

## Mix design and properties evaluation of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)

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### ABSTRACT

Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) is a potential candidate for protective constructions. This paper addresses the mix design and properties assessment of an UHPFRC. The design of the concrete composites is based on the modified Andreasen & Andersen particle packing model. Limestone and quartz powders were utilized as replacement materials for cement to reduce the cost of UHPFRC. The workability, porosity, cement hydration degree, flexural and compressive strength of the UHPFRCs were measured and analysed. The results show that utilizing the improved packing model, it is possible to produce a type of UHPFRC with a low porosity and low binders amount. The addition of fillers to replace around 30% cement can significantly improve the workability of UHPFRC and increase the efficiency of cement to the flexural and compressive strengths. Additionally, after 28 days of curing, there is still a large amount of unhydrated cement in the UHPFRC matrix, which could be further replaced by other fillers (limestone powder, etc.) to improve the workability and cost efficiency of UHPFRCs.

**Keywords:** Mix design, fillers, properties evaluation, Ultra-High Performance Concrete (UHPC), Ultra-High Performance Fibre Reinforced Concrete (UHPFRC)

### INTRODUCTION

The development of new plasticizing concrete admixtures during the past years as well as improvements in the technology of cement and other fine materials production regarding their quality and fineness, offered new possibilities for the design of high performance concrete mixes [1]. Not only new materials but also new insights in the particle packing and the influence of the particle packing on the mechanical properties allowed the design of concrete mixes that have higher strength and deformation capacity than normal strength concrete (NSC) [2-4]. Based on this knowledge, the Ultra-High Performance Fibre Reinforced Concretes (UHPFRC) are produced and become more and more popular in recent years.

UHPFRC is a combination of high strength concrete and steel fibre reinforcement. According to Richard and Cheyrezy [5], UHPFRC represents the highest development of High Performance Concrete (HPC) and its ultimate compressive strength depends among others on the curing conditions, possible thermal treatments as well as the adopted manufacturing technique. In 2005, Rossia [6] investigated the bending and compressive behaviour of a cement composite developed in the Laboratoire Central des Ponts et Chaussées (LCPC). Its characteristic strength and ultimate strain in compression were equal to 205 MPa and  $4 \cdot 10^{-3}$ , respectively. Additionally, to reduce the cost of UHPFRC, some wastes or cheaper materials are also included in the concrete design and production in recent years. For example, Tuan [7-8] investigated the possibility of using rice husk ash (RHA) to replace the silica fume (SF) in producing UHPC (about 1000 kg/m<sup>3</sup> of binders were utilized). Yang [9] utilized recycled glass cullet and two types of local natural sand to replace the more expensive silica sand, normally used to produce UHPFRC (about 1200 kg/m<sup>3</sup> of binders were utilized).

However, as can be noticed when producing UHPC or UHPCRC, the binder content is always relatively high (normally more than 1000 kg/m<sup>3</sup>), which have negative influence on economical and environmental aspects. Especially today, as more attention has been paid to the reduction of the released CO<sub>2</sub> and developing sustainable materials, how to rationally design and produce UHPC and UHPFRC is still an open question. As

commonly known, an optimum packing is the key for a good and durable concrete [3-4]. Nevertheless, from available literature, it can be found that the investigation focus on this field is not sufficient [10]. In most cases, the recipes of UHPC or UHPFRC are given directly, without detailed explanation or theoretical support. Hence, it can be predicted that a large amount of binders are not well utilized.

The objective of this study is to effectively design and produce the UHPFRC. The design of the concrete is based on the aim to achieve a densely compacted cementitious matrix, employing the modified Andreasen & Andersen particle packing model.

## METHODOLOGY

### Materials

The cement used in this study is Ordinary Portland Cement (OPC) CEM I 52.5 R, provided by ENCI (the Netherlands). A polycarboxylic ether based superplasticizer is used to adjust the workability of concrete. The limestone and quartz powder are used as fillers to replace cement. Two types of sand are used, one is normal sand with the fractions of 0-2 mm and the other one is micro-sand with the fraction 0-1 mm (Graniet-Import Benelux, the Netherlands). One type of commercial microsilica (powder) is selected as pozzolanic material. Short straight steel fibres (length of 13 mm and diameter of 0.2 mm) are employed to produce UHPFRC. The particle size distributions of used materials are summarized in Figure 1.

