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Effect of cementitious material composition on the mechanical properties of ultra-high strength concrete

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In order to investigate the effect of cementitious material composition on the mechanical properties of ultra-high strength concrete, a series of UHSC were fabricated by changing the addition of silica fume (SF) and fly ash. The mechanical properties, including compressive strength, flexural strength, and splitting tensile strength, were evaluated using a hydraulic servo universal testing machine. Fracture parameters such as fracture toughness and characteristic length were measured using the three-point bend loading method after prefabricating a crack in the sample. The results showed that the strength of UHSC increased with SF content and the maximum compressive strength and flexural strength can reach 130.24 MPa and 20.61 MPa, respectively. Adding fly ash may decrease the compressive strength of UHSC slightly. UHSC exhibited pronounced brittle fracture characteristics, with an increasing brittleness trend as its strength rises. Incorporating fly ash into the concrete can enhance its characteristic length and fracture energy while diminishing its fracture toughness. Our study may offer recommendations to reduce the brittleness of ultra-high-strength concrete.

Key words: UHSC, cementitious material composition, fracture toughness, brittleness, fracture energy

Вплив складу в'яжучого матеріалу на механічні властивості надвисокоміцних бетонів. *Jiankai Liao*

Досліджено вплив в'яжучого матеріалу різного складу на механічні властивості надвисокоміцного бетону (UHSC). Використовувалися добавки мікрокремнезему та летючої золи. Механічні властивості, включаючи міцність на стиск, міцність на вигин та міцність на розкол, оцінювали за допомогою універсальної випробувальної машини з гідравлічним сервоприводом. Параметри руйнування, такі як в'язкість руйнування та характерна довжина, вимірювалися з використанням методу триточкового згину після попереднього виготовлення тріщини у зразку. Результати показали, що міцність бетону збільшується зі збільшенням вмісту кремнезему, максимальна міцність на стиск та вигин можуть досягати 130,24 МПа та 20,61 МПа відповідно. Додавання летючої золи може трохи знизити міцність на стиснення UHSC. UHSC продемонстрував виражені характеристики крихкої руйнації з тенденцією до збільшення крихкості в міру підвищення його міцності. Включення летючої золи в бетон може збільшити його характерну довжину та енергію руйнування, одночасно зменшуючи його в'язкість.

1. Introduction

Ultra-high strength concrete (UHSC) is a remarkable construction material known for its exceptional mechanical properties and superior durability. Developed through advanced engineering and material science, UHSC possesses compressive strengths exceeding 120 MPa, significantly higher than conventional concrete. This outstanding strength, coupled with its enhanced resistance to chemical attacks and extreme weather conditions, has made UHSC increasingly popular in various construction applications worldwide [1-3]. The formulation of UHSC involves a precise combination of cementitious materials, aggregates, and chemical admixtures, along with strict quality control measures, resulting in an exceptional material with enhanced characteristics. High-performance cement, fine aggregates, and specially selected silica fume or ultrafine fly ash are typical components used in the production of UHSC, which reduce porosity, increase density and increase its strength. The unique properties of UHSC make it ideal for critical structural elements that require superior strength, such as high-rise buildings, bridges, dams, and infrastructure subjected to heavy loads or harsh environments [3, 4]. Its exceptional durability also contributes to increased service life, reducing maintenance costs and improving sustainability. Moreover, UHSC offers additional benefits such as increased resistance to fire, abrasion, and impact, making it an attractive option for structures exposed to extreme conditions. Its enhanced performance in terms of crack resistance and impermeability ensures better protection against corrosion and improves the structural integrity.

While Ultra-High Strength Concrete (UHSC) offers numerous advantages, it is essential to acknowledge its drawbacks. Firstly, the workability of UHSC is poorer than that of conventional concrete due to low water content and dense microstructure. Moreover, UHSC is prone to higher shrinkage rates compared to conventional concrete, which can lead to cracking, particularly in large, unreinforced elements. Most importantly, outstanding compressive strength of UHSC can sometimes lead to its brittleness. Unlike conventional concrete that exhibits ductile behavior before failure, UHSC tends to exhibit minimal deformation and sudden brittle failure once it reaches its ultimate capacity. This characteristic makes it less forgiving to design errors, sudden loading, or excessive vibrations, which may cause unexpected failures without warning [5].

