Mechanical Properties of Desert Sand-Based Fiber Reinforced Concrete (DS-FRC)

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Featured Application: The main purpose of this paper is to prepare high ductility Fiber Reinforced Concrete (FRC) by using high volume of fly ash and replacing fine river sand with the Mu Us desert sand. It will fully reduce the preparation cost and promote the application of FRC in engineering fields. Besides, it will also offer a practical guidance to the feasibility of the desert sand as engineering sand.

Abstract: This paper presents the study on the properties of high-ductility fiber reinforced concrete made with desert sand from China’s Mu Us desert. The workability and uniaxial tensile/compression properties of undisturbed desert sand-based fiber reinforced concrete (DS-FRC) with the change of water-to-binder ratio (W/B), sand-to-binder ratio (S/B) and desert sand replacement rate (DSRR) were experimentally investigated. Experimental results reveal that the appropriate W/B and desert sand content are conducive to the workability development of DS-FRC. The uniaxial tension/compression properties of DS-FRC are mainly affected by the W/B. Especially, the highest uniaxial tensile/compression stresses and corresponding strains are obtained at the W/B of 0.29. The S/B has similar effects on the uniaxial tensile/compression properties, and an S/B of 0.36 is the optimal ratio. In terms of the DSRR, it shows less effect on the uniaxial tensile/compression properties, even for the DSRR of 100%. The results of the tests indicate that undisturbed desert sand can be used as silica sand in high-ductility fiber reinforced concrete.

Keywords: fiber reinforced concrete; uniaxial tensile/compression properties; experimentally investigated; desert sand

1. Introduction

With the ever-increasing development of construction, there is an urgent need for high performance building materials to meet structural performance requirements. The high ductility cementitious composites, with the aim of enhancing the seismic performance of structures, have received great attentions. They have the characteristics of higher tensile ductility and compression deformation properties, and the uniaxial tensile and compression strains can be over 3% and 0.5%, respectively [1,2]. Although, there are varieties of names such as engineered cementitious composites (ECC) [3,4], ultra-high performance fiber reinforced cementitious composites (UHPFRCC) [5,6], strain hardening cementitious composites (SHCC) [7–9], ultra-high toughness cementitious composites (UHTCC) [10–12] and fiber reinforced concrete (FRC) [13,14], they all maintain the essence of high ductility and have achieved good engineering applications [15–19]. The high ductility cementitious composites are composed of polyvinyl alcohol fiber (PVA) and fine aggregates, such as cement, fly ash, and fine river sand. The lack of coarse aggregates leads to the excessive consumption of raw materials, especially for...
river sand. In addition, the excessive mining of river sand has resulted in serious environmental damages. Therefore, there is an urgency to find suitable replacement of river sand with low cost and environmental protection. Currently, the worldwide use of high volumes of mineral admixtures (such as fly ash or slag) and available fine aggregates (such as tailings, sea sand and desert sand) are the main solutions. In addition, uniaxial tensile/compression tests are widely used to verify the high ductility of cementitious composites [14,20–27].

The high ductility of cementitious composites can be achieved by optimizing the material components, as is shown by Li et al. [28]. The fracture toughness of matrices and the tensile ductility of composites will be effectively improved with fine aggregates [29,30]. When the size of particles exceeds 300 µm, the fracture toughness of matrices may enhance significantly, which is bad for the development of tensile strain hardening. Besides, some recent studies [31,32] have confirmed that the very fine particles play an important role in promoting hydration and optimizing material properties. All above alternatives meet the demand of small particles and can contribute to the ductility development of cementitious composites. Duxson et al. [33] found that the emitted CO$_2$ would be reduced by 80% through the equivalent replacement of cement. The composites exhibited good tensile strain hardening properties [34,35], even for the fly ash replacement rate of 75%. Moreover, Khan et al. [36] confirmed the feasibility of slag in preparing the SHCC with tensile strains of 4–6%. However, the research on the feasibility of alternative fine desert sand mainly focused on mortar or concrete. There are few studies referring to high ductility cementitious composites.

In terms of tailings, some acceptable results have been revealed [37,38]. Tailings with appropriate size can enhance the compression strength and flexural strength of composites. The dispersion of fiber is effectively facilitated which will promote the ductility development of cementitious composites. The results regarding sea sands have showed that reduced compression capacities would be obtained due to the excess of Cl$^-$ [39,40]. Desert sand is abundant in some parts of the world, and the reasonable use of it will slow down the consumption river sands and promote the environment protection. The reasonable use of desert sand has aroused a great attention. It was found that desert sand played an important role in improving the physical and chemical properties of mortar [41]. The strength of desert sand concrete (DSC) was comparable to that of ordinary concrete [32,42–44]. The structures filled by DSC have obtained good engineering applications [45]. However, desert sand from different regions may show significant differences, such as in physical properties and mineral compositions. It is essential to further study intrinsic effects of different desert sands on the mechanical properties of FRC. The cubic compression and the splitting mechanical properties of undisturbed desert sand-based fiber reinforced concrete (DS-FRC) were investigated by our research team [46,47]. In these studies, the control groups without desert sand have been considered by orthogonal experiment. The results showed that compared with the river sand-based FRC, the compression and splitting strengths of DS-FRC slightly decreased with the increase of desert sand replacement rate (DSRR), especially when DSRR exceeds 40%. However, there is a lack of uniaxial tests to evaluate the mechanical properties and deformation performances of DS-FRC, and the components of matrices could be further optimized.

