ISSN 1027-5495. Functional Materials, 29, No.3 (2022), p. 401-407.
doi:https://doi.org/10.15407/fm29.02.401 © 2022 — STC "Institute for Single Crystals"

Investigation on the brittleness of ultra-high strength cement-based materials

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Received July 30, 2022

The aim of this paper is to investigate the factors influencing on the brittleness of ultra-high strength cement-based materials (UHSC). A conventional method was applied to prepare UHSC using normal raw materials. The basic mechanical properties including compressive strength, flexural strength, splitting tensile strength, and elastic modulus were measured. Fracture parameters, such as fracture energy and characteristic length, were determined to evaluate the brittleness of UHSC. The results shows that UHSC has high values of compressive strength over 130 MPa and flexural strength over 20 MPa; the fracture energy and characteristic length of UHSC are lower than that of normal concrete, indicating the high brittleness of UHSC. The strength and brittleness decrease with increasing the water-to-binder ratio. High temperature curing can not only increase strength, but also reduce brittleness. The addition of silica fume may be one of the main reasons for the high brittleness of UHSC. The addition of fly ash can significantly improve the mechanical properties and reduce the brittleness of UHSC.

Keywords: UHSC, mechanical properties, brittleness, fracture energy, characteristic length.

Дослідження крихкості надвисокоміцних матеріалів на основі цементу. *Xuefeng Yuan, Gang Liao*

Ціль роботи дослідженням впливу різних факторів на крихкість надвисокоміцних матеріалів на цементній основі (UHSC). Традиційний метод був застосований для отримання UHSC із використанням звичайної сировини. Були виміряні основні механічні властивості, включаючи міцність на стиснення, міцність на згин, міцність на розрив при розщепленні та модуль пружності. Параметри руйнування, такі як енергія руйнування та характерна довжина, використовувалися для оцінки крихкості UHSC. Результати показали, що UHSC має високу міцність з межею міцності при стисканні понад 130 МПа і міцністю на витримку понад 20 МПа, а енергія руйнування і характеристики UHSC нижчі, ніж у звичайного високоміцного бетону, що вказує на крихкість UHSC. Міцність і хрупкість знижуються зі зростанням співвідношення вода/зв'язувальна речовина. Високотемпературне отвердіння може поліпшити не тільки міцність, але і знизити крихкість. Додавання мікрокремнезему є однією з основних причин високої крихкості UHSC. Додавання золи-винесення може значно поліпшити механічні властивості і знизити крихкість UHSC.

1. Introduction

At present, concrete is the most widely used artificial building material, which is very important for infrastructure construction and national economic development. Therefore, the performance of concrete affects the safety, durability and economy of those projects, which are related to the sustainable development of human society [1]. With the development of social economy, construction projects are constantly moving towards the development of high-rise, light-

Table 1. Mixing ratios of ultra-high-strength cement-based materials

NO.	Cement	Silica fume	Quartz sand	Cement-to-sand ratio	Superplasticizer	Water-to-Binder ratio
W1	0.85	0.15	0.16	0.8	2	0.16
W2	0.85	0.15	0.16	0.8	1.6	0.18
W3	0.85	0.15	0.16	0.8	1.5	0.2
W4	0.85	0.15	0.16	0.8	1.5	0.22
W5	0.85	0.15	0.16	0.8	1.5	0.24
W6	0.85	0.15	0.16	0.8	1.5	0.26

weight and long-span structures. Many special projects, such as offshore and coastal projects, offshore oil rigs, undersea tunnels, and underground spaces et al., have higher requirements for the mechanical properties and durability of cement-based materials [2]. Thus, ultra-high strength concrete has been proposed. In the 1930s, researchers carried out preloading of fresh concrete during the setting process, which made it possible to increase the strength of cement-based materials [3]. With the development of a water-reducing agent and a high activity additive, high strength concrete (HSC) with a compressive strength over 60 MPa was fabricated. In the early 1970s, Oxford University [4] first developed macro defect-free (Macro Defect Free, MDF) cement-based materials, which compressive strength can reach 300 MPa and the elastic modulus can reach 50 GPa. In addition, Roy [5] invented a cement-base material with a compressive strength of 655 MPa. Bache [5] made full use of the compositional effect of silica fume and superplasticizer and prepared the concrete with a compressive strength of 50 ~ 200 MPa by mixing cement, ultrafine particles and superplasticizer. In the 1990s, the France company, Bouygues, successively developed reactive powder concrete (RPC), the compressive strength of which can reach 200 MPa and 800 MPa [6].