Brittleness refers to the tendency of a material to break or fracture without significant deformation. In the case of UHSC, its exceptional strength and dense microstructure contribute to its brittleness. UHSC possesses significantly low tensile strength, leading to minimal ductility before failure. This significant difference between compressive and tensile strength makes UHSC more susceptible to sudden failure under tensile loads or bending moments. It tends to crack abruptly without any visible warning signs since it lacks the ability to withstand large deformations under stress. Once initiated, cracks in UHSC may propagate rapidly through the material due to its dense microstructure and lack of energy-absorbing capacity. The propagation of cracks can compromise the structural integrity of UHSC elements and result in sudden and catastrophic failure [6]. In order to mitigate the brittleness of UHSC, some reinforcement strategies have been employed, such as steel or fiber reinforcement to enhance its tensile capacity and ductility. Fiber reinforcement, in particular, can improve the post-cracking behavior of UHSC, allowing it to exhibit more ductile behavior and redistribute stresses within the material. Additionally, utilizing advanced analytical techniques, such as finite element analysis, can aid in assessing the behavior of UHSC structures under different loading scenarios and ensure that adequate measures are taken to minimize the risk of brittle failure [7].

Yuan et al. [8] investigated the effect of water-to-binder ratio and curing temperature on the mechanical property and brittleness of UHSC. The intrinsic properties of UHSC are determined by the composition of raw materials. Unfortunately, the effect of cementitious material composition on the fracture properties of UHSC has been rarely reported. Therefore, it's necessary to investigate the influence of material composition on UHSC mechanical properties. In this paper, UHSC samples were prepared were prepared by varying the amount of silica fume and fly ash additives, and the mechanical properties and facture parameters were measured. The effect of cementitious materials composition on UHSC was analyzed, and the mechanism was also revealed.

2. Experimental

2.1 Materials

Conch brand P·O 52.5 cement was used in this study. The diameter of super fine quartz sand was lower than 0.25 μm. Silica fume and fly ash were used as supplementary cementitious materials. A highly effective water-reducing agent based on polycarboxylic acid was used.

2.2 Sample preparation

To investigate the effect of silica fume or fly ash content on the mechanical properties of UHSC, a series of UHSC samples were prepared according to mix proportions in Table 1. The process involved in this study began with mixing fresh concrete using a mixer. The resulting mixture was carefully poured into a mould with specific dimensions of 40mm×40mm×160mm. In order to facilitate the determination of fracture parameters, a pre-existing crack was deliberately introduced by embedding a steel

Table 1. Mix proportions of UHSC

No.	Cement	Silica fume	Fly ash	Quartz powder	b/s ratio[a]	w/b ratio[b]
BS1	0.9	0.1	-	0.16	0.8	0.22
BS2	0.85	0.15	-	0.16	0.8	0.22
BS3	0.8	0.2	-	0.16	0.8	0.22
BSF1	0.85	0.05	0.10	0.16	0.8	0.22
BSF2	0.85	0.75	0.75	0.16	0.8	0.22
BSF3	0.85	0.10	0.05	0.16	0.8	0.22

[a] b/s ratio is binder to sand ratio; [b] w/b ratio is water to binder ratio.

plate measuring 40mm×16mm×1mm at the center of each specimen. The crack-depth ratio employed in this experiment was consistently maintained at 0.4. Subsequently, all samples were cured under standard conditions, namely at a temperature of 20±2°C and a relative humidity of more than 95%, for 1 day before removal from the mold. Finally, all samples were continuously cured to 28 days.

2.3 Mechanical and fracture property measurements

The measurement of compressive strength and flexural strength in this study was conducted according to the Chinese standard GB/T 17671-2020. An electro-hydraulic servo universal testing machine was utilized for the application of loads. The loading speed was consistently maintained at 0.5 kN/S. In this research, a beam with a single initial crack model was employed exclusively for computational purposes. Fracture parameters were determined by the three-point loading method, as shown in Fig. 1, using notched specimen testing. The loading rate was regulated by displacement. Up until a threshold of 70 kN, the loading rate remained 0.1m/min, after which, to fix the downward portion of the load-deflection curve, the loading rate was increased to 0.05 m/min The midspan deflection was carefully measured using a dial indicator to produce a deflection versus load curve. Fracture toughness, denoted KIC, is an important parameter in linear elastic fracture mechanics. This important indicator can be determined by evaluating the peak load displayed on the load-deflection curve of the notched specimen. The calculation equation employed to determine the fracture toughness value is as follows: [9]

$$K_{IC} = \frac{P_{max}}{B\sqrt{D}} F(\alpha) \qquad (1)$$

where $F(\alpha)=[(2+\alpha)(0.886+4.64\alpha-13.32\alpha^2+14.72\alpha^3-5.6\alpha^4]/(1-\alpha)^{3/2}$; $\alpha=a_c/D$; D is the height of specimen; B is the width of specimen; a_c is the depth of prefabricated crack; P_{max} is the peak load.