Based on all of the above, this paper further studied the uniaxial mechanical properties of DS-FRC, aiming at promoting the full application of desert sand. The uniaxial tension and compression tests were conducted to investigate the effects of W/B, S/B and DSRR on the mechanical properties and deformation performances of DS-FRC cured for 28 d. In order to provide a better understanding about the action mechanism of desert sand and the microstructural change of DS-FRC, the chemical composition and the microscopic morphology of DS-FRC were analyzed. This research will provide valuable information to the uniaxial properties development of DS-FRC and make a foundation for future studies.
2. Experimental Program

2.1. Mix Proportions and Material Properties

In this experiment, ordinary Portland cement (PO 42.5 R), river sand with a particle size under 1180 μm, fly ash I, undisturbed Mu Us desert sand with a fineness modulus of 0.721, polyvinyl alcohol fiber (PVA) made in Japan, superplasticizer and fresh water were the main ingredients used to prepare DS-FRC. Chemical compositions of raw materials and properties of PVA fiber are revealed in Tables 1 and 2. Besides, the particle size distribution of raw materials and the appearance of river sand and desert sand are showed in Figure 1a–c.

| Description     | Al₂O₃ | Na₂O | CaO | SiO₂ | P₂O₅ | SO₃ | Fe₂O₃ | K₂O | TiO₂ | Cl  | MgO |
|-----------------|-------|------|-----|------|------|-----|-------|-----|------|-----|-----|
| Cement          | 5.05  | 0.73 | 60.24| 21.22| /    | 2.67| 3.26  | 0.50| /    | /   | 0.97|
| Fly ash         | 23.6  | 13.2 | 6.12 | 38.5 | 1.06 | 2.13| 7.49  | 1.84| /    | /   | 0.26|
| River sand      | 11.8  | 16.0 | 6.87 | 45.2 | 1.01 | 0.58| 6.33  | 4.65| 0.86 | 0.33| /   |
| Desert sand     | 12.3  | /    | 4.83 | 74.2 | 0.80 | 0.50| 3.69  | 2.62| 0.49 | 0.41| /   |

Table 1. Chemical composition analysis of the raw material.

| Description | Length (mm) | Diameter (μm) | Specific Gravity (kg/m³) | Ultimate Tensile Strength (MPa) | Young’s Modulus cN/dtex |
|-------------|-------------|---------------|--------------------------|-------------------------------|------------------------|
| PVA         | 12          | 40            | 1300                     | 1600                          | ≥380                   |

Table 2. The properties of polyvinyl alcohol fiber (PVA).

![Figure 1](image)

Figure 1. Particle size distributions of raw materials and appearances of two sands: (a) particle distribution; (b) river sand; (c) desert sand.

It can be observed (see Table 1) that the content of silica in the sand used in this study was lower than that of other researches. In terms of river sand and desert sand, the silica contents were only 45.2% and 74.2%, respectively. Besides, the content of calcium in the fly ash was also low, which may have had a certain impact on the mechanical properties of DS-FRC. PVA fiber with a diameter of 40 μm and a length of 12 mm was used in this experiment (see Table 2).

As clearly illustrated in Figure 1a, the particle distributions of cement and fly ash were comparable with smaller particle size, which will facilitate fiber dispersion. The particle size of desert sand, with a size under 450 μm, was approximately 2.5 times lower than that of the sieved river sand. The median particle sizes of cement, fly ash, desert sand and river sand were 10.82 μm, 9.68 μm, 130.11 μm, and 235.6 μm, respectively. As in [29], the strain hardening property of cementitious composites will be activated only when the particle sizes of aggregates are under 300 μm. However, it is
worth noting that the particle size of sand used in this experiment was far greater than that recommended by Li, and desert sand exhibits relatively poor particle gradation, which may limit the ductility property of DS-FRC. Additionally, the appearance colors of two sands (see Figure 1b,c) were significantly different due to the differences of material compositions, which was consistent with the results of Table 1. As for the desert sand, its color was slightly reddish while the river sand was gray. It was also observed that desert sand and river sand had less-angular appearances which are anticipated to promote fiber slippage and dispersion and facilitate to the strain hardening development of DS-FRC.

The reasonable optimization of raw materials, such as fly ash or fine sand, is the driving force for achieving the successful strain-hardening and multiple-cracks properties of high ductility cementitious composites. Therefore, in this study, ten mixtures were designed to further study the effect of W/B, S/B and DSRR (replacing the equivalent weight of river sand) on uniaxial tensile/compression properties of FRC. The control group without desert sand has been included in previous research [47], so there is no discussion about it. Moreover, the mechanical properties of DS-FRC without superplasticizer were compared to that with superplasticizer. The constant volumes of fly ash about 60% and PVA fiber about 2% by volume were used to prepare the FRC, and the change ranges of W/B, S/B and DSRR were 0.26–0.29–0.32–0.35, 0.30–0.36–0.42, 40%–60%–80%–100%, respectively. The mixture proportions of components are listed in Table 3.

