A Review on Raw Materials and Curing Methods Applied in Production of Ultra High Performance Concrete

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Abstract. Ultra high performance concrete (UHPC) refers to cement based materials exhibiting high compressive strength, tensile strength and excellent durability. This paper reviews the raw materials, preparation techniques and curing methods have significant influence on properties of UHPC. The use of very high cement content, high strength cement and silica fume may improve the strength and compactness but increase the production cost. The use of high temperature curing leads to denser microstructure and better performance than room temperature curing and water curing do, but obviously limits its application of UHPC. Thus, preparation of UHPC using widely and locally available raw materials such as ordinary Portland cement CEM Type 1 42.5N and common technology such as room temperature curing are trends in production of UHPC.

1. Introduction

Ultra high performance concrete (UHPC) is characterised by very high cement content (over 600 kg/m³), very low water to cement ratio (less than or equal to 0.2), use of silica fume, fine sand, superplasticizer and no coarse aggregate. In general it exhibits high compressive strength (over 120 MPa) and tensile strength (over 10 MPa) as well as very low water permeability [1]. The manufacturing of UHPC normally adopts thermal curing at 90°C or higher [2]. Despite the fact that this process significantly improves the mechanical and durability properties of UHPC, it causes in high manufacturing cost and limits its application. Lately, more researchers investigated the influence of the use of conventional raw material and common technology on the mechanical and durability properties of UHPC. These efforts have extended the application of UHPC and reduce the production cost of UHPC.

This paper summarizes the raw material, mixing methods as well as curing regime for UHPC to provide some insights and suggestions for further research works to produce economic and wide application UHPC.
The typical raw materials of UHPC include cement, silica fume, fine sand, water and superplasticizer as shown in Table 1. In terms of cement content, many previous studies used CEM Type 1 52.5N in producing UHPC [3-6]. However, the use of lower strength cement (CEM Type 1 42.5N) does not hinder UHPC to attain high compressive strength of 160 MPa [7-9]. Normally, cement content in UHPC is double compared to conventional concrete and it lies between 600 to 1100 kg/m³ as shown in Table 1. Due to low water-cement ratio of UHPC (which is around 0.2), not all of the cement particles can react with water, so the remaining cement will improve the particle packing density [6]. Current development shows that the cement content in UHPC is less than 1000 kg/m³ and using lower cement grade of CEM Type 42.5N. This trend shall significantly reduce the production cost of UHPC.

The packing density of grain mixture is a critical issue in manufacturing UHPC. In order to obtain maximum high compacity, de Larrad & Sedran [1] suggested the optimum ultrafine to fine ratio is 37% by volume (1/3 ultrafines + 2/3 fines). Note that, fine is particle smaller than 0.125 mm (e.g.

### Table 1. UHPC mixture from previous studies [3-10]

| References          | Name         | Cement | Sand | Silica Fume | Water | Super plasticizer | Others                  | Compressive Strength (MPa) |
|---------------------|--------------|--------|------|-------------|-------|-------------------|--------------------------|----------------------------|
| Lutfi Ay [11]       | Plain        | 1083   | 757  | 173         | 206   | 38.0              | Quartz powder            | 140                        |
| Graybel [8]         | CM24         | 745.1  | 80.4 | 193.7       | 199   | 49.2              | Limestone filler         | 120                        |
| Denarie [7]         | CM33_9       | 756.7  | N/A  | 196.8       | 206.7 | 54.5              | Limestone filler & Thixotropizing admixture | 120                        |
| Yu et al [6]        | UHPC 1,2,3   | 612.4  | 1273.4 | 43.7       | 202.1 | 45.9              | N/A                      | 100                        |
| Choe et al [5]      | UHSC2        | 652    | 1318 | 124         | 150   | N/A               | Coarse Aggregate, Slag and Gypsum | 125                        |
| Muhd Norhasri et al. [10] | NMKA1      | 800    | 433  | 160         | 16.0  | Coarse aggregate (800 kg/m³) | 164                        |
| Kahanji et al. [4]  | UHSC2        | 967    | 675  | 251         | 244   | 77.0              | Polypropylene and steel fibre | 128                        |
| Muhd Norhasri et al. [11] | OPC     | 800    | 433  | 160         | 16.0  | Coarse Aggregate (800 kg/m³) | 160                        |