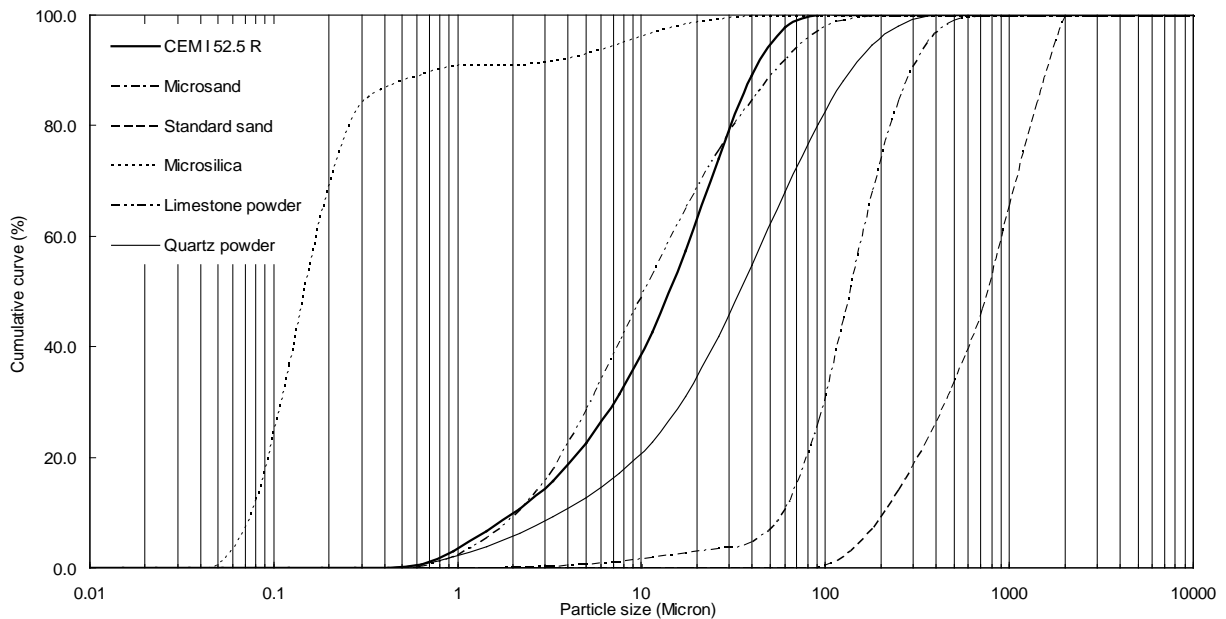


Figure 1. Particle size distribution of the used materials.

### Mix design of UHPFRC

As commonly known, the performance of composite materials is strongly linked to their porosity, which is related to the sizes, the composition and packing of all the applied solid ingredients in the mix [11]. In this study, all the concrete composites are designed based on this modified Andreasen and Andersen model, which is shown as follows [12]:

$$P(D) = \frac{D^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q} \quad (1)$$

where  $P(D)$  gives the cumulative passing fraction at a sieve with opening  $D$ ,  $D_{\max}$  is the maximum particle size ( $\mu\text{m}$ ) and the  $D_{\min}$  is the minimum particle size ( $\mu\text{m}$ ),  $q$  is distribution modulus. Brouwers [13] demonstrated that theoretically a  $q$  value range of 0 - 0.28 would result in an optimal packing. Hence, in this research, the value of  $q$  is fixed at 0.23.

In this study, the modified Andreasen and Andersen model (Eq. (1)) acts as a target function for the optimization of the composition of mixture of granular materials. When the deviation between the target curve and the composed mix, expressed by the sum of the squares of the residuals (RSS) at defined particle sizes, is minimized, the composition of the concrete is treated as the best one [3-4].

$$RSS = \sum_{i=1}^n (P_{mix}(D_i^{i+1}) - P_{tar}(D_i^{i+1}))^2 \quad (2)$$

where  $P_{mix}$  is the composed mix, and the  $P_{tar}$  is the target grading calculated from Eq. (2).

Based on the optimized particle packing model, the developed UHPC mixtures are listed in Table 1. In total, three different types of UHPC composite are designed. The reference concrete mixture (UHPC1) has high cement content (about  $875 \text{ kg/m}^3$ ). In UHPC2 and UHPC3, around 30% and 20% cement was replaced by limestone and quartz powder, respectively. Although the raw material is different in each mixture, the particle parking of the UHPC1, UHPC2 and UHPC3 are very similar. Hence, according to the comparison of the properties of the designed UHPCs, it is possible to evaluate the cement efficiency in UHPFRC and try to produce a dense UHPC matrix with low binder content. Additionally, to investigate the effect of fibres on the properties of UHPFRC, the steel fibres are added into the each UHPC mixes in the amount of 0.5%, 1.0%, 1.5%, 2.0% and 2.5% (volume percentage of concrete), respectively.