### Table 3. Mixture proportion of desert sand-based fiber reinforced concrete (DS-FRC).

| Mix NO. | 1     | 2     | 3     | 4     | 5     | 6     | 7     | 8     | 9     | 10    |
|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| W/B     | 0.26  | 0.29  | 0.32  | 0.35  | 0.29  | 0.29  | 0.29  | 0.29  | 0.29  | 0.29  |
| S/B     | 0.36  | 0.36  | 0.36  | 0.36  | 0.36  | 0.36  | 0.36  | 0.36  | 0.36  | 0.36  |
| DSRR    | 40%   | 40%   | 40%   | 40%   | 40%   | 40%   | 40%   | 40%   | 80%   | 100%  |
| Cement  | 550.22| 541.35| 532.47| 514.72| 559.10| 514.73| 541.35| 541.35| 541.35| 541.35|
| Fly ash | 825.33| 812.02| 798.71| 772.09| 838.64| 772.08| 812.02| 812.02| 812.02| 812.02|
| Water   | 357.64| 392.48| 421.54| 450.38| 399.35| 377.17| 392.48| 392.48| 392.48| 392.48|
| River sand | 292.86| 292.33| 287.53| 277.95| 252.92| 332.80| 194.88| 97.44 | 0     | 292.33|
| Desert sand | 195.24| 194.88| 191.68| 185.30| 168.61| 221.86| 292.33| 389.77| 487.21| 194.88|
| PVA fiber | 26     | 26     | 26     | 26     | 26     | 26     | 26     | 26     | 26     | 26     |
| Superplasticizer | 0.78  | 0.77  | 0.75  | 0.73  | 0.79  | 0.73  | 0.77  | 0.77  | 0     | 0     |
| Density  | 1949.5 | 1949.2 | 1874.0 | 1815.8 | 1910.5 | 1918.8 | 1859.5 | 1853.4 | 1861.9 | /     |
| Consistency | 35 | 74     | 78     | 133    | 74     | 70     | 59     | 67     | 63     | 66    |
| Elastic Modulus GPa | / | 19.16  | /      | /      | 18.31  | 18.39  | 19.28  | 17.31  | 13.13  | /     |

In order to control the fluidity of DS-FRC, the fiber was added before the superplasticizer in this test, which was different from the traditional preparation method of high ductility cementitious composites. It was difficult to obtain good fiber dispersion properties if the superplasticizer was added in advance. The phenomenon of fiber floating with large content of superplasticizer would be observed, limiting the development of material properties of DS-FRC.

A forced pre-wet mixer was used to prepare the DS-FRC. First, the raw materials were mixed for 2 minutes at low speed, following the order of fly ash, cement, desert sand and river sand. Then, the water was added slowly along the mixer’s wall for about 2 minutes at high speed. Subsequently, dispersed fibers were incorporated rapidly along the mixing direction for another 2–3 minutes at low speed. Finally, a constant volume of superplasticizer with 0.05% of cementitious materials was added. In order to improve the mixing efficiency, it was added with a frequency of 0.5 g/s until the mixture was evenly dispersed without cluster. It took about 10–12 minutes for the whole mixing process.
The specimens for uniaxial tensile/compression testing were prepared by directly pouring the mixture into steel molds. It was noted that the compression cylindrical specimens with a size of \( \phi 75 \text{ mm} \times 150 \text{ mm} \) (diameter \( \times \) height) were cast in two layers for good compactness, and slight insertion and vibration for about 10–12s was used after each time. However, the tensile dumbbell-type specimens with the size of \( 330 \text{ mm} \times 60 \text{ mm} \times 13 \text{ mm} \) (length \( \times \) wide \( \times \) thickness) were cast in only one layer with the vibration time of about 10–12s. Subsequently, the cast process of DS-FRC was completed by smoothing the surface of specimens. The specimen size for the uniaxial tensile test was recommended by [48] while for compression tests is in agreement with [49].

The specimens were kept in a chamber at 20 \( \pm \) 2\( ^\circ \)C for 24h until demolding. Then, the specimens were placed into a standard curing room (with a temperature of 20\( \pm \) 2\( ^\circ \)C and relative humidity of 95\%) until the curing period of 28 days was reached. The specimens were then removed and were ready to test. In each mixture, twelve specimens including six tensile and six compression specimens were tested to evaluate the mechanical properties of DS-FRC.

2.2. Test Setup and Loading Procedure

2.2.1. Consistency and Density Test

The consistency and density test were conducted in accordance with JGJ/T70-2009 [50] to determine the workability of fresh composites with different mixtures and weight of specimens. The average value obtained from three repeated tests was used as the evaluation index.

2.2.2. Uniaxial Tensile and Compression Test

The uniaxial tensile test is the most direct method to evaluate the tensile ductility and strain hardening properties of cementitious composites. It has been extensively used in evaluating the tensile properties of high ductility cementitious composites, although there are no uniform codes. Currently, there are many practical tensile test methods in the world, such as in the United States and Japan [48,49,51]. In this experiment, the uniaxial tensile and compression tests were in accordance with Japan Society of Civil Engineers (JSCE) [48] and American Society for Testing Materials (ASTM ) C39 [52].

Twelve specimens were made, including six dumbbell-type specimens for the tension stress-strain curves of DS-FRC and six cylinders, in which three cylinders were used for obtaining uniaxial compression strengths and stress-strain curves and other cylinders for Elastic Modulus and Poisson’s ratio. The uniaxial tensile and compression test were conducted on the electronic universal testing machine with the capacity of 1000 kN. The tensile/compression specimens were loaded under the displacement control with constant rates of 0.5 mm/min and 1.0 mm/min, respectively. The stress was measured by the data logging system from machine. Two extensometers were attached to the mid-heights of tensile specimens symmetrically to measure elongation over a gauge of 50 mm, while compression strains were detected by two linear variable differential transformers (LVDT) attached to the mid-heights of specimens. When the deformation of specimens increasingly increased after ultimate compression stresses, the disturbances at the contact points of LVDT were obvious, which lead to the strain readings dispersed and erratic. In this study, exploring the effect of factors on the mechanical properties of DS-FRC was main purpose and the system data can also meet the requirements. Therefore, the load-displacement curves obtained from machine systems were used to calculate the stress–strain relations under the uniaxial compression test. Through keeping the slope of elastic deformation stage consistent, the initial concave phenomenon of compression stress–strain curves caused by the poor contact between the loading surface and the specimen has been adjusted. All compression specimens’ ends were capped with sulfur compound to meet the planeness requirements and reduce errors. The test was stopped when load decreased to 20–30% of the ultimate load. The schematics of test devices and methods under uniaxial tensile and compression tests are illustrated in Figure 2a–c.
Therefore, it was essential to evaluate the Elastic Modulus of DS-FRC for verifying its engineering applicability. In this experiment, the elastic deformation analysis of structure. It describes the initial elastic response of DS-FRC specimens.

