Effect of Doped Glass Fibers on Tensile and Shear Strengths and Microstructure of the Modified Shotcrete Material: An Experimental Study and a Simplified 2D Model

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Abstract: Shotcrete material has found extensive applications as a reinforcing material in the engineering sector. This study examined the effect of doped glass fibers on the mechanical performance of the modified shotcrete material composed of aeolian sand, fly ash, cement, quicklime, and doped glass fibers. Its tensile and shear strengths values were experimentally determined via a WAW-1000D computerized hydraulic universal tensile testing machine. Its microstructure was analyzed via a size analyzer, scanning electron microscope (SEM), and X-ray diffractometer (XRD). A 2D simplified mechanical model was elaborated to reflect the influence mechanism of the doped glass fibers on the mechanical performance of the modified shotcrete material. The experimental and mechanical analysis results indicated that, at the macroscopic scale, the experimental tensile and shear strengths of the shotcrete material doped with glass fibers were significantly higher than those of the undoped shotcrete material (by up to 310% and 596%, respectively). These results were in concert with the proposed model predictions, where the compound stresses in the shotcrete material were derived as the sum of the stress borne by the shotcrete material itself and the bridging stress exerted by the glass fibers. At the microscopic scale, SEM observations also revealed that the glass fibers were intertwined with each other and tightly enveloped by the shotcrete material particles within the modified shotcrete specimens, connecting the particles of different components into a whole and improving the overall mechanical strength. In addition, the relationships of the compound stress of the shotcrete material vs. embedment length, embedment angle, and cross-sectional area of the glass fibers were established. The research findings are considered instrumental in clarifying the mechanism by which the glass fibers influence the mechanical performance of shotcrete materials and optimize their solid waste (fly ash and quicklime) utilization.

Keywords: glass fiber; shotcrete material; mechanical performance; microstructure; bridging stress

1. Introduction

Coal is the leading energy source in China and occupies the predominant position in China's primary energy consumption [1–3]. According to the statistics released by the National Bureau of Statistics, China's total energy consumption amounted to 4.98 billion tons of standard coal in 2020. Coal consumption accounted for 56.8% [4–6]. Along with the high-intensity mining of the coal resources, the shallow coal resources in Eastern China are on the verge of depletion. Currently, the depth of coal mines is extending at an annual rate of 10–25 m [7–10]. The high-intensity mining of coal resources is inevitably accompanied by the production of a large amount of solid waste. For example, fly ash is the main byproduct of burning coal at coal-fired generating plants, which causes soil,
surface water, groundwater, and air contamination [11–13]. In addition, the in situ stress increases with the mining depth. Rib spalling and roadway floor heaving are more likely to occur under higher in situ stress, and reduce the service life of the roadway and coal mine [14–16]. Reinforcement by shotcreting using concrete-based material is the conventional method to address the problems of rib spalling and roadway floor heaving [17,18]. Concrete is mainly composed of such natural resources as river sands, gravel, and cement. The habitual use of concrete-based material for shotcreting may place a significant burden on depletable resources and the environment. In addition, the concrete-based material is costly, and its manufacturing process is complex [19–21]. Furthermore, the concrete has the defects of low tensile strength, small ultimate elongation, and brittleness. The reinforcing effect of the shotcrete materials is significantly weakened because of these defects. The development of a safe, reliable reinforcement material to be used in the coal mining sector is urgently needed.

Among the raw materials used as manufacturing modified shotcrete materials, aeolian sand serves as the aggregate; fly ash is the cementitious material and is used for alkali activation; and cement is used to increase the mechanical strength of the shotcrete materials [22,23]. Modified shotcrete materials can replace the conventional shotcrete reinforcement materials, thus reducing the use of depletable resources. In addition, the manufacturing of modified shotcrete materials requires a large amount of fly ash, a waste that is discarded in piles in the open. The use of modified shotcrete material can reduce environmental contamination caused by piles of fly ash.