The key to improve the strength of ultra-high strength cement-based materials is to improve its C–S–H gel, pore structure, interfacial transition zone and other microstructure properties, which increases the density of the cement matrix and reduces internal defects [7–8]. However, due to the intrinsic properties of the main components of concrete (hardened cement and aggregates), concrete has a high compressive strength and stiffness, but its tensile strength and ductility are poor, showing obvious brittleness [9–10]. With an increase in the concrete strength, its brittleness becomes more and more obvious, which greatly limits the application of ultra-high strength cement-based materials. Therefore, it's necessary to investigate the factors influencing on the brittleness of ultra-high strength cement-based materials (UHSC).

In this paper, UHSC was prepared by mixing water, cement, quartz sand, silica fume (or fly ash) and superplasticizer. The basic mechanical properties as well as fracture parameters were studied. The fracture energy and characteristic length were used to evaluate the brittleness of UHSC. The effects of water-to-binder ratio, mix proportion of cementitious materials, and curing condition on the brittleness of UHSC were investigated. The novelty of this work is that the relationship between the mechanical properties and brittleness of UHSC is revealed, and the research direction of reducing the brittleness has been proposed.

2. Experimental

The cement was Three Gorges Brand PO 52.5; fly ash was first class with a fineness of 10 %. The average diameter of silica fume was 0.1 ~ 0.3 μm. The apparent density and diameter of quartz sand were 2650 kg/m^3 and 0.2 ~ 1.65 mm, respectively. The water reducing agent was polycarboxylate superplasticizer with a solid content of 40 %, and the water reducing rate was about 35 % ~ 40 %.

Ultra-high strength cement-based materials of various strength grades are presented in Table 1. The fresh concrete was casted in a triple module, and a steel plate (16 mm×1 mm) was embedded in the center of the sample, forming a 16 mm crack with a crack height ratio of 0.4. After demolding, the samples were cured for desired time (3 d, 7 d, and 28 d).

An electro-hydraulic servo universal testing machine was used for loading. According to the Standard for Test Methods of

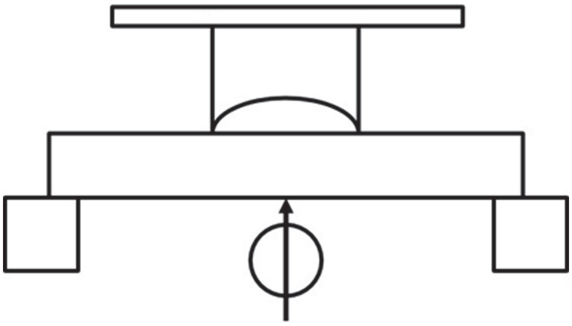

Fig. 1. Three-point bending method for measuring the fracture parameters.

Mechanical Properties of Ordinary Concrete (GB/T50081-20021), the compressive strength of specimens was calculated under continuously and uniformly loading of the specimens at a rate of 0.5 KN/S until the specimens were destroye
d. In the bending test, the three-point loading method was used as shown in Fig. 1. The loading rate was controlled by displacements of points and varied over the sections. Before the load reached the peak of 70 kN, the loading rate was constant at 0.1 m/min. After reaching 70 kN, the loading rate was changed to 0.05 m/min in order to get the descending portion of the load-deflection curve. The deflection of the mid-span was measured with a dial indicator, and the load-deflection curve was obtained.