3. Results and Discussion

3.1. Workability

Good workability is an important premise to guarantee the material properties development of composites. The consistency test was used to assess and monitor the workability of DS-FRC. The average consistency value and the density are shown in Table 3.

It was observed that the composites with different mixtures showed similar consistency values of about 60–70 mm, except for critical W/B. The consistency value of DS-FRC with the lowest W/B was approximately 50% lower than that of general condition, which may cause inconveniences in casting and greater construction problems. It may be attributed to less water consumption and higher water absorption of undisturbed desert sand. It is worth noting that the content of superplasticizer was constant in all mixtures. The consistency value significantly increased at the highest W/B, which led to segregation. Besides, it was found that the clumping (balling) or floating of fibers was dominant at the highest W/B, which limited the effect of fiber toughening. The high content of desert sand had a negative effect on the workability of DS-FRC, which is in line with the previous research [53]. As is shown in Table 3, when the DSRR was constant, the consistency value of DS-FRC with the S/B of 0.42 was the lowest. At the S/B of 0.36, optimal workability was obtained due to improved fluidity caused by fine desert sand.

The densities of DS-FRC with different mixtures kept a comparable level, approximately 1900 kg/m³. The densities of DS-FRC were 10% lower than that of ordinary concrete due to the lack of coarse aggregate and slight porosity caused by the adding of fiber. This is in line with the previous research [54].

3.2. Elastic Modulus

The Elastic Modulus is an important mechanical parameter of engineering materials for the elastic deformation analysis of structure. It describes the initial elastic response of DS-FRC specimens. Therefore, it was essential to evaluate the Elastic Modulus of DS-FRC for verifying its engineering applicability. In this experiment, the effect of S/B and DSRR on the Elastic Modulus of DS-FRC under
the uniaxial compression test were studied. The results show that the Elastic Modulus of DS-FRC were about 13–20 GPa, which were lower than that of the ordinary concrete due to the increased porosity caused by the addition of fiber, the small particle size of aggregates and the low S/B, which is in line with previous research [55]. The Elastic Modulus of DS-FRC decreased with the increase of DSRR. Especially, it was only 13 GPa at the DSRR of 100%. As is shown in Table 1, the relatively low content of silica in desert sand may have had a certain effect on the reduced Elastic Modulus of DS-FRC. When the DSRR was low, few changes of the Elastic Modulus were observed with the increase of S/B. The values of the Elastic Modulus were approximately 18–19 GPa.

The Poisson’s ratio, referring to the ratio between lateral strains and longitudinal strains, ranged from 0.18 to 0.25, which was also smaller than the ordinary concrete, attributed to the bridging effect of fibers. It restricted cracks opening in the lateral direction.

3.3. Uniaxial Tensile Properties of DS-FRC

3.3.1. The Failure Mode of Specimens

The failure form and the multiple cracks pattern of specimens under the uniaxial tensile test are presented in Figure 3. Some visible and tightly arranged micro-cracks with a crack width under 100 μm were observed on the surface of specimens after unloading. As is clearly revealed in Figure 3a,b, the average crack space was about 2000 μm, except for individual wide cracks with a maximum crack space of about 3900 μm. However, the minimum crack space was only 500 μm. However, according to Li et al. [29,56], many micro-cracks were closed after unloading due to the elastic recovery of elongated PVA fibers bridging across the matrix cracks, which would lead to difficulty in clearly describing the multiple cracks. The residual crack width was approximately 70% of actual crack opening width under the ultimate tensile load. Therefore, it was also impossible to accurately describe the detailed crack condition in this experiment.

![Figure 3. The failure mode of specimens under uniaxial tensile test: (a) the partial magnification of multiple cracks; (b) the crack space of multiple cracks.](image)

3.3.2. The Strength Development and Stress–Strain Curves

The mechanical parameters of DS-FRC under the uniaxial tensile test are shown in Table 4. Tensile stress–strain curves of DS-FRC and counterparts without the superplasticizer are presented in Figures 4 and 5. In this experiment, the uniaxial tensile properties of DS-FRC were not comparable to that of typical because the particle size of sand used in this experiment was larger than that of high ductility cementitious composites, which caused relatively poor tensile strain hardening response.
However, it has been proved that FRC with only 1% tensile strain and relatively poor tensile strain hardening properties could still show good structural applicability [57–61]. When it is applied to structure, such as coupling beams, columns and shear walls, good tensile/shear ductility, high flexural toughness and high energy consuming properties will be obtained. Therefore, the DS-FRC prepared in this experiment is anticipated to achieve good engineering application. The results of the uniaxial tensile properties of DS-FRC are as follows.