**Table 1.** Recipes of developed UHPCs

Materials	UHPC1 ( $\text{kg/m}^3$ )	UHPC2 ( $\text{kg/m}^3$ )	UHPC3 ( $\text{kg/m}^3$ )
CEM I 52.5 R	874.9	612.4	699.9
Limestone powder	0	262.5	0
Quartz powder	0	0	175.0
Microsand	218.7	218.7	218.7
Sand 0-2 (mm)	1054.7	1054.7	1054.7
Microsilica	43.7	43.7	43.7
Water	202.1	202.1	202.1
Superplasticizer	45.9	45.9	45.9
Water/binder ratio	0.22	0.22	0.22
Water/powder ratio	0.19	0.19	0.19

### Workability test of UHPFRC

To evaluate the workability of UHPFRC, the flow table tests were performed following EN 1015-3 [14]. From the test, two diameters perpendicular to each other ( $d_1$  and  $d_2$ ) can be determined. Their mean is deployed to compute the relative slump ( $\xi_p$ ) via:

$$\xi_p = [(d_1 + d_2)/2d_0]^2 - 1 \quad (3)$$

where  $d_0$  represents the base diameter of the used cone (mm), 100 mm in case of the Hägermann cone. The relative slump  $\xi_p$  is a measure for the deformability of the mixture, which was originally introduced by Okamura and Ozawa [15] as the relative flow area R.

### Mechanical properties test of UHPFRC

After performing the workability test, the UHPFRC was cast in moulds with the size of 40 mm × 40 mm × 160 mm and compacted on a vibrating table. The prisms were demoulded approximately 24 h after casting and then cured in water at about 21 °C. After curing for 7 and 28 days, the flexural and compressive strength of the specimens were tested according to the EN 196-1 [16]. At least three specimens were tested at each age to compute the average strength.

### Porosity of UHPFRC

The porosity of the designed UHPFRC was measured applying the vacuum-saturation technique, which is referred to as the most efficient saturation method [17]. The saturation was carried out on at least 3 samples (100 mm × 100 mm × 20 mm) for each mix, following the description given in NT Build 492 [18] and ASTM C1202 [19]. The water permeable porosity is calculated from the following equation:

$$\varphi_{v,water} = \frac{m_s - m_d}{m_s - m_w} \cdot 100 \quad (4)$$

where  $\varphi_{v,water}$  is the water permeable porosity (%),  $m_s$  is the mass of the saturated sample in surface-dry condition measured in air (g),  $m_w$  is the mass of water-saturated sample in water (g) and  $m_d$  is the mass of oven dried sample (g).

### Cement hydration degree of UHPC paste

Here, the loss-on-ignition (LOI) measurements of non-evaporable water content for hydrated UHPFRC paste were employed to estimate the hydration degree of cement [20]. Assuming that the UHPFRC paste is homogeneous system, the hydration degree of the cement in UHPFRC paste is calculated as:

$$\beta_t = \left( M_{105} - M_{1000} - M_{CaCO_3} \right) / M_{Water-Full} \quad (5)$$

where  $\beta_t$  is the cement hydration degree at hydration time (%),  $M_{105}$  is the mass of UHPC paste after heat treatment under 105 °C for 2 hours (g),  $M_{1000}$  is the mass of UHPC paste after heat treatment under 1000 °C for 2 hours (g),  $M_{CaCO_3}$  is the mass change of UHPC paste caused by the decomposition of  $CaCO_3$  during the heating process (g), and  $M_{Water-Full}$  is the water required for the full hydration of cement (g). The amount of non-evaporable water content of 0.24 g  $H_2O/g$  cement for fully hydrated cement pastes is used in this paper [20].