Results and discussion

3.1. Mechanical properties

As shown in Fig. 2(a), the compressive strength of samples decreased with water/binder ratio. After 3 days and 28 days, the compressive strength of as-prepared samples can reach 75 MPa and 132 MPa, respectively, which corresponds to ultra-high strength cement-based materials. This result is close to the strength of reactive powder concrete (140 MPa) reported by Chen [11]. It should be noted that the sample with the *w/b* ratio of 0.18 has the highest compressive strength. The reason is that the water/binder ratio used in this study was very low, and the cement mixture is difficult to mix uniformly, so

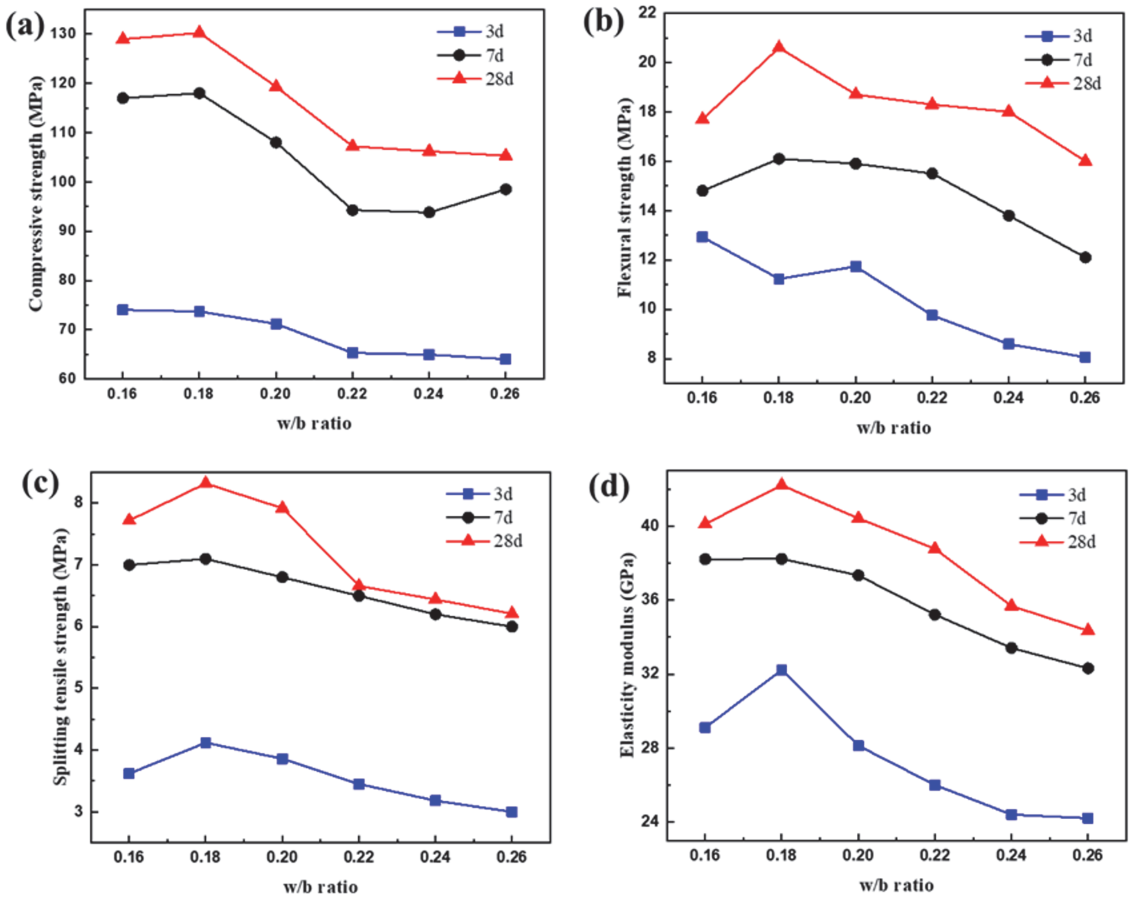

Fig. 2. Effect of water-to-cement ratio on mechanical properties: (a) compressive strength; (b) flexural strength; (c) splitting tensile strength; (d) elastic modulus.