### Table 4. Basic properties of DS-FRC.

| Mix NO. | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|---------|----|----|----|----|----|----|----|----|----|----|
| Tensile Initial Cracking Stress (MPa) | 2.20 | 2.95 | 1.85 | 0.99 | 2.04 | 2.00 | 1.96 | 2.08 | 2.04 | 4.20 |
| Tensile Initial Cracking Strain (%) | 0.07 | 0.07 | 0.07 | 0.04 | 0.03 | 0.04 | 0.06 | 0.06 | 0.05 | 0.03 |
| Ultimate Tensile Stress (MPa) | 4.01 | 5.42 | 3.83 | 2.71 | 5.01 | 4.61 | 4.65 | 3.79 | 4.78 | 7.25 |
| Ultimate Tensile Strain (%) | 3.63 | 3.50 | 1.44 | 2.77 | 3.32 | 4.43 | 3.68 | 1.87 | 1.57 | 0.7 |
| Ultimate Compression Stress (MPa) | 46.3 | 43.3 | 35.1 | 31.4 | 40.5 | 39.9 | 40.4 | 36.8 | 40.2 |
| Ultimate Compression Strain (%) | 1.17 | 1.08 | 1.26 | 1.06 | 1.13 | 1.36 | 1.00 | 1.37 | 1.19 | 0.97 |

Tensile cracking point: The proportional limit point of the tensile stress–strain curves.

![Figure 4](image-url)

**Figure 4.** The effect of different factors on the ultimate tensile/compression stress: (a) W/B; (b) S/B; (c) DSRR; (d) with or without superplasticizer (SP).

The initial cracking stress, the initial cracking strain, the ultimate tensile stress and corresponding strain with different mixtures are presented in Table 4. With the increase of W/B, the initial cracking stress first increased and then decreased. The maximum value was obtained at the W/B of 0.29. Besides, the higher tensile initial cracking stresses were, the higher corresponding strains were. The DS-FRC without superplasticizer showed higher initial cracking stress and lower initial cracking...
strain than that with superplasticizer. It may be attributable to the nature of the superplasticizer, which is beneficial to the development of strength while it weakens the strain.

With regards to the ultimate tensile stress and the corresponding strain, it was observed that the ultimate tensile stress of DS-FRC was significantly higher than the initial cracking stress regardless of mixtures. As is shown in Figures 4a and 5a, the ultimate tensile stress first increased then decreased while the corresponding strain gradually decreased overall with the increase of W/B. The optimal mechanical properties were observed at the W/B of 0.29 with the ultimate tensile stress of 5.42 MPa and the corresponding strain of 3.50%. The ultimate tensile stresses showed a similar trend where the increase of S/B and the comparable ultimate tensile strains were obtained, as is revealed in Figures 4b and 5b. The optimal mechanical properties were observed at the S/B of 0.36. According to the Figures 4c and 5c, the DSRR showed a relatively small effect on the ultimate tensile stress of DS-FRC, even for the DSRR of 100%. However, the ultimate tensile strain, with the maximum value of 3.68%, slightly reduced which is still acceptable. It is worth noting that the DS-FRC without superplasticizer showed unconventional mutation due to the errors caused by operation during the test, as is illustrated in Figures 4d and 5d.

Currently, the conclusions made by Guettala et al. [62] have revealed that the desert sand powder can be considered as an active component, except for inert fine fillers. Besides, the fine particles of fly ash can promote hydration due to their good binding activity [63] and the improved fracture toughness of the matrix. Therefore, the synergistic interaction of spherical fly ash particles and fine desert sand particles may effectively improve the mechanical properties of DS-FRC, which responds to the relatively high tensile properties of composites. However, the tensile strain hardening properties of all specimens could not match with typical high ductility cementitious composites. It is due to that the aggregate size in DS-FRC is larger than that recommended by typical high ductility cementitious composites. Even so,
the DS-FRC is expected to meet performance demands and achieve good engineering applications, as discussed above.

Considering the defects of presented DS-FRC, in further studies, the matrix components will be continuously modified in order to optimize mechanical properties and achieve good tensile strain hardening properties.

3.4. Uniaxial Compression Properties of DS-FRC

3.4.1. The Failure Mode of Specimens

The actual failure mode and the failure schematic of DS-FRC are shown in Figure 6a–f. Instead of the brittle splitting failure of ordinary mortar or concrete, the DS-FRC subjected to the uniaxial compression test exhibited obvious shear ductile failure due to the effect of fiber bridging. Among all DS-FRC specimens, the typical ductile failure could be divided into two forms, (as is clearly exhibited in Figure 6a,b,d,e). The main cracking plane was approximately 45° and 60° from the horizontal plane, respectively. It could be attributed to the change of stress states and microstructures in different specimens. Additionally, the vertical splitting failure appeared in few specimens, resulting from the uneven surface, as is shown in Figure 6c,f. However, all DS-FRC specimens still maintained good integrity until the compression softening stage, in which the crack width was controlled to a relatively small size and there was no phenomenon of fragmentation similar to the brittle failure. It is worth nothing that the activated fiber bridging effect provided effective lateral constraint to the crack width with the continuous loading. Some micro-cracks around the main crack appeared due to the fiber bridging effect.

![Figure 6](image_url)

**Figure 6.** The failure mode of specimens under uniaxial compression test: (a–c) the actual failure mode of DS-FRC; (d–f): the schematic of failure mode.