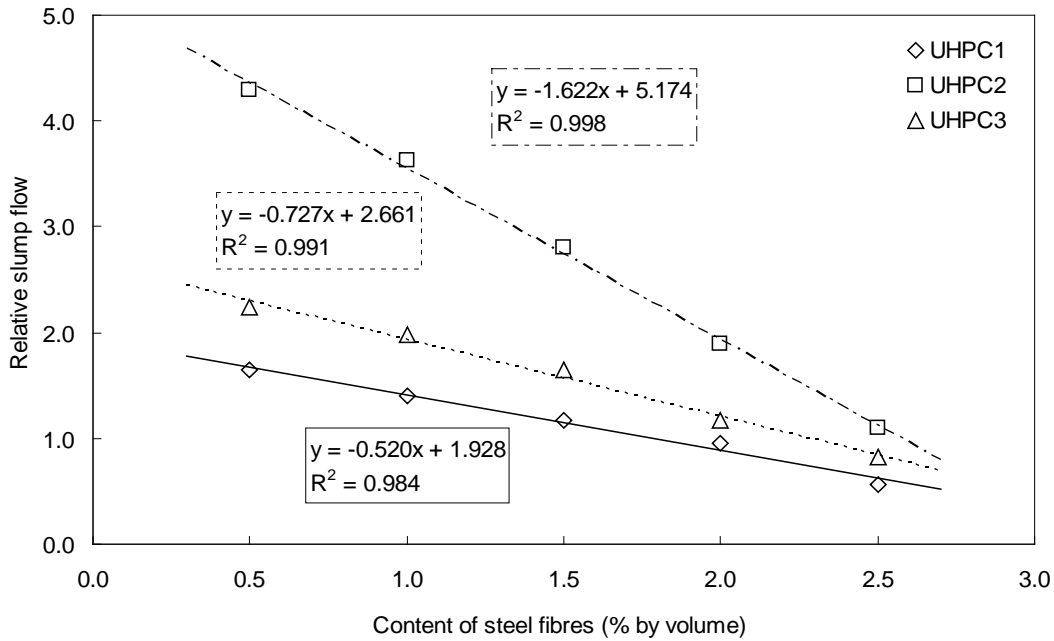
## EXPERIMENTAL RESULTS AND DISCUSSION

### Relative slump flow ability of UHPFRC

The relative slump flow of fresh UHPFRC mixes versus the volumetric content of steel fibres is depicted in Figure 2. The data illustrates the direct relation between the additional steel fibres content and the workability of the fresh UHPFRC. It is important to notice that with the addition of steel fibres, the relative slump flow ability of all the UHPFRCs linearly decreases. Moreover, with the same content of steel fibres, the relative slump of UHPC2 is always the largest, which is followed by UHPC3 and UHPC1, respectively. This difference between them is quite obvious at the beginning and then gradually declines, with the increase of additional fibre content. The phenomenon described above should be attributed to the increase in the internal surface area that produced higher cohesive forces between the fibres and concrete matrix. As the results presented by Edgington [21], with the increase of the additional fibre content, the workability of the normal concrete decrease sharply. Furthermore, the difference of cement content in each UHPFRC should also be considered. The cement content

of UHPC1, UHPC2 and UHPC3 is 875 kg/m<sup>3</sup>, 612kg/m<sup>3</sup> and 699 kg/m<sup>3</sup>, respectively. Hence, with the same water amount, utilizing fillers to replace cement can significantly improve the workability of concrete, similar to the results shown in [22-23].

Consequently, due to the high cohesive forces between the fibres and concrete matrix, the addition of steel fibres will decrease the workability of UHPFRC. The linear decrease tendency of the relative slump of UHPFRC with the increase of steel fibre content can be observed in this research. However, similar as normal concrete, appropriate utilizing the fillers to replace the cement could also be treated as an effective method to improve the workability of UHPFRC.