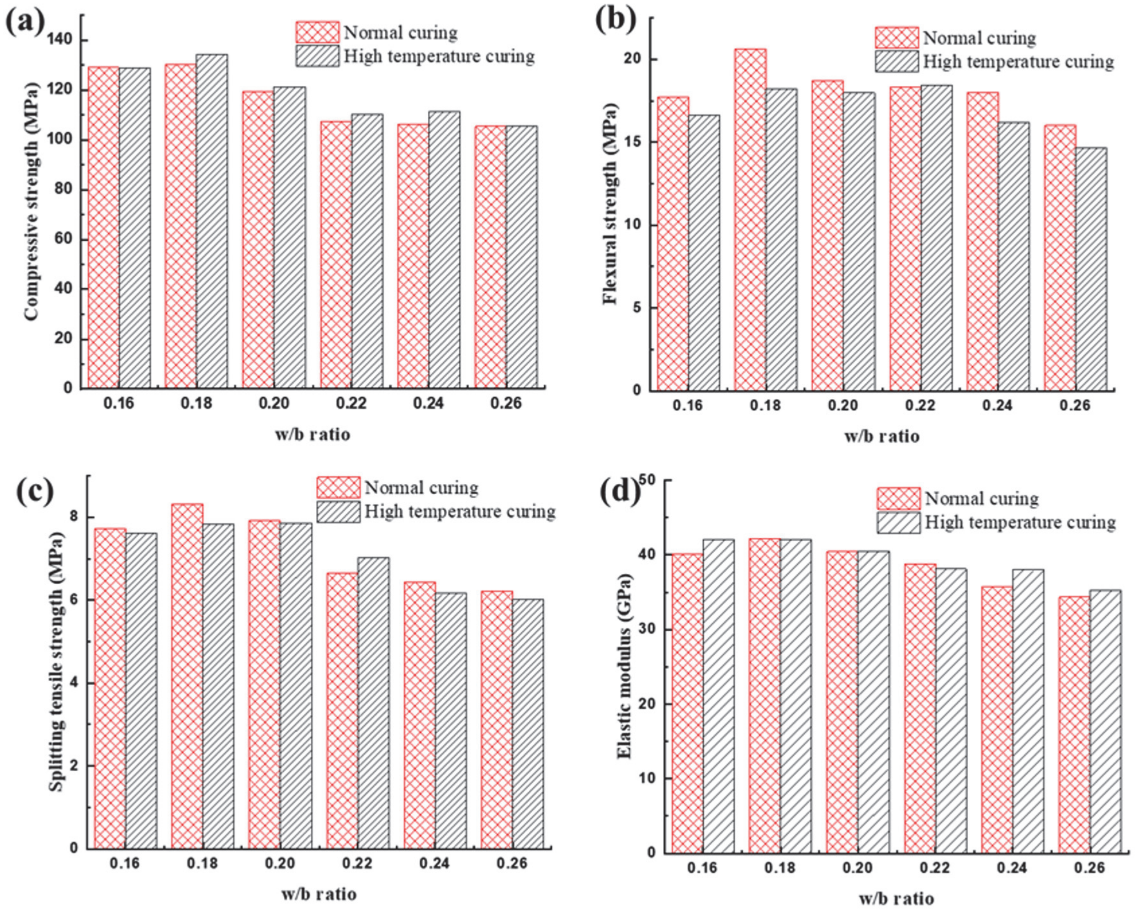

Fig. 3. Effect of curing conditions on mechanical properties: (a) compressive strength; (b) flexural strength; (c) splitting tensile strength; (d) elastic modulus.

some voids are formed and the density of the cement is reduced, which negatively affects the strength of cement-based materials. With a higher *w/b* ratio, the cement mixture can be mixed well, reducing the defects and increasing the compressive strength. The flexural strength and splitting tensile strength follow the same trend as compressive strength in Fig. 2(b) and (c), respectively. However, the flexural compression ratio of UHSC was higher than that of ordinary concrete, indicating that low w/b ratio can significantly improve the flexural compression ratio. The tension-compression ratio was lower than that of ordinary concrete, indicating the toughness of UHSC is poor. The splitting tensile strength of UHSC is higher than that of nano-SiO_2 modified concrete (4 MPa) produced by Cao et al., but the ratio of the splitting tensile strength to compressive strength is lower [12]. Fig. 2(d) displays the elastic modulus of samples. The elastic modulus can exceed 45 GPa after aging for 28d. The samples experienced explosive damage when the ultimate load was exceeded. All information shows that UHSC is highly brittle.