3.4.2. The Strength Development and Stress–Strain Curves

As is shown in Figures 4 and 7 and in Table 4, the mechanical parameters are presented, including compression strengths and compression stress–strain curves of DS-FRC with different mixtures. According to Figure 7, the stress–strain curve under the uniaxial compression test was divided into three stages, referring to the elastic stage, the cracking stage and the strain softening stage. The DS-FRC with different mixture showed similar trend until the branch point at the elastic stage, at which there are no micro-cracks. Then, the cracking stage prevailed with the increase of the load, at which the micro-cracks increasingly developed and the bridging effect of fiber was activated. Finally, the curves show a relatively fast declining trend after ultimate compression stresses. It is worth noting that the slope of the descending branch was relatively steep for DS-FRC, which was different from the typical high ductility cementitious composites. It may be attributed to that the particle size of desert sand was larger than that recommended by high ductility cementitious composites.
However, it was still relatively high, which reveals the feasibility of desert sand as a substitution for engineering sand. Illustrated in Figures 4c and 7c, ultimate compression stresses which could be up to about 40 MPa to 46.3 MPa. However, it first increased and then decreased with the change of S/B, according to Figures 4b and 7b. The maximum value was obtained at the S/B of 0.36. In terms of DSRR, as is shown in Figures 4a and 7a. The maximum ultimate compression stress could be up to 20 MPa at the S/B of 0.36. It can be observed that the initial cracking strength was reduced with the increase of DSRR, except for in NO.8 which had a slight increase. The similar initial cracking strains ranging from 0.3–0.45% were obtained in all mixtures under the uniaxial compression test, which may be due to the improved matrix toughness of DS-FRC caused by fine undisturbed desert sand.

The slightly reduced ultimate compression stress may be due to the relatively high content of mud from 0.3–0.45% were obtained in all mixtures under the uniaxial compression test, which may be due to the improved matrix toughness of DS-FRC caused by fine undisturbed desert sand. Additionally, the slight porosity caused by the adding of PVA fiber may be related to the compression strain of DS-FRC. Although the ultimate compression stress was slightly lower than that with superplasticizer, were observed. Based on above analysis, the appropriate high ultimate compression stress about 40.2 MPa and the corresponding strain about 0.97%, which assured by using the composites with similar properties, according to previous researches. Compared to the ordinary concrete, the relatively high corresponding strain about 1.19% could still be obtained. As illustrated in Table 4, the DSRR of 100% had no negative effects on the ultimate results of about 1%. As illustrated in Figure 4c and Figure 7c, ultimate compression stresses which could be up to about 40 MPa.

![Figure 7](image_url)

**Figure 7.** The effect of different factors on uniaxial compression stress–strains of DS-FRC: (a) W/B; (b) S/B; (c) DSRR; (d) with or without SP.

It can be revealed in Table 5 that the initial cracking stress first decreased and then increased with the increase of W/B, while it exhibited an opposite trend for the S/B with the maximum about 20 MPa at the S/B of 0.36. It is clearly illustrated that the ultimate compression stress of DS-FRC decreased with the increase of W/B, as is shown in Figures 4a and 7a. The maximum ultimate compression stress could be up to 46.3 MPa. However, it first increased and then decreased with the change of S/B, according to Figures 4b and 7b. The maximum value was obtained at the S/B of 0.36. In terms of DSRR, as is illustrated in Figures 4c and 7c, ultimate compression stresses which could be up to about 40 MPa slightly reduced, except for the DSRR of 100%, at which the ultimate compression stress was 36.8 MPa. However, it was still relatively high, which reveals the feasibility of desert sand as a substitution for engineering sand.

| Table 5. The parameter of compression toughness. |
|-----------------------------------------------|
| Mix NO. | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| $\sigma_0$/MPa | 20.95 | 20.32 | 13.83 | 15.61 | 18.76 | 16.69 | 15.67 | 16.46 | 15.12 | 19.00 |
| $\varepsilon_0$/% | 0.39 | 0.42 | 0.34 | 0.33 | 0.37 | 0.51 | 0.30 | 0.33 | 0.44 | 0.39 |
| $A_{eq}/1{m}^3$ | n = 3 | 26.78 | 28.36 | 16.76 | 16.69 | 23.15 | 30.73 | 17.09 | 17.23 | 25.47 | 25.24 |
|             | n = 5.5 | 50.84 | 43.32 | 37.54 | 35.04 | 37.82 | 43.17 | 33.97 | 41.97 | 41.72 |
| $f_{eq,u}$/MPa | n = 3 | 34.33 | 33.76 | 24.65 | 25.29 | 31.28 | 30.13 | 28.48 | 26.11 | 28.94 | 32.36 |
|             | n = 5.5 | 28.97 | 22.92 | 24.54 | 23.60 | 22.71 | 18.81 | 25.16 | 28.26 | 21.07 | 22.48 |
| $R_{eq}$ | 1.5 | 1.2 | 1.0 | 1.7 | 0.5 | 0.6 | 1.1 | 0.7 | 1.0 | 1.3 |
| $\sigma_0/\sigma_u$ | 0.45 | 0.47 | 0.39 | 0.49 | 0.46 | 0.42 | 0.39 | 0.41 | 0.41 | 0.47 |
| $f_{eq,u}/\sigma_u$ | n = 3 | 0.74 | 0.80 | 0.70 | 0.81 | 0.77 | 0.76 | 0.70 | 0.65 | 0.79 | 0.81 |
|             | n = 5.5 | 0.63 | 0.53 | 0.70 | 0.75 | 0.56 | 0.47 | 0.62 | 0.70 | 0.57 | 0.60 |
In regard of the corresponding strain, the DS-FRC with different mixtures revealed comparable results of about 1%. As illustrated in Table 4, the DSRR of 100% had no negative effects on the ultimate compression strain of DS-FRC. Although the ultimate compression stress was slightly lower than that of the ordinary concrete, the relatively high corresponding strain about 1.19% could still be obtained. The slightly reduced ultimate compression stress may be due to the relatively high content of mud in desert sand. Additionally, the slight porosity caused by the adding of PVA fiber may be related to the reduced compression strength of DS-FRC. However, good structural applicability can be still assured by using the composites with similar properties, according to previous researches. Compared with the DS-FRC without superplasticizer, as is illustrated in Figures 4d and 7d, the relatively high ultimate compression stress about 40.2 MPa and the corresponding strain about 0.97%, which was lower than that with superplasticizer, were observed. Based on above analysis, the appropriate content of the desert sand, as the substitution for fine aggregates, may effectively guarantee the mechanical properties development of FRC.

