Development of sustainable ultra-high performance concrete

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Abstract. To design Ultra-high performance concrete (UHPC) in a sustainable way, this paper investigates the properties of UHPC containing supplementary cementitious materials (SCMs), such as fly ash (FA) and silica fume (SF). The flexural strength, compressive strength, and microstructure of the UHPC are examined. Results indicate that it is possible to design UHPC with very low cement amount. On the basis of 30% FA replacement, the incorporation of 10% and 20% SF shows equivalent or higher mechanical properties compared to the reference samples. The microstructure and pore volume of developed UHPC indicated a high correlation with its compressive strength. Efficiency factor (k-value) is calculated as an indicator to predict the flexural and compressive strength of UHPC with SCMs in terms of their synergistic effects.

1. Introduction

Ultra-high Performance Concrete (UHPC) has superior properties compared to normal strength concrete in terms of mechanical property and durability. The benefits of using UHPC in a structure includes reducing concrete amount, which in turn reduce concrete formwork, labor and equipment for erection, and construction time. However, given the recognized benefits, it is surprising that UHPC is not applied universally, which can be attributed to the high cost and high environmental impact per cube meter concrete. On the other hand, the global concrete producing makes up more than 5% of anthropogenic carbon dioxide emissions each year, namely from the production of cement. These issues can be addressed by incorporating supplementary cementitious materials (SCMs) to replace cement in a compressive way [1]. Therefore, great attentions have been paid to produce UHPC with less cost and lower emission while providing the equivalent properties.

For instance, Yu et al. [2] produced UHPC with 620 kg/m$^3$ cement content to obtain a compressive strength of 100 MPa. Ghafari et al. [3] utilized about 950 kg/m$^3$ cement and 250 kg/m$^3$ silica fume to produce UHPC. Hassan et al. [4] exhibited mechanical investigation with 657 kg/m$^3$ cement, 418 kg/m$^3$ GGBS and 119 kg/m$^3$ silica fume. Aldahdooh et al. [5] utilized 638 kg/m$^3$ cement to design UHPC with 120 MPa of compressive strengths.

Although much work has been conducted on this aspect, there still exists plenty of scopes that need to be investigated further [6]. Fly ash, a by-product of the industrial waste, has been proved to be useful in addressing the challenges of minimizing industrial waste and sustainable construction. It is worth mentioned in China, over 620 million tons of fly ash has been generated every year. However, the utilization ratio is still below 50%. Meanwhile, to overcome the deficiency of fly ash’s the slowdown in pozzolanic reaction, the incorporation of silica fume is supposed to expedite the pozzolanic reaction at the early age, as the silica fume particles can fill pores between larger particles of cement, sand and other fillers.

The aim of this work is to evaluate the possibility of replacing cement up to 50% of various SCMs through maintaining the equivalent performance compared to reference sample. Emphasis is focused...
on the synergistic effects and optimum proportion of these materials. For this purpose, the essential properties of UHPC, such as workability, flexural strength, and compressive strength is analyzed. Microstructure characteristics of mixture is examined by scanning electron microscopy (SEM). Barrett–Joyner–Halenda (BJH) method is used to calculate the pore size and distribution. Finally, based on the results, efficiency factor (k-value) is calculated as an indicator of synergistic effects efficiency of these SCMs.

2. Materials and experimental methodology

2.1. Raw material
An Ordinary Portland Cement (OPC, P.O 52.5) in accordance with the Chinese Standards GB175-2007 is used to produce HPC. China ISO Standard Sand (in accordance with ISO 679) is used as the aggregate with the fractions of 0-2 mm (D10=320um, D50=930um, D90=1600um). The commercially available superplasticizer (SP, powder, water reducing ratio >30%) is employed to adjust the workability of concrete. The detailed information of raw materials is presented in Table 1.

| Material | Density (kg/m³) | D10 (µm) | D50 (µm) | D90 (µm) | SSA (m²/g) | CaO (%) | SiO₂ (%) | Al₂O₃ (%) | Fe₂O₃ (%) |
|----------|----------------|----------|----------|----------|------------|---------|----------|-----------|-----------|
| OPC      | 3100           | 2.02     | 14.5     | 44.9     | 0.35       | 61.8    | 20.3     | 5.1       | 3.4       |
| FA       | 2300           | 2.80     | 15.9     | 55.6     | 0.33       | 3.26    | 53.5     | 20.6      | 3.18      |
| SF       | 2160           | 0.09     | 0.35     | 12.1     | 21.7       | —       | 91.2     | 0.41      | 0.32      |