2. Raw Material

The typical raw materials of UHPC include cement, silica fume, fine sand, water and superplasticizer as shown in Table 1. In terms of cement content, many previous studies used CEM Type 1 52.5N in producing UHPC [3-6]. However, the use of lower strength cement (CEM Type 1 42.5N) does not hinder UHPC to attain high compressive strength of 160 MPa [7-9]. Normally, cement content in UHPC is double compared to conventional concrete and it lies between 600 to 1100 kg/m³ as shown in Table 1. Due to low water-cement ratio of UHPC (which is around 0.2), not all of the cement particles can react with water, so the remaining cement will improve the particle packing density [6]. Current development shows that the cement content in UHPC is less than 1000 kg/m³ and using lower cement grade of CEM Type 42.5N. This trend shall significantly reduce the production cost of UHPC.
cement) and ultrafine is particle with a diameter D90 (90% fractile) smaller than 5 um (e.g. silica fume). The fine sand usually has a particle size from 150 to 600 um and is dimensionally the largest granular material used in manufacturing UHPC [10]. Hamiruddin et al [11] have used four different sand gradation of 63-300 um, 300-600 um, 600-1180 um, and normal sand, and they reported that the UHPC with sand size between 600-1180 um possess highest compressive strength. Recently, Norhasri et al., [7] and Norhasri et al., [8] used coarse aggregate (granite) with maximum size of 10 mm in UHPC and sand passing 4.75 mm as coarse and fine aggregate with ratio 1/3 for fine aggregate and 2/3 of coarse aggregate. The introduction of coarse aggregate in UHPC may create more voids and may impair the durability properties of UHPC. Therefore, durability related test such as water absorption and permeability test need to be conducted to UHPC mixture with coarse aggregate.

Silica fume is the most popular ultrafine material utilized in UHPC to enhance its packing density and durability properties. However, in terms of workability, the increase of amount of silica fumes to cement ratio lead to decrease the workability of UHPC due to its high surface area which absorbs more water. The slump flow of UHPC increases up to certain amount of silica fume and after that the increase of silica fume content decreased the slump flow [12]. Recent studies show that the absent of silica fume does not detriment the compressive strength of UHPC as shown in Table 1 [7-8]. However, further investigation need to be carried out to check on the durability properties such water absorption and permeability of those mixtures. This is because UHPC is not only good in mechanical properties it also has excellent durability properties.

The high packing density property of UHPC make it susceptible to explosive spalling failure under high temperature event [13]. Therefore, the increase of void when introducing coarse aggregate without reducing the mechanical properties may give benefit to the UHPC at elevated temperature. This is because it may help to reduce the pore pressure during high temperature event and will directly reduce the explosive spalling risk of UHPC. However, the drawback of high void content in UHPC is it may reduce the bond strength between UHPC matrix and steel fibre [14], in case steel fibre is to be used to improve the ductility of UHPC. Hence, further test need to be conducted to confirm this hypothesis.

It can be seen in from Table 1 that the water-cement ratio for UHPC is around 0.2 or less. This has become among the main features of UHPC to achieve high strength concrete. The water-cement ratio for an UHPC typically lies between 0.16 and 0.2. UHPC has lower water-cement ratio than conventional concrete, which is lies between 0.4 and 0.7. Lower water-cement ratio not only improves compressive strength of UHPC but also play a very important role on the magnitude of the shrinkage of UHPC. When those ratios remains lower than 0.2, the shrinkage is not significantly higher than in normal concretes. However, when they increase above 0.20 up to 0.30, the shrinkage also increases in a significant way, as shown by Loukili et al., [15]. Thus, as far as possible, it is better to keep the water-cement ratio lower than 0.2 in UHPC matrices and the lowest possible, considering the necessary rheology to obtain a self-compacting character and adapted to the conditions of application. It is worth mentioning that despite the fact that the water-cement ratio of UHPC is dramatically smaller than in usual concretes (0.16 to 0.20 typically instead of 0.4 to 0.6), the absolute water quantity used in the mix remains in the same range (150 to 250 litres per m3). Hence, the only reason for the extremely low water-binder or water-cement ratio in UHPC is the very high cement content.