3.4.3. The Uniaxial Compression Toughness

The compression toughness was proposed to evaluate the compression deformation performance of DS-FRC. Currently, there are no uniform evaluation standards for the compression toughness of high ductility cementitious composites. Therefore, the area under the uniaxial compression stress–strain curve was used to evaluate the compression toughness and deformation performances of DS-FRC in this study, according to Cai and Xu [64]. The performance parameters are shown in Table 5, such as the cracking stress, the cracking strain, the post-crack strain energy density, the equivalent compression strength and the post-peak toughening index of fiber.

It is noted that the cracking point was determined as the proportional limit point of uniaxial compression stress–strain curves. The cracking point considered the relation between DS-FRC and ideal elastoplastic materials. In this point, the covered area under the compression stress–strain of DS-FRC was no more 10% than that of the ideal elastic material. The cracking point (referring to the proportional limit point of the compression stress–strain curve), the cracking strain energy density and the equivalent compression strength were calculated, according to Equations (1)–(3).

$$\frac{A_{FRC} - A_e}{A_{FRC}} = \frac{\int_{\epsilon_0}^{\epsilon_0} \sigma(\epsilon) d\epsilon - \frac{1}{2} \sigma_0 \epsilon_0}{\int_{\epsilon_0}^{\epsilon_0} \sigma(\epsilon) d\epsilon} \leq 10\%,$$

(1)

$$A_{np} = \int_0^{n \epsilon_0} \sigma(\epsilon) d\epsilon - \int_{\epsilon_0}^{\epsilon_0} \sigma(\epsilon) d\epsilon,$$

(2)

$$f_{eq,n} = \frac{A_{np}}{(n-1)\epsilon_0}.$$

(3)

In the above equations $\sigma_0, \epsilon_0$ are cracking stress and cracking strain, and $\sigma, \epsilon$ are the stress and strain at a certain point. $A_{FRC}, A_e$ are cracking strain energy density absorbed by DS-FRC and ideal elastic material, respectively; $n$ is the constant, which is 3 or 5.5; $A_{np}$ is absorbed strain energy density after initial cracking; $f_{eq,n}$ is the equivalent compression strength.

It was observed that there was no particularly significant post-peak ductility in DS-FRC, and the slope of compression stress–strain curves quickly dropped to the horizontal trend after the ultimate compression stress. Therefore, the value of $n$ was defined as 3 or 5.5 to evaluate the post-peak strain energy density and the equivalent compression strength of DS-FRC, according to Cai and Xu. The post-peak toughening index of fiber was calculated to quantitatively evaluate the post-peak toughness performances of DS-FRC. The point corresponding to the ultimate compression stress was defined as the limit of energy absorption. The post-peak fiber toughening index was obtained by Equation (4).

$$RT_f = \frac{A_{3u} - A_u}{A_u}.$$
\( A_u \) is the absorbed post-peak strain energy density corresponding to \( \varepsilon_u \), and \( A_{3u} \) is the value corresponding to 3\( \varepsilon_u \).

As is shown in Table 5, the ratio of \( \sigma_0 \) and \( \sigma_u \) was in the range of 0.39–0.49. Compared with the ordinary concrete, the proportional limit is slightly raised. It is observed that the fiber post-peak toughening effect is not obvious with the \( RT_f \) of about 1.0, which is in agreement with the relatively rapid drop of the compression stress–strain curves after \( \sigma_u \). Under the different W/B (see NO.1, 2, 3 and 4 of Tables 4 and 5), it was found that the \( RT_f \) ranged from 1.0 to 1.5 and slightly increased with the increase of \( \sigma_u \). Besides, the relation between \( \sigma_u \) and \( A_{up} \) was discussed with the increase of compression strengths. As is shown in Figure 8, the similar trends which first decreased then increased were observed under the different \( n \). The \( A_{up} \) at the \( n \) of 5.5 was higher than that of 3, and the difference can be up to 60%. In terms of the ratio between \( f_{eq,u} \) and \( \sigma_u \), it was about 0.5–0.8. Therefore, the relatively high compression deformation property can be obtained through the appropriate use of undisturbed desert sand.