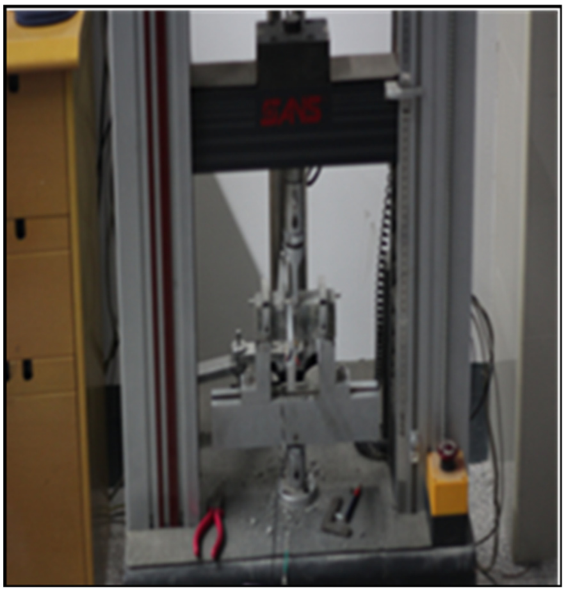

Fig. 1 Apparatus for measuring the mechanical properties

The characteristic length, denoted as L_{ch}, signifies the extent of plastic deformation occurring in the vicinity of the crack tip, thereby serving as an indicator of the brittleness of concrete. A smaller value of L_{ch} corresponds to a higher degree of brittleness in the concrete material. The L_{ch} value is determined by the following equation: [10]

$$L_{ch} = \frac{E_c G_F}{f_t^2} \qquad (2)$$

where, E_c is the elastic modulus; G_F is fracture energy; f_t is the axial tensile strength.

3. Results and discussion

3.1 Mechanical property

Fig. 2 shows the mechanical properties of UHSC samples. The compressive strength of

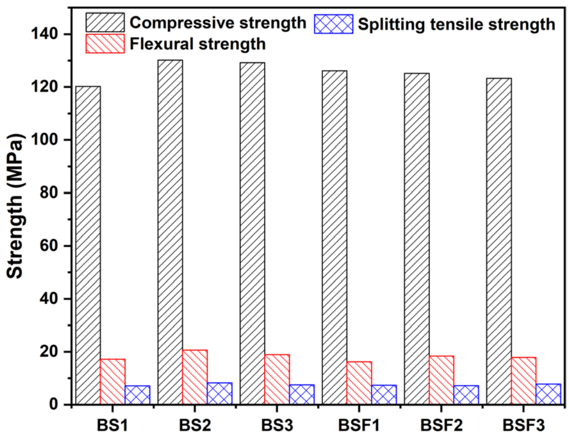

Fig. 2 Compressive strength, splitting strength, and flexural strength of samples

samples increased with a silica fume (SF) content, exceeding 120 MPa. When the SF content was 15% by mass of binder, the compressive strength can reach as high as 130.24 MPa. The high compressive strength was mainly attributed to the hydration and filling effect of SF microaggregates. The flexural strength and splitting strength of samples exhibited the similar trend with compressive strength. The highest flexural strength and splitting strength were 20.61 MPa and 8.32 MPa, respectively. The difference between the compressive and tensile properties of UHSC is significant. After replacing SF by fly ash (FA) partially, there was a small decline of compressive strength as well as flexural and tensile strength. But the compressive strength still exceeded 120 MPa, which was in accordance with UHSC. This indicated that the use of a composite cementitious material including SF and FA will not harm the mechanical properties of UHSC [11, 12].