To date, numerous studies have been conducted of these modified shotcrete materials in relevant sectors. Zhou et al. [24] determined and optimized the physical and mechanical properties of the sand-based cement ed filling materials. Zhou et al. [25] conducted indoor tests of the aeolian sand-based cemented filling materials to study the influence of the doping amounts of fly ash, cement, and lime slags on their physical and mechanical properties. Ouyang et al. [26] investigated the mechanical performance at the interface between the cemented filling material and the hydration products. They further performed SEM to observe the fracture propagation and fracture surface characteristics of the shotcrete specimens. Deng et al. [27] studied the influence of different aggregate particles on the rheological behavior and setting time of the shotcrete material. The existing studies were mainly focused on applying modified shotcrete materials composed of aeolian sand, fly ash, cement, and quicklime to the underground filling working face. A small number discussed modified shotcrete materials for filling and reinforcing the roadway ribs and roadway floors that underwent heaving. In addition, most researchers only investigated the tensile strength of shotcrete materials, and not their tensile and shear strength parameters, which may be relevant in solutions to the problems of roadway rib spalling and floor heaving.

Fibers are widely used in various sectors due to their high tensile strength and high corrosion resistance. Fibers are a non-organic non-metal material composed of continuous or discontinuous filaments. The diameter of a single filament constituting fibers varies between several to two dozen micrometers. Fibers have been widely used to prepare fiber-doped concrete due to their high tensile strength and high corrosion resistance. Fiber-doped concrete is a composite made of fibers and cement slurry. This material has high tensile and cracking strengths. In addition, the doped fibers can prevent crack propagation in the concrete substrate, thereby improving the concrete’s crack resistance. The potential of fiber-doped concrete has drawn widespread attention. Sucharda et al. [28] conducted a three-point bending test of fiber-doped concrete beams to evaluate the basic properties of the fiber-doped concrete material. Liang et al. [29] studied the influence of the doped polypropylene and basalt fibers on the fracture toughness of concrete. The results showed that, compared with basalt fibers, polypropylene fibers had a more significant impact on the fracture toughness of the reinforced concrete. Saini et al. [30] built a constitutive model of low-speed impact, proving that ultrahigh-performance fibers significantly enhanced concrete’s impact resistance. Ranjbar et al. [31] assessed the influence of
three types of fiber on the mechanical and fracture performance of the composite polymer materials. The results showed that an appropriate addition of fibers altered the fracture performance of the composite materials; that is, the composite materials changed from being brittle to tough, with a reduction in the number of cracks in the materials. Ayazian et al. [32] optimized the reliability of the steel-reinforced concrete columns doped with carbon fibers and proposed an optimization strategy considering a time-varying degeneration model. Then, the optimal time and the optimization degree of doping carbon fibers into the steel-reinforced concrete columns were determined. However, the above studies devoted to fibers doped in concrete are mainly concerned with the ductility and internal damage mechanism of concrete. Few researchers have investigated the mechanical performance and microstructure of the modified shotcrete materials made of solid waste (e.g., fly ash and aeolian sand) doped with glass fibers.

To develop a sustainable, safe, reliable, and green reinforced shotcrete material, we doped glass fibers into the shotcrete material made of solid wastes, including aeolian sand and fly ash. This modification was expected to strengthen the mechanical and environmental-friendly performance of the reinforced shotcrete material. A WAW-1000D computerized hydraulic universal tensile testing machine and SEM were employed to analyze the effect of doped glass fibers on the tensile strength of the modified shotcrete material and the shear strength at different curing ages. We also observed the microstructure of the modified shotcrete materials and constructed a 2D simplified mechanical model of the fiber-doped shotcrete material. The mechanism by which the glass fibers influenced the mechanical performance and microstructure of the shotcrete material was tentatively proposed.

2. Materials and Methods

This section briefly outlines the raw materials used in the manufacturing process and the experimental scheme, sample preparation method, and experimental process.

2.1. Test Materials

The present study used aeolian sand as aggregate, fly ash and cement as binders, and quicklime as an additive. The glass fibers were doped as a novel ingredient to improve the tensile and shear strengths of the shotcrete material. More details on the raw materials are given below.