![Figure 8. The relation between \( A_{up} \) and \( \sigma_u \).](image)

### 3.5. Microstructure

The optical microscope and scanning electron microscope (SEM) were used to understand the microscopic morphology of DS-FRC and the interface properties between fiber and matrix. Through 80 times optical microscope (see Figure 9a), it could be clearly illustrated that the micro-crack width in DS-FRC ranged approximately from 40\( \mu \)m–60\( \mu \)m due to the fiber bridging effect, which was anticipated to match with excellent crack controlling properties of high ductility cementitious composites and achieve good durability. Besides, the de-bonding between fiber and matrix (see Figure 9b–d) and the microstructure (see Figure 9e) of DS-FRC were clearly revealed by SEM images with 500–2000 magnification. According to Figure 9b, c, a larger area of single fiber detached from the matrix, and obvious de-bonding traces (see Figure 9d) were observed. The surface of fiber was covered by full hydration products, leading to relatively high interfacial adhesion and the fiber bridging effect. On the other hand, the hydration product covering the surface of fibers gave a friction which facilitated mechanical interlocking during the slippage of fiber. They all were beneficial to deformation performances of DS-FRC, especially for the tensile strain hardening property and the compression ductility. Besides, the hydroxyl group of PVA fiber was extremely easy to react with water to form hydrogen bonds, which formed good bonding between fiber and matrix and promoted the post-hydration reaction of DS-FRC. The full hydration reaction was essential to the strength development of composites. As is shown in Figure 9e, the compactness of the matrix was effectively improved due to the filling effect of small particle desert sand and rich hydration products, which filled the cementitious matrix, refined internal air voids and resulted in the strength development of uniaxial tensile and compression of DS-FRC. Moreover, the Si\textsuperscript{4+} dissolved from desert sand with fine particles might promote the pozzolanic reaction which was also conducive to the development of strength.
However, it might be due to the relatively low content of silica in desert sand that the slightly reduced ultimate compression strengths were observed. It was worth noting that there were few unreacted spherical fly ash granules which might have a negative effect to the mechanical properties of DS-FRC, attributed to relatively high volume of the fly ash.

Figure 9. The microstructure of composites: (a) micro-crack; (b) the single fiber pulled from the matrix; (c) the debonding between fiber and matrix; (d) the debonding trace; (e) the compactness of the matrix.

4. Conclusions

In this study, the uniaxial tensile and compression properties of DS-FRC with the changes of W/B, S/B and DSRR were experimentally investigated, including workability, stress–strain curves, uniaxial compression toughness and microstructures. According to the results, the following conclusions can be drawn:

1) The close consistency values of approximately 60–70 are observed in most DS-FRC, except for the critical W/B, such as the highest and lowest. The W/B and the content of desert sand are main factors affecting the workability of DS-FRC. At the highest W/B, the phenomenon of clumping (balling) or floating of fibers is observed. The high content of desert sand is bad for the fluidity of DS-FRC. Besides, the densities of DS-FRC maintain a comparable level, approximately 1900 kg/m$^3$, which are 10% lower than that of ordinary concrete, resulting from the lack of coarse aggregates and the porosity caused by the addition of fibers.

2) The Elastic Modulus of DS-FRC are about 13–20 GPa which are lower than that of the ordinary concrete due to the lack of coarse aggregate and increased porosity caused by the addition of fiber. The high content of desert sand has a negative effect on the Elastic Modulus of DS-FRC. It will decrease with the increase of DSRR. When the DSRR was low, the comparable Elastic Modulus
are observed with the increase of S/B. The Poisson’s ratio of DS-FRC is smaller than that of the ordinary concrete, approximately 0.18–0.25. That is because the lateral deformation of DS-FRC is limited by the bridging effect of fibers.

(3) The uniaxial tension and compression properties of DS-FRC are mainly affected by the W/B and S/B. The optimum uniaxial mechanical performances are obtained at the W/B of 0.29 and the S/B of 0.36, respectively. The ultimate tensile stresses and corresponding strains are up to 4–5 MPa and 3%, respectively. However, for the uniaxial compression performance, all specimens maintain a high level more than 40 MPa and 1.0%, respectively.

(4) In terms of the DSRR, it is observed that slightly improved ultimate tensile stresses due to improved matrix compactness and reduced corresponding strains are obtained. However, for the uniaxial compression performance, slightly reduced ultimate compression stresses and comparable strains approximately 1% are observed. It has few effects on the mechanical properties of DS-FRC, even for the DSRR of 100%, which reveals the feasibility of desert sand as the replacement of fine aggregates.

(5) Compression toughness indexes are calculated to evaluate the compression deformation performance of DS-FRC, such as the initial cracking strain, the cracking strain energy density, the equivalent compression strength and post-peak fiber toughening index. The results show that the ratio of the cracking stress and the ultimate stress is at the range of 0.39–0.49, while the ratio of the equivalent compression strength and the ultimate compression strength is about 0.5 to 0.8. The cracking strain energy density is closely related with the ultimate compression stress. Besides, all specimens have the characteristics of the multiple cracking before the compression destruction. It reveals that DS-FRC can be determined as a ductile material.

(6) As far as the microstructural of DS-FRC, the excellent crack controlling performance with micro-crack widths of about 40–60 µm is observed. The phenomenon of fiber debonding and pulling out is obvious, which promotes the development of tensile strain hardening. Besides, good compactness of the matrix is obtained due to the filling effect of fine undisturbed desert sand.

Currently, the structural health monitoring technology has become a research focus [65–67]. The piezoceramic transducers are one of the most studied monitoring technologies [68,69], which can achieve the real-time monitoring of slurry compaction [70], internal microstructures [71] and interface debonding problems [72,73]. Considering the advantages of the piezoceramic transducer, the real-time monitoring based on it for DS-FRC members will be targeted in future research work, including the internal compactness, internal damage properties and interface debonding properties between fiber and matrix. This approach is expected to provide more insight into damage mechanisms of cementitious composites. Additionally, it can also provide a theoretical basis for further optimization of material properties and promoting the structural applicability of DS-FRC.

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