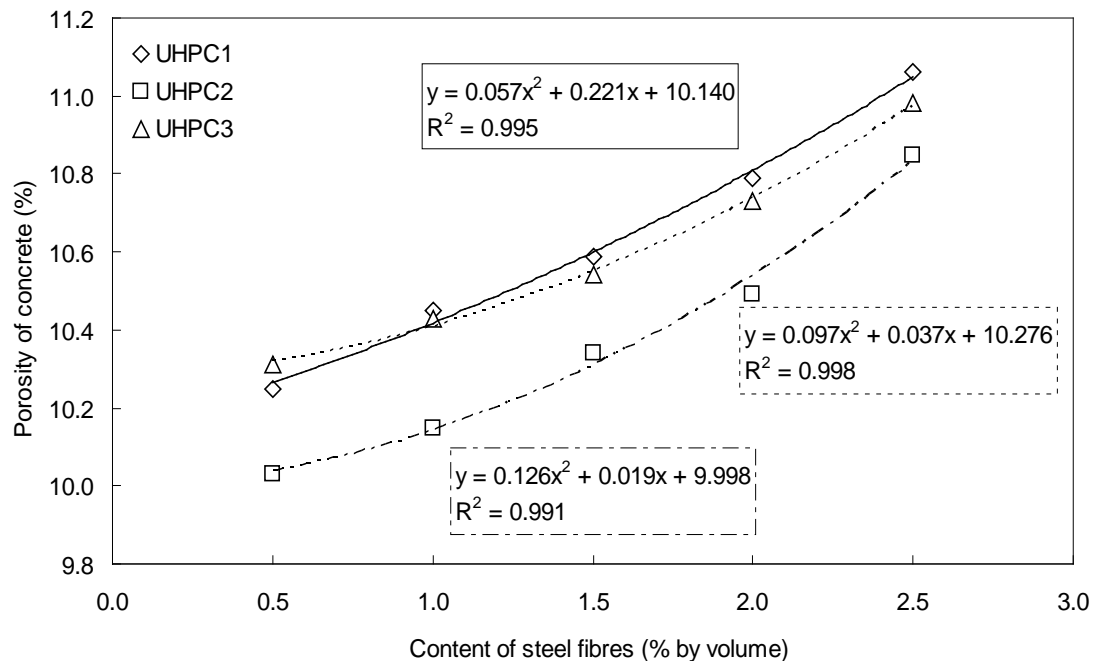


**Figure 2.** relative slump flow of UHPFRC with different cement and steel fibre content

### Porosity analysis of UHPFRC

The porosity of UHPFRCs in hardened state is presented in Figure 3. As can be seen, with the increase of the additional content of steel fibres, the porosity of each UHPFRC parabolically grows. Moreover, the porosity values shown in this study are smaller compared to conventional concrete. For instance, Safiuddin and Hearn [17] reported a porosity of 20.5% of the concrete produced with a water/cement ratio of 0.60, employing the same measurement method (vacuum-saturation technique). This should be attributed to the optimized particle packing of concrete composites and the low water/binder ratio, which causes the designed UHPFRC has a lower porosity and a denser internal structure.

Hence, it can be summarized that with the optimal particle packing skeleton, the porosity of the UHPFRC can be reduced and a denser structure can be obtained.



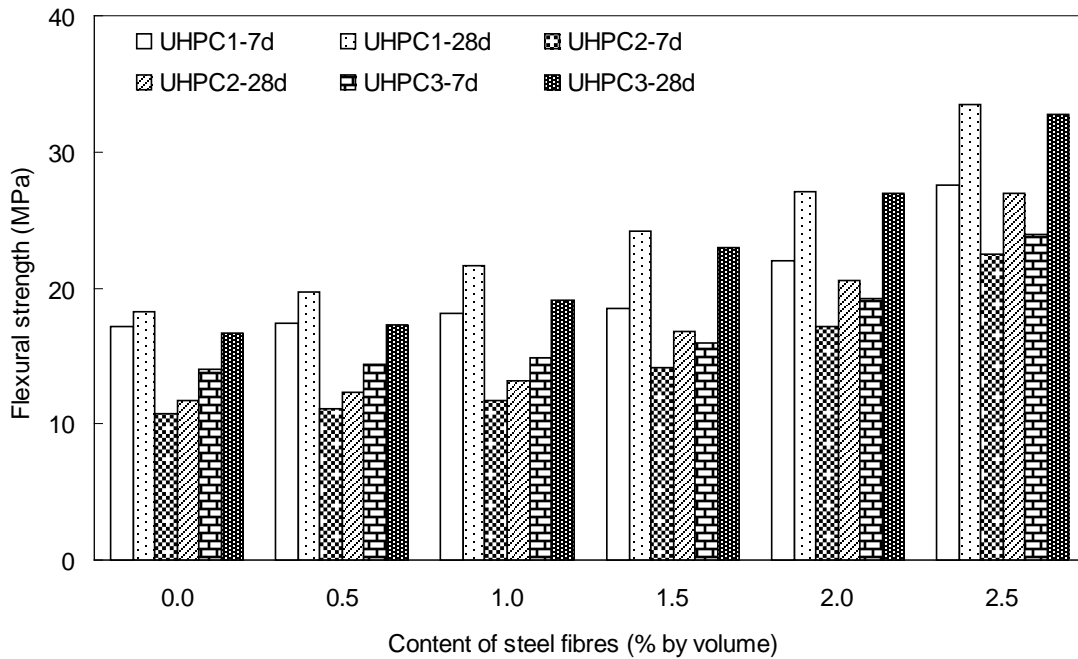
**Figure 3.** The porosity of UHPFRC with different cement and steel fibre content