To investigate the relationship between the tensile and compressive properties, the bending-compression ratio and tension-compression ratio of samples were calculated as shown in Fig. 3. The tensile strength of concrete is typically much lower than its compressive strength. Concrete has a relatively low tensile strength, ranging from about 5% to 15% of its compressive strength. Therefore, the tension-compression ratio of concrete is generally considered to be around 0.05 to 0.15. This means that concrete can withstand about 5% to 15% of the compressive load in tension before failing. Although the tensile strength of UHSC is higher than that of conventional concrete, the tension-compression ratio is much lower, as the highest tension-compression ratio was only 0.064, indicating that the addition of a mineral admixture led to poor tensile property. For conventional concrete, the bending-compression ratio ranged from 0.08 to 0.1. It should

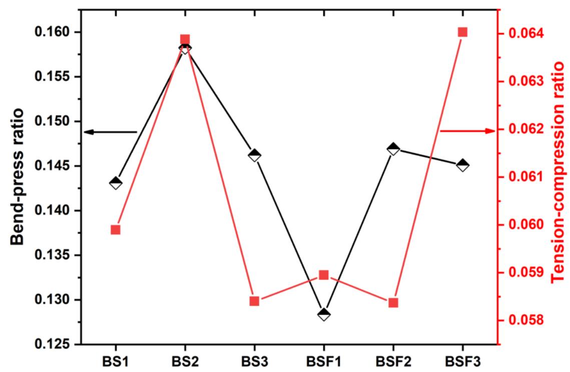

Fig. 3. Bending-compression ratio and tension-compression ratio of samples

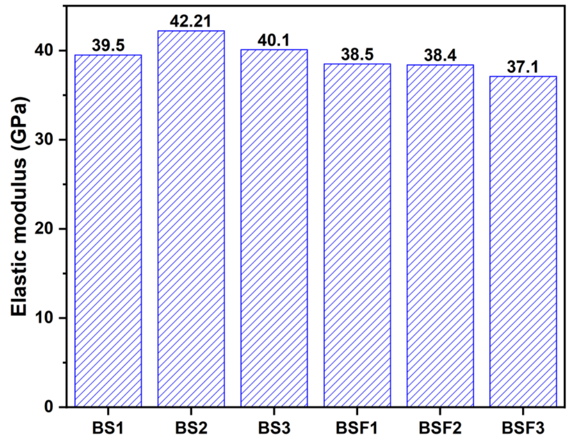

Fig. 4. Elastic modulus of samples

be noted that the lowest bending-compression ratio of UHSC is 0.128, which is higher than that of conventional concrete. This does not demonstrate the improvement in the tensile properties of UHSC, since flexural strength is affected by both compressive and tensile properties, and the enhanced bending-compression ratio of UHSC was primarily resulted from the increase in compressive strength. For samples with only SF added, the tension-compression ratio and the bending-compression ratio reached the highest as the SF content was 15%. And after adding FA, the tension-compression ratio and the bending-compression ratio increased with a content of FA. This suggests that the effect of incorporation of composite cementitious materials on compressive strength is relatively less pronounced compared to tensile strength. In another word, adding a composite cementitious material can improve the tensile properties of UHSC.

The elastic modulus refers to the stiffness or rigidity of a material and is a measure of its ability to deform under stress and return to its original shape when the stress is removed. Therefore, the elastic modulus of UHSC plays a significant role in determining its mechani-