Fig. 3 shows the effect of curing conditions on the mechanical properties of as-prepared samples. It can be seen that the compressive strength of sampled cured in hot water is higher compared to samples cured at room temperature. This is because high temperature can accelerate the hydration of cement and form more hydration products, and the improvement effect is more obvious at an early stage of aging. On the contrary, the flexural strength and splitting tensile strength decreased slightly after curing in hot water. The curing conditions have little effect on the elastic modulus. This can be explained by the fact that the compression resistance of UHSC is much higher than the tensile strength. High temperature accelerates the hydration reaction of cement and the consumption of water, and the autogenous dry shrinkage of the cement matrix induces some micro-cracks inside cement, which does not affect compressive strength,

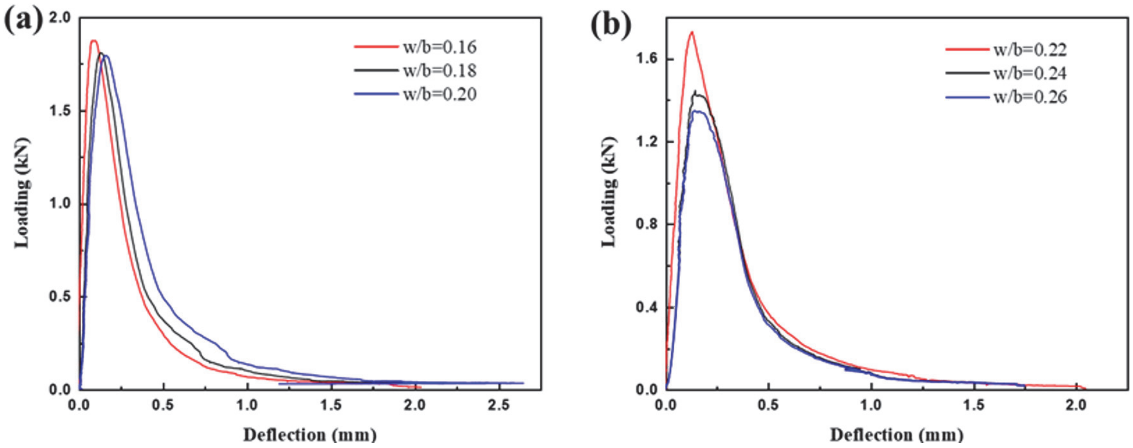

Fig. 4. Load-deflection curve at (a) low w/b ratio, (b) high w/b ratio.

but reduces flexural strength and splitting tensile strength.

3.2. Factors affecting fracture properties

3.2.1. Water-to-binder ratio

The load-deflection curves are shown in Fig. 4. It can be seen that the ascending section of the curve is close to a straight line, and the peak load is close to the limit. This may be due to the removal of coarse aggregate in the components of UHSC. The composition is uniform, and the fracture surface is no longer mainly the transition zone between the slurry and interface. The specimen may break right through the aggregate. As the strength of concrete increases, the peak load increases. With an increase in the w/b ratio, the peak load generally tends to decrease; when the water-binder ratio is 0.22, the value reaches the maximum, which is consistent with the compressive strength. Due to the rigidity of the testing machine, the descending section of the load-deflection curve was not measured in this test, and the brittle fracture was observed when the peak load was reached during the experiment, indicating that UHSC is highly brittle.