### Mechanical properties analysis of UHPFRC

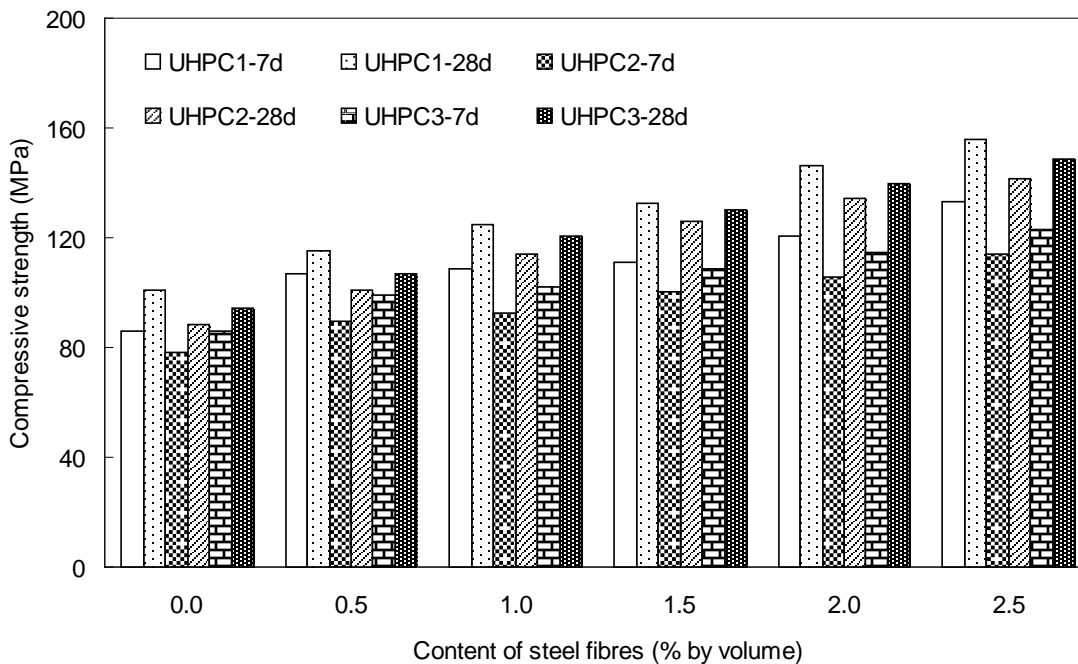
The flexural and compressive strengths of UHPFRCs at 7d and 28d versus the volumetric steel fibres content are shown in Figure 4 and 5. It is important to notice that with the addition of steel fibres, the flexural and compressive strengths of UHPFRCs can be significantly enhanced, similar to the results shown in [24-26]. Taking UHPC3 as an example, with the addition of steel fibres, the flexural strength at 28 days increases from 16.7 MPa to 32.7 MPa, and the compressive strength increases from 94.2 MPa to 148.6 MPa. Moreover, with the same fibre content and curing time, the flexural and compressive strength of UHPC1 are always larger than those of UHPC2 and UHPC3. For instance, with the addition of 2.5% (by volume of concrete) steel fibres, the flexural and compressive strength of UHPC1 at 28d are 33.5 MPa and 156 MPa, while that of UHPC2 are 27.0 MPa and 141.5 MPa, respectively.

Due to the addition of fibres, the fibres can bridge cracks and retard their propagation, which directly cause that the strength (especially the flexural strength) of concrete significantly increase. Additionally, the cement content also has close relationship with the strength of concrete. As the investigation of Sun [27], with the increase of water/cement ratio, the interface between matrix and aggregate or fibre will become denser. However, it should also be noticed that the strength difference between UHPC1 and UHPC3 is not so obvious after hydrating for 28 days, though that there is a 175 kg/m<sup>3</sup> difference in the content of cement between them.

In summary, it can be concluded that when utilizing 20-30% quartz or limestone powder to replace the cement in UHPFRC will decrease its strengths by about 10%. However, due to the optimized particle packing condition and low water/binder ratio, it is possible to produce a type of UHPFRC with low binder amount.