2.1.1. Glass Fibers

The Hunan Xinchuang Glass Factory, China, provided the glass fibers. The glass fibers were primarily composed of quartz, limestone, and dolomite. As a non-organic non-metal material, glass fibers are generally known for their high tensile strength and high corrosion resistance. In engineering application scenarios, glass fibers are usually used as a reinforcing material for composite materials. For example, the present study utilized the advantages of doping glass fibers to improve the tensile strength of the shotcrete material. The diameter of glass fibers varied between 0.3 and 0.4 mm, and the density was 2.4–2.76 g/cm³. The specific parameters are shown in Table 1.

The lengths of the glass fibers used for the experiment were 3, 6, and 15 mm. The mix ratios of the glass fibers were 1‰, 3‰, 5‰, 10‰ and 15‰. The basic properties, characteristics, and dimensions of the glass fibers are summarized in Figure 1.
Figure 1. Characterization of glass fibers.

Table 1. The basic parameters of glass fiber.

| Diameter | Elongation at Break | Young Modulus | Density | Tensile Strength |
|----------|---------------------|---------------|---------|-----------------|
| 0.3–0.4 mm | 3.3–3.6% | 7300–8600 MPa | 2.4–2.76 g/cm³ | 3100–4650 MPa |

2.1.2. Aeolian Sand

The aggregate of the modified shotcrete material was predominantly aeolian sand. The aeolian sand was the deposited sand subject to the long-term effects of the natural environment in Yulin City, Shanxi Province, China. Figure 2a is a photo of the aeolian sand. Figure 2b is the observation under the SEM. The magnification factor was 50×.

Figure 2. A photo of the aeolian sand (a) and microscopic structure of aeolian sand 50× (b).
As shown in Figure 2b, the aeolian sand was of varying particle sizes and shapes, which implied its stress transfer capability within the shotcrete material, increasing the overall shotcrete material strength.

2.1.3. Cement

The portland cement was acquired from the Jinniu Coal Mine, Yulin City, Shanxi Province, China, where it was used as a binder, which improved the mechanical performance of the shotcrete materials. Figure 3 shows the EDS analysis results for the cement, and its particle size distribution graph is plotted in Figure 4. Table 2 shows the main chemical composition of the cement.

![EDS analysis result for the cement.](image)

![Particle size distribution of the cement.](image)

As shown in Figure 3 and Table 2, the cement was mainly composed of O, Si, and Al elements, which were conducive to the cement’s hydration. In the presence of fly ash with an alkali activation effect, the cement improved the mechanical strength of the shotcrete material. Figure 4 shows that the cement particle sizes mainly ranged from 20 to 60 μm.

| Element | Weight Percent, wt% | Atomic Percent, at% |
|---------|---------------------|---------------------|
| O       | 46.61               | 61.04               |
| Si      | 20.59               | 15.36               |
2.1.4. Fly Ash

Fly ash is a pulverized solid waste produced from coal burning at power plants. Acting as the binding material in the shotcrete material, fly ash was added due to its alkali activation. Figure 5 and Table 3 show the contents and types of chemical elements in the fly ash. Fly ash was mainly composed of O, C, Si, and Fe elements. Figure 6 shows the particle size distribution of fly ash, which ranged from 45 to 90 μm. Smaller particle sizes were conducive to increasing the contact surface, thus accelerating the hydration.

![Figure 5. EDS analysis result for fly ash.](image1)

![Figure 6. Particle size distribution of fly ash.](image2)

| Element   | Weight Percent, wt% | Atomic Percent, at% |
|-----------|---------------------|---------------------|
| O         | 43.36               | 45.77               |
| C         | 27.18               | 38.22               |
| Si        | 11.99               | 7.21                |
| Other elements | <10            | <10                |
2.2. Mix Ratios

The raw materials for manufacturing the modified shotcrete material were aeolian sand, fly ash, cement, and quicklime. The slurry concentration was 78% in the shotcrete material. The aeolian sand, fly ash, cement, and quicklime accounted for 47.5, 35, 12.5, and 5% of the total dry weight, respectively. Here, glass fibers were doped into the shotcrete material as a novel ingredient. The lengths of the doped glass fibers were 3, 6, and 16 mm. The mix ratios of the doped glass fibers were 1‰, 3‰, 5‰, 10‰, and 15‰. Given the low mass fraction of glass fibers, its influence on the mass fraction of the whole slurry was negligible.