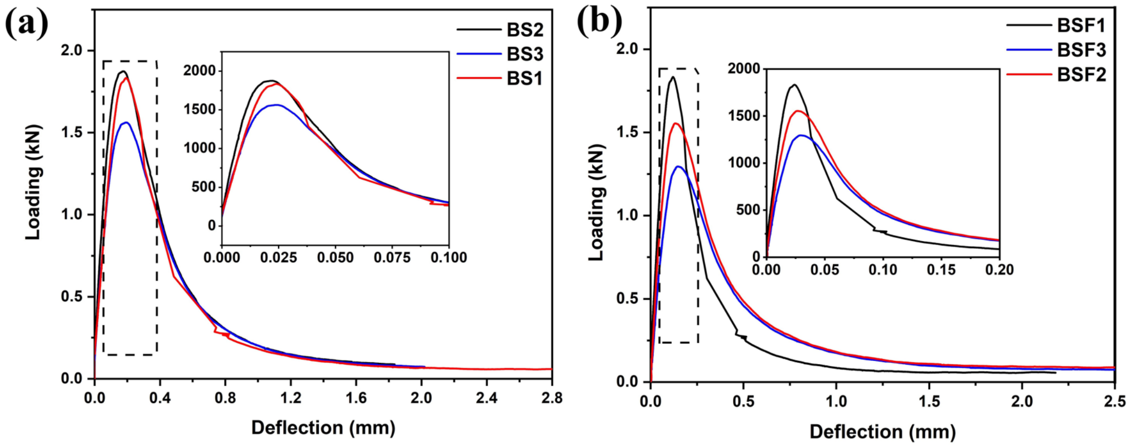

Fig. 5 Load-deflection curves of samples

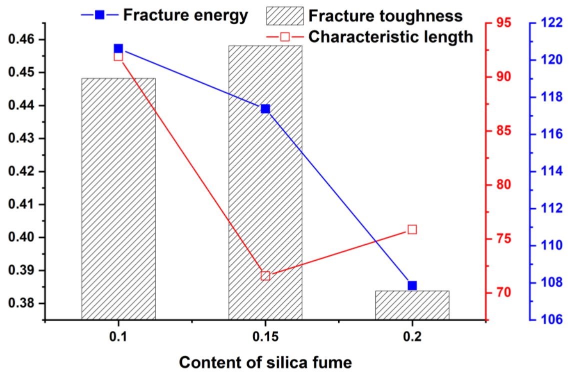

Fig. 6 Effect of silica fume content on fracture parameters

cal properties. As shown in Fig. 4, the elastic modulus of all the samples is similar, suggesting that the inclusion of SF and FA has a minimal effect on the elastic modulus. Compared to conventional concrete, the elastic modulus can reach as high as 42.21 GPa. UHSC with a higher elastic modulus exhibits greater stiffness, resulting in reduced deformations under load. A higher elastic modulus allows UHSC to bear higher loads before reaching its limit of deformation and experiences less long-term deformation under sustained loads.

3.2 Fracture property

Fig.5 shows load-deflection curves of all samples. As shown in Fig. 5(a), the load-deflection curves exhibit an approximately linear ascending segment and the peak of the curve approaches the ultimate load. The descending portion of the curves cannot be measured due to limitations in the rigidity of the test equipment, and specimens exhibit explosive failure after reaching the peak load, indicating a high level of brittleness in UHSC [13, 14]. This behavior can be attributed to the high homogeneity of UHSC due to the exclusion of a coarse aggregate. The presence of cracks primarily occurs within the matrix itself rather than in the interface transition zone (ITZ) between the cement paste and the fine aggregate. It is noteworthy that the peak load demonstrates an increase as the SF content increases, consistent with the observed correlation with compressive strength. The fracture behavior of samples with different addition of SF was similar. As shown in Fig. 5(b), after adding FA, load-deflection curves exhibited a similar trend, but the peak load decreased with the FA content, while deflection increased with the FA content. This means that the incorporation of FA can augment the plastic deformability of UHSC, while reasonable design of the cementitious material composition can reduce the brittleness of UHSC.

Fig. 6 displays the effect of the SF content on the fracture parameters of UHSC. Fracture toughness reflects the ability of materials to resist unstable crack propagation, namely, brittle fracture. When the SF content was 15% by mass of cement, UHSC had the highest fracture toughness. The enhanced fracture toughness was due to the improved binding capacity of cement. The higher the SF addition, the more hydration product paste. As the SF content increased to 20%, fracture toughness declined dramatically. This was because at high SF content, autogenous shrinkage was severe and numerous microcracks were formed in the cement matrix. Therefore, UHSC with a high content of SF was prone to cracking. Moreover, fracture energy and characteristic length also decreased with the SF content, confirming the enhanced effect of SF on brittleness.

Fig. 7 shows the effect of fly ash content on fracture parameters. As illustrated in Fig. 7(a), the fracture toughness exhibited a decreasing trend with increasing FA content, which was consistent with the behavior of compressive strength. This can be explained by the fact that the activity of FA was lower than that of