**Figure 4.** Flexural strength of UHPFRC after curing for 7 and 28 days

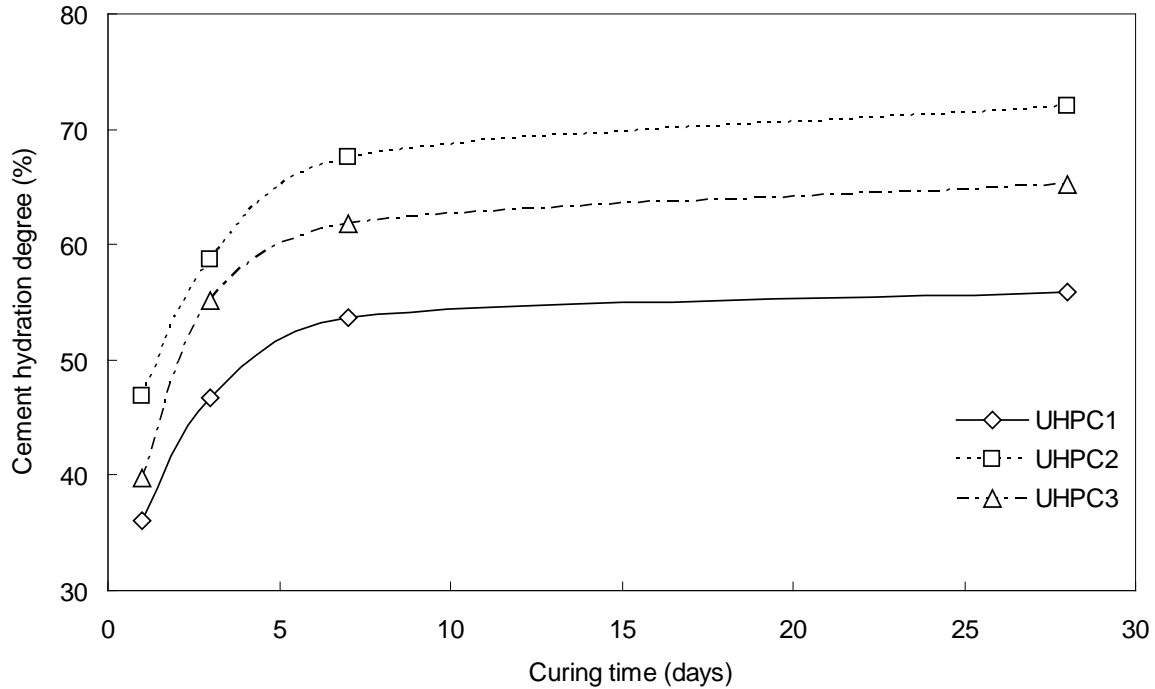


**Figure 5.** Compressive strength testing results of UHPFRC after curing for 7 and 28 days

### Cement hydration degree analysis of UHPFRC

The hydration degree of the cement in UHPFRC paste after hydrating for 1, 3, 7 and 28 days are indicated in Figure 6. The shape of these curves can be characterized with a sharp increase before 3 day, followed by a gradual slowing down between 3 and 7 days and a region of a very low increase later. This indicates that the hydration speeds of cement in UHPC paste is fast during the first 3 days, then gradually become slower and very

slow after 7 days. This phenomenon can be owed to the difference of cement content in each sample, which means that with the same content of water, the increase amount of cement will reduce its hydration degree. To sum up, it can be found that due to the low water/binder ratio, there are still a lot of unreacted cement particles in UHPFRC. Hence, in the mix design and production of UHPFRC, appropriate utilizing fillers (such as limestone powder and quartz powder in this study) to replace the cement can significantly enhance the cement hydration degree and its service efficiency.



**Figure 6.** Cement hydration degrees in each UHPC paste

## CONCLUSIONS

This paper presents the mix design and properties assessment for an Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). The design of the concrete composites is based on the aim to achieve an densely compacted cementitious matrix, employing the modified Andreasen & Andersen particle packing model. From the results addressed in this paper the following conclusions are drawn:

- Using the Andreasen & Andersen particle packing model, a dense and homogeneous skeleton of UHPC with low binder amount can be obtained. The compressive and flexural strengths of the designed UHPFRC are about 150 MPa and 30 MPa, respectively.
- In the reference concrete mixture, due to the low water/binder ratio and large cement content, its cement hydration degree is small. Hence, it is reasonable and available to replace these unreacted cement particles with filler materials (such as limestone and quartz powder) to enhance the efficiency of the used cement.
- Using fillers (such as limestone and quartz powder) as a replacement for the cement to produce UHPFRC can significantly improve its workability and enhance the efficiency of steel fibres and cement.
- The addition of steel fibres can decrease the relative slump flow of UHPFRC, and increase its porosity in the hardened state. Nevertheless, an appropriate particle packing and low cement content should be treated as the effective methods to reduce the negative influence of the additional steel fibres.