The low water-cement ratio in UHPC mixture has made UHPC stiff and less workable. This is the reason for superplasticizer comes in UHPC mixtures and the superplasticizer used in making UHPC is not a common one, it is polycarboxylate type of superplasticizer normally used in manufacturing self-compacting concrete. Typical superplasticizer-cement ratios in UHPC are much higher than in usual concretes or self-compacting concrete, and in the range of 2 to 4 % mass. A study of the efficiency of superplasticisers as a function of their dosage is crucial step in the design of a UHPC formulation. The superplasticiser dosage at saturation in which there is no increment of slump diameter is a critical factor. One of the common method used to determine slump diameter is using inverted slump test method following ASTM 1611 [16] and the optimum slump diameter is in the range of 600 to 760 mm. Figure 1 show the measurement of slump diameter after the cone is lifted in inverted slump test.
Furthermore, it is worth trying different superplasticiser available locally, from different brands, to try overcoming workability barriers. The high superplasticiser dosages in UHPC also induce a significant delay of setting (from 12 to 36 hours typically). This can be avoided by the use of accelerating admixtures if needed.

![Figure 1. Measuring slump diameter of UHPC [17]](image)

3. Mixing Technique
Besides that, mixing sequence and mixing method also significantly influence the properties of UHPC. Based on the mixture proportion of DENSIT and Reactive Powder Concrete (RPC), Benson and Karihaloo [8] has invented and patented the mixing procedure of UHPC named as CARDIFRC®. It is learned that, the mixing procedure designed by Benson and Karihaloo [18] is to ensure even fibre distribution and fluidisation of dry constituents with a mixture of water and superplasticizer to produce UHPC with superior mechanical performance. These procedures are summarized below. First, all the dry materials are placed in the mixing pan with following sequence: coarsest sand, microsilica, cement, next coarsest sand, least coarse sand, 13 mm long steel fibre and finally 6 mm steel fibre. Note, before each addition the constituents are thoroughly mixed for at least 2 min. In order to obtain well distributed fibre, the sieve pan is used. Then, mix the water and two-thirds of the superplasticiser together, and gradually added the water/superplasticiser mixture to the mixed dry constituents. Finally, add the remaining one-third of the superplasticiser and mix until the constituents are thoroughly mixed and wetted. There is not many researcher explain in detail the mixing sequence of UHPC as presented by Benson and Karihaloo [18]. Therefore, the above mixing sequence shared by Benson and Karihaloo [18] can be used at the beginning of the study to produce UHPC with good mechanical properties.

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 UHPC 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. Figure 2 shows the mixer to prepare UHPC [17].
4. Curing method
Curing regime significantly influences the mechanical and durability properties of UHPC. In comparison with normal concrete, UHPC has much lower water content which is about 0.2 of cement content compared to 0.5 for normal concrete. This would cause surface crack to occur if the surface is not protected from drying. Moreover, it is well known that self-desiccation occur within the whole mass of concrete and drying process begins at the surface of concrete. This may lead to tensile stress gradient at the surface. Therefore the curing membrane that is adequate for normal concrete may not be suitable for UHPC.