2.2. Mixture proportions and specimen preparation
In this work, the modified A&A theory is used to design the mix proportion of UHPC. The reference UHPC has the highest cement content (875 kg/m³). Afterwards, the volume of FA is held constant by 30% replacement level, the SF in increment of 5%. For example, FA30SF20 represent that 30% cement is replaced by FA and 20% cement by SF. The mix design for each group is presented in Table 2.

| NO.       | OPC  | FA  | SF  | Sand | Water | SP  | W/B |
|-----------|------|-----|-----|------|-------|-----|-----|
| Reference (C1) | 875  | 0   | 44  | 1273 | 202   | 6.9 | 0.22|
| FA30SF5 (C2)  | 612  | 263 | 44  | 1273 | 202   | 9.5 | 0.22|
| FA30SF10 (C3) | 568  | 263 | 88  | 1273 | 202   | 10.6| 0.22|
| FA30SF15 (C4) | 524  | 263 | 132 | 1273 | 202   | 11.3| 0.22|
| FA30SF20 (C5) | 480  | 263 | 176 | 1273 | 202   | 11.9| 0.22|

A JJ-5 Cement & Mortar Mixer with two revolving speeds (140 or 285 rpm) in accordance with BS EN196-1 [7] is used to produce mixture. In total, 4 min and 30s is required to produce UHPC in the mixing procedure. After that, the slump flow of the fresh concrete is examined according to BS EN 1015-3 [8]. The amount of superplasticizer is adjusted until achieving a constant flow value between 250 to 280mm at a water to binder ratio (W/B ratio) of 0.22. Finally, the fresh mixture is cast into steel moulds with size of 40×40×160mm and compacted through a vibrating table for 1 min. After 24 hours, the specimen is demoulded and cured under the conditions (20°C±2°C, RH>90%) for the designed ages.
Flexural and compressive strength are examined according to BS EN196-1. At least three samples were put in the test for each group at different ages (7, 28, 90 and 365 days). For SEM test, sample is cut into the small cube with the dimension of 1×1×1cm after 90 days. For pore size distribution test, a weight of approximately 1.7-2.5g that extracted from mixture is tested by a ASAP 2020 at 365 days.

3. Results and discussion

3.1. Flexural strength

The flexural strength of developed UHPC at 7, 28, 90 and 365 days are presented in Fig.1a. It is apparent that the flexural strength of UHPCs decrease with the increase of FA alone. However, in combination with SF, the flexural strength of UHPCs increase. With the increase of SF, the flexural strength of UHPC increase gradually. The maximum flexural strength is obtained by C5 (FA30SF20), which is followed by C1 and C4. This means that with a total of 50% cement replacement, the flexural strength of C5 is equivalent to C1–marginally higher than that of reference sample. Furthermore, the flexural strength of each group increase with the progression of time, regardless of concrete type. This improvement is especially evident from 90 days to 365days. This can be attribute to the fact that FA’s slowdown in early strength development.

3.2. Compressive strength

The compressive strength of developed UHPC at 7, 28, 90 and 365 days are presented in Fig.1b. Similar to the tendency of flexural strength, with the increase of SF, the compressive strength of each group increase steadily. At 28 days, the highest compressive strength was obtained by C5, followed by C1 and C4. This fact can be explained by the filler effect of SF, which is responsible for the strength enhancement at early ages. At 365 days, the compressive strength of C2 and C3 approach C1, while compressive strength of both C4 and C5 exceed that of the C1. It is noticed that C5 has cement amount of 480 kg/m³, which means that it is possible to design UHPC with low cement.

It has been reported that the CaO/SiO₂ ratio have a strong effect on the strength development and optimal ratio of CaO/SiO₂ is about 1.30 [9]. In this study The CaO/SiO₂ of C1 to C5 are 2.46, 1.22, 1.02, 0.86 and 0.72, respectively. However, the C2 group fails to have a better compressive strength, although their CaO/SiO₂ ratio is most closing to 1.3. As such, it can be concluded that CaO/SiO₂ ratio should be used with caution and preferably in conjunction with the fineness and Al/Si or Ca/(Si+Al) ratio as a compressive strength predictor.