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## REFERENCES

- [1] Madani H., Bagheri A., Parhizkar T., The pozzolanic reactivity of monodispersed nanosilica hydrosols and their influence on the hydration characteristics of Portland cement. *Cem Concr Res* 2012; 42(12):1563-1570.
- [2] Brouwers H.J.H., Radix H.J., Self compacting concrete: theoretical and experimental study. *Cem Concr Res* 2005; (35): 2116-2136.
- [3] M. Hunger, An Integral Design Concept for Ecological Self-Compacting Concrete. PhD thesis. Eindhoven University of Technology, the Netherlands (2010).
- [4] G. Hüsken, A Multifunctional Design Approach for Sustainable Concrete with Application to Concrete Mass Products. PhD thesis. Eindhoven University of Technology, the Netherlands (2010).
- [5] Richard P., Cheyrezy M., Composition of reactive powder concretes, *Cem Concr Res* 1995; 25 (7): 1501-1511.
- [6] Rossia P., Arc A., Parant E., Fakhri P., Bending and compressive behaviour of a new cement composite. *Cem Concr Res* 2005; 35: 27-33.
- [7] Tuan N.V., Ye G., Breugel K., Copuroglu O., Hydration and microstructure of ultra-high performance concrete incorporating rice husk ash. *Cem Concr Res* 2011; 41: 1104-1111.
- [8] Tuan N.V., Ye G., Breugel K., Fraaij A.L.A., Dai B. D., The study of using rice husk ash to produce ultra-high performance concrete. *Constr Build Mater* 2011; 25: 2030-2035.
- [9] Yang S.L., Millard S.G., Soutsos M.N., Barnett S.J., Le T.T., Influence of aggregate and curing regime on the mechanical properties of ultra-high performance fibre reinforced concrete (UHPFRC). *Constr Build Mater* 2009, 23: 2291-2298.
- [10] Toledo Filho R.D., Koenders E.A.B., Formagini S., Fairbairn E.M.R., Performance assessment of Ultra-High Performance Fibre Reinforced Cementitious Composites in view of sustainability. *Mater Des* 2012; 36: 880-888.
- [11] Andreasen, A.H.M., and Andersen, J., Über die Beziehungen zwischen Kornabstufungen und Zwischenraum in Produkten aus losen Körnern (mit einigen Experimenten). *Kolloid-Zeitschrift* 1930; 50: 217-228 (In German).
- [12] Funk, J.E., and Dinger, D.R., Predictive Process Control of Crowded Particulate Suspensions, Applied to Ceramic Manufacturing. Kluwer Academic Publishers, Boston, the United States, 1994.
- [13] Brouwers, H.J.H., Particle-size distribution and packing fraction of geometric random packings. *Phys. Rev. E* 2006; 74: 031309-1-031309-14.
- [14] BS-EN-1015-3. Methods of test for mortar for masonry - Part 3: Determination of consistence of fresh mortar (by flow table). British Standards Institution-BSI and CEN European Committee for Standardization (2007).
- [15] Okamura, H., and Ozawa, K., Mix-design for self-compacting concrete. *Concrete Library JSCE* 1995; 25: 107-120.
- [16] BS-EN-196-1. Methods of testing cement - Part 1: Determination of strength. British Standards Institution-BSI and CEN European Committee for Standardization (2005).
- [17] Safiuddin M.d., Hearn N., Comparison of ASTM saturation techniques for measuring the permeable porosity of concrete. *Cem Concr Res* 2005; 35: 1008-1013.
- [18] NT Build 492. Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments. Nordtest method, Finland (1999).

- [19] ASTM C1202. Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. In Annual Book of ASTM Standards, vol. 04.02. American Society for Testing and Materials, Philadelphia, July (2005).
- [20] Feng X, Garboczia EJ, Bentza DP. Estimation of the degree of hydration of blended cement pastes by a scanning electron microscopy point-counting procedure. *Cem Concr Res* 2004; 34(10): 1787-93.
- [21] Edgington J., Hannant D.J., Williams R.I.T., steel fibre reinforced concrete, fibre reinforced materials, the construction press, Lancaster, England, 112-128.
- [22] Violeta B. B., SCC mixes with poorly graded aggregate and high volume of limestone filler, *Cem Concr Res* 2003; 33(9): 1279-1286.
- [23] Mehmet G., Erhan G., Mustafa E. K., Veysel B., Kasım M., Fresh and hardened characteristics of self compacting concretes made with combined use of marble powder, limestone filler, and fly ash. *Constr Build Mater* 2012, 37: 160-170.
- [24] Zhang Y., Sun W., Liu S., Jiao C., Lai J., Preparation of C200 green reactive powder concrete and its static-dynamic behaviours. *Cem Concr Comp* 2008; 30: 831-838.
- [25] Romualdi J., Mandel, J., Tensile Strength of concrete affected by uniformly distributed and closely spaced short lengths of wire reinforcement. *J. Amer conc Inst*; 1964; 61(6): 657-671.
- [26] Rossi, P., Acker, P., Malier, Y., Effect of steel fibres at two stages: the material and the structure. *Mater Stru* 1987; 20: 436-439.
- [27] Wei S., Mandel J.A., Said S., Study of the interface strength of steel fibre reinforced cement based composites. *ACI Mate J*; 1986; 83: 597-605.
- [28] Su N., Hsu K. C., Chai H. W. A simple mix design method for self-compacting concrete. *Cem Concr Res* 2001, 31(12): 1799-1807.