There are various curing methods applied for UHPC namely normal room temperature curing, heat or steam or warm water curing with atmospheric pressure and autoclave curing. For room temperature curing, the specimen is left in room temperature environment for 28 days or until the day of testing. The specimens can be wrapped with plastic sheet as shown in Figure 3 to minimize the moisture loss. It is the most economical curing method. Meanwhile, for warm water curing, normally specimen is submerged in water at 90 to 100°C for certain period of time. Zhang et al [19] left the specimens in warm water for two days and Yang et al [20] took longer time which was seven days in warm water before kept the specimens in standard room environment until the day of testing. Zhu et al [21] heat the specimens at 100°C for two days and Yazici [22] steam cure the ultra-high strength concrete cube for six and twelve days at 90°C with heating rate of 11°C/hour. The prolong heat curing duration improve the pozzolonic activity of silica fume and also enhance the chain length of C-S-H [23]. It was reported that after 48 hours of heat curing, about 10 to 50 MPa of compressive strength could be further gained when compared to that after 28 day of standard room curing [19,21]. It was reported that the UHPC matrix is much denser when it is heat cured due to enhanced hydration procedure compared to normal cured one [3]. There are additional calcium silicate hydrates (C-S-H) when concrete is cured at elevated temperature. This leads to greater compressive strength, tensile strength, better bond strength and excellent durability properties due to lower permeability and porosity [24]. Study by Kahanji et al [3] shows that the compressive strength of heat cured UHPFRC specimen was 172 MPa and normal cured UHPFRC was 128 MPa. In this case, the hot cured specimens were submerged in hot water for 7 days with temperature of 90°C and then, they were stored in conditioning room in conformity with BS EN 1363-1 [25], meanwhile for normal cured specimens, they were cured in water at ambient temperature for 28 days. It shows that the compressive strength of heat cured UHPFRC was approximately 34% higher than water cured specimens.

Moreover, for autoclave curing, the specimens will be heated to about 200°C and pressed at certain magnitude of pressure. For example, Zhang et al [20] applied 1.2 MPa of pressure at 200°C for 6 hours and Yazici [22] applied 2.0 MPa at 210°C for 24 hours. The compressive strength of autoclave cured UHPC is greater than heat and normal room temperature cured UHPC [10]. The improvement is about 10 to 40 MPa [19]. This is because autoclave curing may improve cement hydration degree and polymerization degree of C-S-H compared to normal room temperature curing and heat curing.
Moreover, autoclave also may improve the pore structure by reducing the total porosity and the content of large pores. Autoclave curing also can enhance the interfacial zone area (ITZA) between the quartz sand and the cement matrix [19].

![Figure 3](image)

**Figure 3.** Specimens are wrapped with plastic sheet to minimize the moisture loss [17]

Curing regime also affect the shrinkage of UHPC. Zhu et al. [21] reported that no shrinkage was observed after heat curing process regardless of free shrinkage and restrained shrinkage. However for UHPC under normal temperature curing, in the first three day shrinkage developed at slower rate than heat curing did and after 150 days there was still slight increase of shrinkage for normal curing UHPC. For cast in place application like repair works, ambient curing is more favourable since heat curing as well as autoclave curing at site requires extra cost and works. Table 1 shows a number of researchers and their mixture proportions of normal cured UHPFRC with high compressive strength of more than 120 MPa. This indicates that it is possible to produce UHPFRC with high compressive strength of more than 120 MPa without heat or steam curing. However, extra care must be taken when applying normal curing as water cement ratio of UHPC is very low which is about 0.2. This may cause the shrinkage crack at the surface of the specimens. To avoid the shrinkage crack, Lutfi Ay [9] suggested to seal the specimens with plastic sheeting to prevent the moisture exchange of the specimens from the environment.

5. Conclusion
With regards on the above reviews and discussions, following summaries can be made:

i. The current trend in production of UHPC by using only fine and coarse aggregate, superplasticizer, water and relatively low content of CEM 1 42.5 type of cement may reduce the cost of UHPC without compromising its compressive strength. However, further research work need to be done to assess the durability properties such as impermeability and heat resistance as well as other mechanical properties such as tensile strength and fibre pull out strength.

ii. Furthermore, the quantity of superplasticizer also can be optimized by using mixer with various speeds. This will leads to reduction of setting time to obtain high early strength and also may contribute to raw material cost saving.

iii. The potential of using room temperature curing in producing UHPC will broaden the application of UHPC. The previous studies showed that room temperature cured UHPC possess comparable compressive strength, however, further research works are required to investigate the effect of room temperature curing induced shrinkage on the durability properties of UHPC.
References