To further characterize the brittleness of UHSC specimens, the fracture energy and characteristic length were determined. Fig. 5 shows the change of the fracture energy and characteristic length with the w/b ratio. The fracture energy of UHSC is lower than that of high strength concrete, and is much less than that of ordinary concrete. The fracture energy is in the range of 100 ~ 150 J·m^{-2}. When the w/b ratio is 0.16 ~ 0.26, the fracture energy increases first and

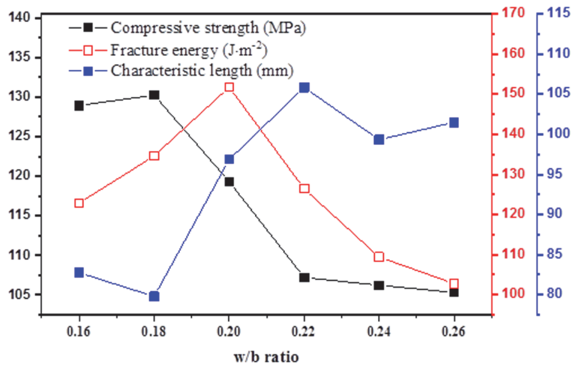

Fig. 5. Effect of the w/b ratio on fracture parameters.

then decreases with the w/b ratio; it reaches its maximum at a water-binder ratio of 0.20. In the range of w/b ratio 0.22 ~ 0.26, the characteristic length does not change significantly. In the range of w/b ratio 0.18 ~ 0.22, the compressive strength increases with a decrease in the w/b ratio, while the characteristic length decreases significantly. According to the definition of the characteristic length in the virtual fracture model, the smaller is the value of l_{ch}, the greater brittleness. When the w/b ratio is low, the brittleness of UHSC increases significantly with increasing strength.

2.2 Curing conditions

Fig. 6 displays the effect of curing conditions on the fracture energy and characteristic length. The fracture energy of specimens cured in hot water is much lower than that cured at normal temperature. The fracture energy of samples cured at high temperature is about half that of conventional samples. Hot water curing does not affect ultimate load, and the characteristic

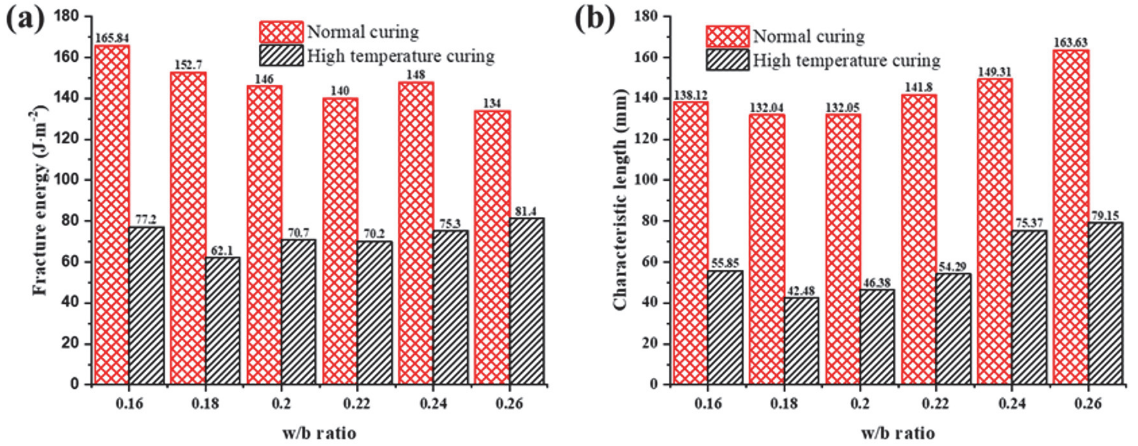

Fig. 6. Effect of curing condition on (a) fracture energy and (b) characteristic length.

length of hot water cured specimens is significantly shorter than that of specimens cured at normal temperature. The test results of the tension-compression ratio in the previous chapter also reflect that the brittleness of the specimen increases sharply after hot water curing, but the characteristic length of the material decreases; the load-deflection curve of the loading point obviously becomes steeper, and the area under the curve, namely the fracture energy, decreases, and the brittleness increases significantly. This proves that hot water curing not only increases the strength of UHSC, but also markedly increases brittleness.