To clarify the efficiency of SCMs on compressive strength, the effect of FA+SF can be expressed as an efficiency factor (k-value) [10]. A k-value approaching one means that the addition is equivalent to cement. Based on the experimental results in this work, the k-value for FA30SF5, FA30SF10, FA30SF15 and FA30SF20 are 0.88, 0.95, 1.00 and 1.03, respectively.

3.3. Microstructure of UHPC

![Figure 1. (a) Flexural strength of UHPC (b) Compressive strength of UHPC](image-url)
The microstructure of concrete can influence the mechanical properties and could be explicated by the SEM observation [11]. Fig 2 shows the microstructure picture of each group observed at 90 days. It can be seen that FA30SF20 have the least capillary pores and the densest matrix compared to other groups, which is consistent with the compressive strength results—they had higher compressive strength. This indicates a positive effect of SF on the microstructure as well as strength enhancement.

It is reported that BJH method can be used to quantify the small pores in the range of 2-50nm [12,13]. As an exploratory attempt, the present work employ this method to quantify the pore size and distribution of developed UHPC. The pore size range, total volume and area of the UHPCs are shown in Table 3. The pore volume and area decrease with the increase of compressive strength. When the pore volume and area show the lowest value, the compressive strength obtain the highest value among the UHPCs. Therefore, it can be concluded that the BJH method seems to be an effective way to quantify the pore size and distribution of UHPCs.

| No. | >200nm $(10^{-3} \text{cm}^3/\text{g})$ | 110-200nm $(10^{-3} \text{cm}^3/\text{g})$ | 40-110nm $(10^{-3} \text{cm}^3/\text{g})$ | 10-40nm $(10^{-3} \text{cm}^3/\text{g})$ | <10nm $(10^{-3} \text{cm}^3/\text{g})$ | Total pore volume $(\text{cm}^3/\text{g})$ | Total pore area $(\text{m}^2/\text{g})$ |
|-----|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| C1  | 0.563                          | 0.613                           | 1.287                           | 1.683                           | 0.815                           | 0.0050                          | 0.969                           |
| C2  | 0.758                          | 0.985                           | 2.136                           | 2.274                           | 2.659                           | 0.0088                          | 1.586                           |
| C3  | 0.702                          | 0.816                           | 1.742                           | 1.987                           | 2.063                           | 0.0073                          | 1.343                           |
| C4  | 0.626                          | 0.693                           | 1.558                           | 1.669                           | 1.552                           | 0.0061                          | 1.159                           |
| C5  | 0.537                          | 0.572                           | 1.241                           | 1.533                           | 0.762                           | 0.0047                          | 0.932                           |

4. Conclusions
This paper evaluates the possibility of designing UHPC with low cement by using SCMs. The flexural strength, compressive strength, and microstructure of the UHPC are examined. From the results, the following conclusions are drawn:

(1) The addition of 30% FA decrease both flexural and compressive strengths compared to the reference sample. However, with the increase of SF, the mechanical properties can be improved gradually. The UHPC made by 30% FA and 20% SF shows the highest flexural and compressive strength in all mixtures. While the UHPC made by 30% FA and 10% SF exhibit equivalent mechanical properties in comparison with the reference sample.
(2) Based on the experimental results, the efficiency factor (k-value), which can be considered as synergic effect efficiency on compressive strength, is calculated. The highest k-value (1.03) was obtained by ternary blend of cement with 30% FA and 20% SF, followed by blend with 30% FA and 10% SF (1.00). It can be concluded that it is possible to produce UHPC with low cement (480 kg/m$^3$).

(3) The microstructure observation and pore volume results indicate a high correlation with mechanical properties. The mixture with densest matrix and least capillary pores shows the highest flexural and compressive properties. Furthermore, the BJH method is validated to be an effective way to quantify the pore size distribution of UHPC.

Acknowledgments
The authors gratefully acknowledge the Institute of Road and Bridge Engineering of Dalian Maritime University for funding this research.

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