[1] de Larrard F and Sedran T 1994 *Cement and Concrete Research* 24 997-1009.
[2] Voo Y L, Nemtollahi B, Mohamed Said A B, Gopal B A and Yee T S 2012 *International Journal of Sustainable Construction Engineering & Technology* 3 2180-3242.
[3] Kahanji C, Ali F, Nadjai A and Alam N 2018 *Construction and Building Materials* 182 670-681.
[4] Choe G, Kim G, Gucunski N and Lee S 2015 *Constructions and Building Materials* 86 159-168.
[5] Caplar R and Kulic P 1973 Proc. Int. Conf. on Nuclear Physics (Munich) vol 1 (Amsterdam: North-Holland/American Elsevier) p 517
[6] Graybeal B A 2007 *ACI Materials Journal* American Concrete Institute 104 2.
[7] Norhasri M S M, Hamidah M S, Mohd Fadzil A 2019 *Construction and Building Materials* 201 590-598.
[8] Norhasri M S M, Hamidah M S, Mohd Fadzil A and Megawati O 2016 *Construction and Building Materials* 127 167-175.
[9] Schmidt M, Fehling E and Geinsenhansluke C 2004 *Ultra high performance concrete (UHPC)* (Structural Material and Engineering Series) p 695-701.
[10] Caijun Shi, Zemei Wu, Jianfan Xiao, Dehui Wang, Zheng Yu Huang and Zhi Fang 2015 *Construction and Building Materials* 101 741-751.
[11] Hamiruddin N A, Abd Razak R, Muhamad K, Zahid M Z A M, Aziz C N S 2018 *Solid State Phenomena* 280 476-480.
[12] Wu Z, Shi C and Khayat K H 2016 *Cement and Concrete Composites* 71 97-109.
[13] Mohamed Nazri F, Ramadhansyah Putra Jaya, Abu Bakar B H, Raudhah Ahmad 2017 *Fire Resistance Of Ultra-High Performance Fibre Reinforced Concrete Due To Heating And Cooling* (MATEC Web of conferences) p 01021.
[14] Liu J, Han F, Cui G, Zhang Q, Lv J, Zhang L, Yang Z 2016 *Construction and Building Materials* 12 310-318.
[15] Loukili A, Roux N, Arlot D and Feylessoufi A 1996 *Effect of high reduction in initial water content in cement based matrix* (International Symposium on the Utilization of High Strength/High Performance Concrete) pp 1367-1373.
[16] Zahid M M, Bakar B A, Nazri F M, Ayob And Razak R A 2020 Manufacturing of cast in situ ultra high performance fibre reinforced concrete (uhpfc)-Workability, Tensile and Compressive Strength (IOP Conference Series: Materials Science and Engineering) 743.
[17] Mohd Zahid M Z A 2020 *PhD Thesis* (Universiti Sains Malaysia).
[18] Zahid M M, Bakar B A, Nazri F M, Ayob And Razak R A 2020 Manufacturing of cast in situ ultra high performance fibre reinforced concrete (uhpfc)-Workability, Tensile and Compressive Strength (IOP Conference Series: Materials Science and Engineering) 743.
[19] Zhang H, Ji T, He B N and He L 2019 *Construction and Building Materials* 213 469-482.
[20] Yang S L, Millard S G, Soutsos M N, Barnett S J and Le T T 2009 *Construction and Building Materials* 23 2291-2298.
[21] Zhu Y, Zhang Y, Hussein H H, Liu J and Chen G 2020 *Cement and Concrete Composites* 110 103602.
[22] Yazici H *Building and Environment* 42 2083-2089.
[23] Masse S, Zanni H 1993 *Cement and Concrete Research* 23 1169-1177.
[24] Yuan J and Graybeal 2015 *ACI Structure Journal* 112 851-860.
[25] BS EN 1363-1: 2012: Fire resistance tests, General requirements. B.S. Institution, London.