2.3. Preparation of Specimens

Glass fibers were doped into the shotcrete material to study their effect on the mechanical strength of shotcrete specimens after their modification. Then, the glass fiber-doped shotcrete material was processed into cube specimens measuring $7.07 \times 7.07 \times 7.07$ cm$^3$ according to the GB T23561.12-2010 Standard [21]. The GB T23561.12-2010 standard includes the following specification: “5.5.2 The specimens should be cured in an environment at 20 ± 5 °C for 24 h to 48 h. Then the specimens should be numbered, and the mold removed. Once the mold is removed, the specimens should be cured in a standard curing box at a temperature of 20 ± 1 °C and a relative humidity above 95%.” The preparation of specimens consisted of the following steps: weighing, mixing, stirring, forming, curing, and mechanical testing. The raw materials were dry-mixed and stirred according to different mix ratios. Then water was slowly added into the well-stirred slurry with mixing to form a modified slurry. A grinding tool was used to process it into cubic shotcrete specimens. Finally, the temperature of the curing box was set to 20 ± 1 °C and the relative humidity of 95%, depending on the actual conditions of the coal mine [22]. A standard curing procedure was implemented. The shotcrete specimens reaching the curing age were subjected to mechanical strength testing. The flowchart of specimen preparation is shown in Figure 7.
2.4. Experimental Method

(1) Mechanical Performance Testing

The mechanical performance testing of the modified shotcrete specimens included tensile and shear strength testing. A WAW-1000A computerized hydraulic universal tensile testing machine (State Key Laboratory of Coal Resources and Safe Mining; China University of Mining and Technology; Xuzhou, China) was used to determine the influence of the doped glass fibers on the mechanical performance of the modified shotcrete specimens. This testing machine provided a maximum axial load of 1000 kN and a 0–250 mm stroke. The mechanical performance testing of the shotcrete specimens was conducted according to the GB T23561.12-2010 Standard [21]. The specification for the testing procedure is as follows: “6.0.4 Before the test, the specimens surface and the upper and lower level plates are wiped clean. Next, the load-bearing face of the specimen should be placed vertically to the top surface upon forming. Finally, when the concrete grade is below C30, the loading rate is 0.5 mm/min. Besides, the arithmetic mean of the measurements of the three specimens is considered the strength of the specimen (exact to 0.1 MPa).” The load was applied under displacement control at a loading rate of 0.5 mm/min. Three specimens were prepared for each condition, and their average value was taken as the final strength.

(2) Microstructural Observations

SEM was employed for microstructure observation of the shotcrete specimens to reveal the mechanism by which the doped glass fibers influenced the mechanical performance of the modified shotcrete specimens. The flowchart of microstructural preparation and observation of the modified shotcrete specimens is shown in Figure 8.

As shown in Figure 8, the microstructural preparation and observation of the modified shotcrete specimens consisted of the following steps: finishing, drying, cutting, metal spraying, and microstructural observation of the specimen surface. Specimens used for microstructural observation were chosen among those that had been subjected to the mechanical tests. The specimens were first dried in a drying box at 40 °C for 8 h. Then, the dried specimens were cut into cube specimens with the length, width, and height not above 10, 5, and 5 mm, respectively, using a cutting tool. The specimens were fixed to the base plate, with the original surface to be observed facing upwards. Metal spraying was conducted to increase the electrical conductivity of the specimens and facilitate SEM
observations. Finally, the surface microstructure of the specimens was observed at magnification factors of ×40, ×80, ×500, ×1000, and ×3000.

3. Experimental Results

We doped glass fibers with varying lengths and at varying mix ratios into the modified shotcrete specimens to observe their effect on the specimens’ mechanical performance and microstructure. The changes in the tensile and shear strengths after the modification were recorded and analyzed. The surface microstructure of the specimens was observed by SEM to reveal the mechanism by which the glass fibers influenced the mechanical strength of the modified shotcrete specimens.

