementitious materials and composites. Specimen shapes, which can be distinguished into dogbone shape [29-31], unnotched [32] and notched prisms or cylinders [33] significantly influence the test results in all three stages of behaviour (i.e. Part I: strain based elastic part, Part II: strain based strain hardening part and Part III: crack opening based softening part). In terms of uniaxial tensile test, this study followed the specimen preparation and testing procedure as proposed by Wille, et al. [11]. In accordance to Wille et al. [11], the UHPFRC was poured in layers in dogbone shaped specimens mould to full capacity, but without any vibration. After casting, the specimens were covered and stored at room temperature for 24 h. Afterward they were removed from their moulds
and stored at room temperature for additional 25 days. All specimens are then tested at 28 days. About 24 h prior to testing, a spray coating was applied on the surface of the middle portion of each specimen for better crack detection. The uniaxial tensile test was conducted using Universal Testing Machine (UTM) Shidmadzu with capacity of 25 kN and loading rate was set to 0.01 mm/s. The dimension of dog bone shaped uniaxial tensile test specimen adopted in this study as per designed and proposed by Wille et al. [11] to full fill the following requirements: 1) Accommodates small specimen in order to reduce the material usage 2) Employs specimens that are easy to cast and prepare 3) Use specimen with region of a constant area to capture multiple cracking. Wille et al. [11] proposed that the largest size of material constituent must be less than one fifth of the smallest specimen dimension that is 3.4 mm. This allows testing paste and mortar like materials, such as the UHPC used in this current research, which has a maximum grain size of 0.8 mm. In comparison to the length of the fibers (13–30 mm), the height and width (17/30 mm) of the specimen moulds are relatively small. This is to ensure fibre alignment parallel with the load direction and it can be improved by placing the fresh material in layers. Finally, the mix proportion by means of the best constituent combination with respect to the maximum compressive strength, workability, tensile strength and strain hardening properties was obtained.

3. Result and Discussion

A series of test were conducted which involved plenty of specimens and it took two years to obtain the suitable mix of UHPFRC that full filled the requirement as repair material. The required properties of UHPFRC to be used as repair material are as follows [8]: 1) Self-compacting characteristic 2) High compressive strength and 3) High tensile strength with strain hardening property.

Even though there were many available UHPFRC mix in previous literature, very few mix satisfy all above mentioned properties at the same time. Moreover, most of the mix available in literature is not made from local available material and it is difficult to achieve satisfactory properties of UHPFRC just by replacing cement and superplasticizer from existing optimized UHPFRC mix with locally available material.

In this current study, the UHPFRC used was designed as self-compacting concrete and to achieve that purpose three different types of superplasticizer (MasterRheoBuild 1000, Glenium 6011, Glenium Ace 8109) have been tested and the one that achieved the targeted slump flow diameter around 600 to 760 mm was chosen. The inverted slump flow test was conducted on one mixture with those three different superplasticizers and it was observed that the flow diameter for Glenium 6011 and Glenium Ace 8109 were 590 mm and 780 mm, respectively, and no spread observed for MasterRheobuild 1000 specimens. Therefore, Glenium Ace 8109 type of superplasticzer was chosen.

It was found that silica fume also significantly affect the rheology property of UHPFRC. As shown in Figure 2, the slump flow decreases as the silica fume content increases from 5% to 20% and there was sharp reduction of slump flow diameter when 20% of silica fume was added into the mixture. It was also observed that the compressive strength of UHPFRC decreases as the silica fume content increases as illustrated in Figure 3. According to Vikan & Justnes [34], when silica fume content exceeds certain value, workability was reduced and greater viscosity lead to more void in fresh concrete. Therefore, this leads reduction of quality of concrete and negatively affects the compressive strength of concrete [22]. Based on these results, the silica fume content in UHPFRC mixture was limited to 10%.

Then the effect of water cement (W/C) ratio also has been examined and as tabulated in Table 1, it was found that reduction of W/C ratio to 0.175 significantly reduced the diameter of slump flow. Therefore, the w/c ratio was maintained to 0.2 as adopted by many researchers.
The influence of sand content also has been studied. Two different percentage of sand content has been considered i.e.: 18% and 88% as tabulated in Table 2. It clearly shows that the increase of sand content has resulted in reduction of slump flow diameter and increment of compressive strength. Therefore, the mix that rich with sand has been chosen in this study.