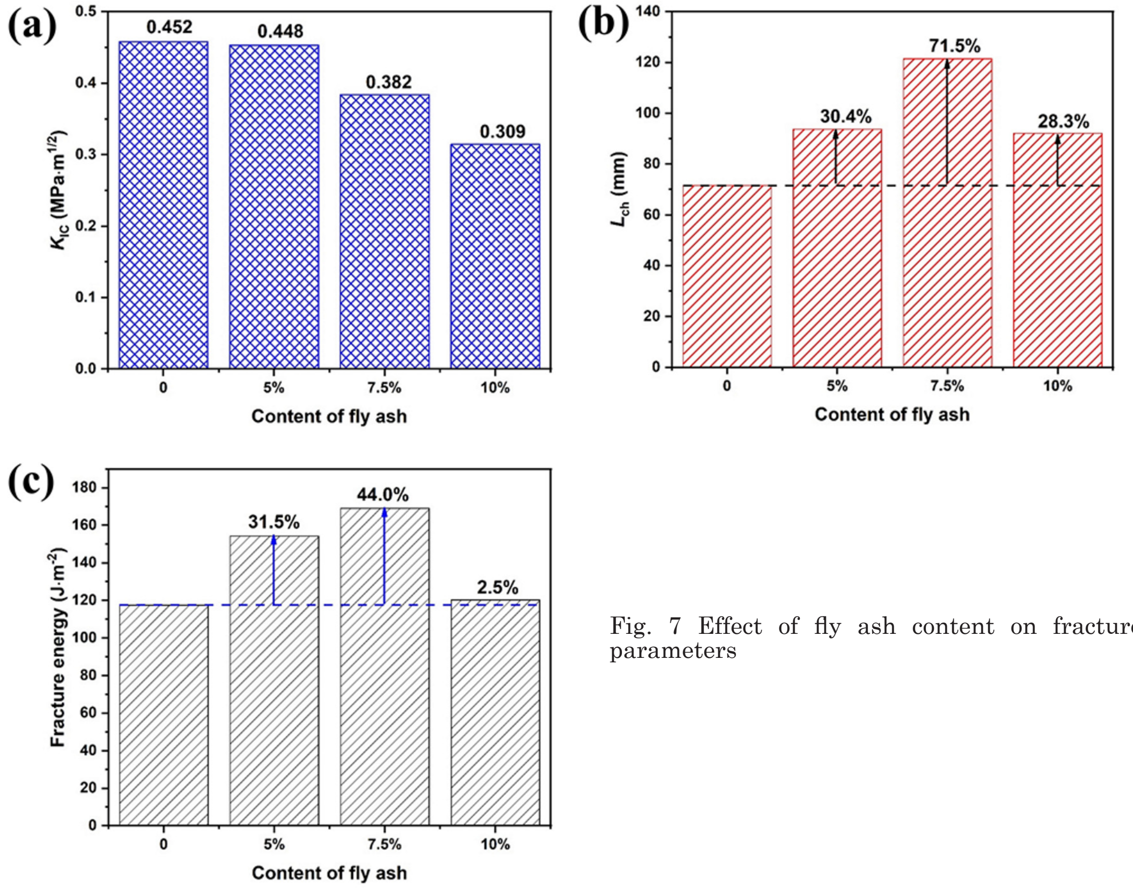

Fig. 7 Effect of fly ash content on fracture parameters

FA, and less products were formed at the same age, so the binding capacity was poorer and the critical load of cracking was lower. However, as shown in Fig. 7(b) and Fig. 7(c), the characteristic length and fracture energy increased increasing FA content. And compared to sample without FA, the characteristic length and fracture energy of sample with 7.5% FA can be increased by 71.5% and 44% at most, respectively. This indicated that the brittleness of UHSC was reduced after adding FA. Specifically, the plastic deformation in the vicinity of the crack tip increased and more energy can be absorbed before fracture failure, exhibiting enhanced toughness. This is related to the composition of hydration products [15, 16]. Since FA contains multiple phases, such as quartz, mullite, and amorphous phase, the hydration products of FA consist of several gels and crystalline phases, such as C-S-H, C-A-H, and quartz et al., which were more complicated than SF. In addition, FA was less active than SF, resulting in fewer microcracks formed during the early stages due to reduced autogenous shrinkage.

4. Conclusion

In this paper, the effect of cementitious material composition on the mechanical properties of ultra-high strength concrete was investigated, and the conclusions are as following. Ultra-high strength concrete (UHSC) was prepared by changing the composition of the cementitious material. Silica fume and fly ash were added to regulate the mechanical and fracture properties of UHSC. The compressive strength, flexural strength and splitting tensile strength can reach up to 130.24 MPa, 20.61 MPa and 8.32 MPa, respectively. When SF alone was added, the compressive strength increased with increasing SF content. While adding some FA, the compressive strength deteriorated slightly, but still exceeded 120 MPa. Although UHSC has a high limit load, it exhibits typical brittle fracture behavior and higher brittleness compared to conventional concrete. In general, the addition of SF increased fracture toughness while decreasing the characteristic length and fracture energy. In addition, incorporated fly ash reduced fracture toughness but improved the characteristic length and fracture energy. This was due to the complicated composition of the hydration products of FA. Fly ash can significantly mitigate the brittleness of UHSC.

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