2.3 Mineral admixtures

Fig. 7 shows the effect of the silica fume content on the fracture properties of UHSC. When the silica fume content is 10 % ~ 15 %, there is no notable change for the limit load and fracture energy, but the characteristic length has noticeably decreased. When the silica fume content exceeds 15 %, there is huge decline for the limit load and fracture energy, and the characteristic length slightly increases. This indicates that the addition of silica fume may increase the brittleness of UHSC; this effect is especially noticeable at a high content of silica fume. This is due to the fact that silica fume mainly consists of amorphous SiO_2 with a high fineness; therefore, highly active silica fume can react intensely with $Ca(OH)_2$, consuming some water and releasing a lot of heat. As a result, the autogenous shrinkage is serious and there are many inner micro-cracks, which will act as fracture paths, and consequently, samples with a high silica fume content break

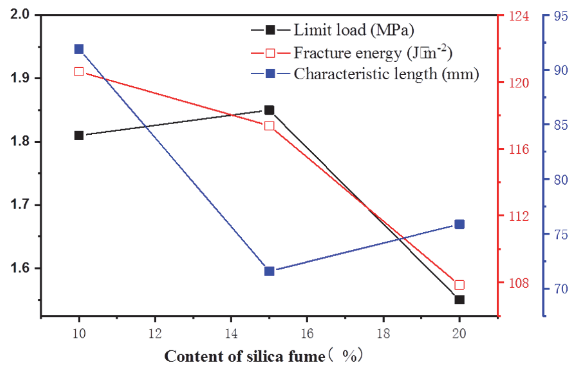

Fig. 7. Effect of the content of silica fume on the fracture parameters.

easily under the same load, showing obvious brittleness.

Fig. 8 shows the effect of the ratio of silica fume to fly ash on the fracture parameters. The limit load decreases with an increase in the ratio of silica fume to fly ash. However, the fracture energy and characteristic length increase with the silica fume content, but decreases when the ratio of silica fume to fly ash exceeds 1:1. When the ratio of silica fume to fly ash is 1:1, the characteristic length and fracture energy reach the highest values and the brittleness is the lowest value. This suggests that mixing silica fume and fly ash can improve the toughness and reduce the brittleness of UHSC, but adding silica fume alone will increase brittleness, consistent with the results reported by Young [13]. This is probably due to the fact that fly ash is less active than silica fume, and the hydration reaction is not as intense as silica fume. Therefore, fewer autogenous shrinkage defects will be generated and the internal microstructure will be improved.

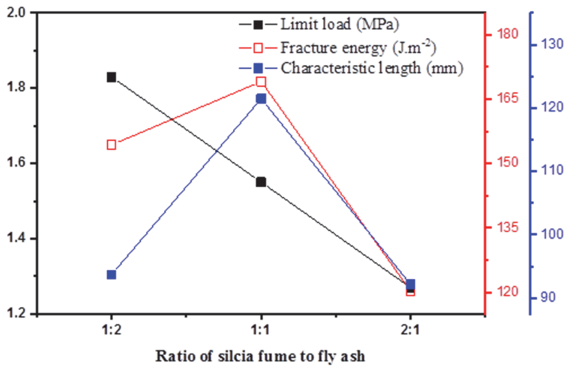

Fig. 8 Effect of the ratio of silica fume to fly ash on the fracture parameters

4. Conclusions

* Ultra-high strength cement-based materials are prepared by using conventional construction technology and common raw materials. The 28-day compressive strength and flexural strength can reach 130 MPa and more than 20 MPa, respectively.

* The fracture surface is smooth. The obtained flexural strength is higher than that of ordinary concrete. The flexural-to-compression ratio of the matrix is about 1/7 ~ 1/9, which is higher than that of ordinary cement-based materials, and the ratio of tension to compression is about 0.06.

* Ultra-high strength cement-based materials can reach high strength at an early stage, with compressive strength of more than 110 MPa after 7 d, and the strength growth is slow after 7 d. High temperature curing can increase the brittleness of UHSC.

* The load-deflection curve of ultra-high strength cement-based materials is very steep after reaching the limit load, and the drop is very large, indicating that the matrix has the characteristics of high brittleness. The characteristic length can better characterize the brittleness change of UHSC.

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