In this current study, amount of steel fibre in UHPFRC is one of the variables considered. Three different amount of steel fibre were taking into account, i.e. 1%, 1.5% and 2% by volume. The compression cube test and uniaxial tensile test were conducted to determine the compressive strength and tensile strength of UHPFRC, respectively. Results of both tests are shown in Figure 4 and 5. It can be seen that the tensile strength increase as amount of steel fibre increases. It is parallel with findings from previous studies [11].

| Water-Cement Ratio | D1 (mm) | D2 (mm) | Average Slump Diameter (mm) | T₅₀₀ (s) |
|--------------------|---------|---------|-----------------------------|----------|
| Specimen 1        | 0.200   | 820     | 835                         | 827.5    | 3.80        |
| Specimen 2        | 0.175   | 535     | 500                         | 517.5    | 74.85       |
Table 2. Effect of sand content.

| Sand Content (%) | Average Slump Diameter, D (mm) | Compressive Strength (MPa) |
|------------------|-------------------------------|---------------------------|
| 18               | 900                           | 81                        |
| 88               | 590                           | 94                        |

The average cube compressive strength of UHPFRC obtained from the compression test of three cube specimens from each concrete batch is shown in Figure 4. It can be seen that the compressive strength of UHPFRC is in the range of 119 MPa to 121 MPa. Most of previous researchers defined minimum compressive strength of UHPFRC is 150 MPa [9-13]. However, for in situ application it is challenging to obtain minimum compressive strength of 150 MPa as it is difficult to apply heat or steam curing at site. Moreover, compressive strength is not the main feature for UHPFRC as tensile strength is more important. The tensile strength of UHPFRC is ranging from 5.92 MPa to 10.43 MPa as shown in Figure 6. It is crucial for cementitious repair material to have minimum tensile strength of more than 10 MPa as shrinkage deformations at early age are restrained to a more or less large extent by the existing structure, which gives rise to very high tensile stresses up to 10 MPa [8,35]. In this study, UHPFRC with 2% amount of fibre full fill this requirement.

Figure 4. Average compressive strength of UHPFRC.

Figure 5. Tensile stress of UHPFRC.

Another important feature of UHPFRC is strain hardening property. Cementitious repair material which has this kind of property able to withstand the development of eigenstress due to restrained shrinkage by old concrete. Strain hardening material is when its tensile strength, $\sigma_{pc}$, is in access of its cracking stress, $\sigma_{cc}$ [36]. Figure 6 shows the stress strain curves resulted from uniaxial tensile test. It clearly shows strain hardening behaviour for UHPFRC with 2% steel fibre amount and its $\sigma_{pc}$ is higher.
than $\sigma_{cc}$. Meanwhile, in specimens with 1% and 1.5% volume of steel fibre, it was observed that there was strain hardening like trend after first cracking stress but the $\sigma_{pc}$ was lower than $\sigma_{cc}$. Therefore, it was not considered as strain hardening property. This shows that the minimum amount of fibre to obtain UHPFRC with strain hardening property is 2% by volume. It is however, possible that these results may be substantially different if the type of steel fibre (e.g.: hooked and twisted type of steel fibre) were used or for greater size of specimens as discussed by Wille et al., [11]. Moreover, UHPFRC with 2% amount of fibre was extremely more ductile than the one with 1% and 1.5% as the maximum strain attained by 2.0% was greater than another two specimens. Finally, based on testing results discussed above, this study propose UHPFRC mixture as shown in Table 3 for cast in situ application like repair works.

![Figure 6. Tensile stress strain curve of UHPFRC.](image)

**Table 3. UHPFRC mixture.**

| Material       | Amount (kg/m³) | Ratio to cement |
|----------------|----------------|-----------------|
| Cement         | 1000           | 1               |
| Silica Fume    | 53             | 0.05            |
| Fine Sand      | 887            | 0.89            |
| Water          | 210            | 0.02            |
| Superplasticizer| 53             | 0.05            |
| Steel Fibers   | 150            | -               |

4. Conclusion
The aim of this study is to manufacture the optimum UHPFRC mixture for in situ application like repair works. The following key mix variables has been investigated 1) Silica fume-cement ratio 2) Water-cement ratio 3) Paste content 4) Type and content of superplasticizer 5) Aggregate size and 6) Cement content. Based on results from slump flow test, compression test and tensile test, the mix proportion that has following properties of flowable, high compressive strength (> 115 MPa), high tensile strength (> 10 MPa) and strain hardening were obtained as shown in Table 3.

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