3.1. Macroscopic Performance Testing

In engineering applications of modified shotcrete materials related to reinforcing the roadway ribs and floors, tensile and shear stresses play an important role, in addition to compressive stresses due to mining-induced displacements. Therefore, in this study, the tensile and shear static strengths of the modified shotcrete materials were experimentally determined. In addition, the effect of glass fibers on the tensile and shear strengths of the modified shotcrete materials was quantitatively described via the proposed model.

3.1.1. Tensile Strength

We studied the influence of the mix ratio of the glass fibers on the tensile strength of the modified shotcrete specimens. One variable was fixed at a time. That is, the tensile strength was determined for a constant length of glass fibers (namely, 3 mm) and a varying mix ratio of the glass fibers (1‰, 3‰, 5‰, 10‰, 15‰). Similarly, at fixed glass fibers’ lengths of 6 and 15 mm, the tensile strengths of specimens with the above variety of glass fibers’ mix ratios were obtained and are plotted in Figure 9. Table 4 shows the tensile strength parameters of the modified shotcrete specimens at different lengths and mix ratios of glass fibers. Figure 10 shows the peak tensile strength curves at different mix ratios of glass fibers plotted using the average peak stress of the shotcrete specimens in Table 4. The effect of the mix ratio of glass fibers on the tensile strength of the shotcrete specimens was further analyzed quantitatively.
Figure 9. Tensile stress–strain curves for different mix ratios (a–o).
Figure 10. Tensile stress vs. mix ratio curves for different lengths of glass fibers. (a) Glass fiber length of 3 mm. (b) Glass fiber length of 6 mm. (c) Glass fiber length of 15 mm.

Table 4. Experimental tensile strength values of tested specimens.

| Sample Designation | Mix Ratio, ‰ | Tensile Strength, kPa | Average Tensile Strength, kPa | Variance | Standard Deviation, % |
|--------------------|--------------|------------------------|------------------------------|----------|-----------------------|
| Fiber length of 3 mm |
| A1                 | 1            | 80                     | 156                          | 11,756   | 108                   |
| A2                 | 1            | 80                     |                              |          |                       |
| A3                 | 310          |                        |                              |          |                       |
| B1                 | 3            | 395                    | 339                          | 6653     | 81                    |
| B2                 | 3            | 224                    |                              |          |                       |
| B3                 | 399          |                        |                              |          |                       |
| C1                 | 5            | 186                    | 346                          | 13,066   | 114                   |
| C2                 | 5            | 446                    |                              |          |                       |
| C3                 | 406          |                        |                              |          |                       |
| D1                 | 5            | 389                    | 429                          | 1122     | 33                    |
| D2                 | 5            | 471                    |                              |          |                       |
| D3                 | 427          |                        |                              |          |                       |
| E1                 | 5            | 179                    | 171                          | 3626     | 60                    |
| E2                 | 5            | 154                    |                              |          |                       |
| E3                 | 180          |                        |                              |          |                       |
| Fiber length of 6 mm |
| F1                 | 1            | 451                    | 451                          | 3626     | 60                    |
| F2                 | 1            | 484                    |                              |          |                       |
| F3                 | 343          |                        |                              |          |                       |
| G1                 | 3            | 536                    | 456                          | 4046     | 63                    |
| G2                 | 3            | 452                    |                              |          |                       |
| G3                 | 380          |                        |                              |          |                       |
| H1                 | 5            | 509                    | 448                          | 4142     | 64                    |
| H2                 | 5            | 359                    |                              |          |                       |
| H3                 | 476          |                        |                              |          |                       |
| I1                 | 10           | 680                    | 585                          | 4509     | 67                    |
| I2                 | 10           | 548                    |                              |          |                       |
| I3                 | 529          |                        |                              |          |                       |
| J1                 | 15           | 524                    | 523                          | 2.8      | 1.6                   |
| J2                 | 15           | 525                    |                              |          |                       |
| J3                 | 521          |                        |                              |          |                       |
| Fiber length of 15 mm |
| K1                 | 1            | 100                    | 102                          | 9.5      | 3                     |
| K2                 | 1            | 107                    |                              |          |                       |
| K3                 | 101          |                        |                              |          |                       |
As seen in Figure 9 as the mix ratio of the glass fibers increased, the peak stress–strain curve also presented an increasing trend. This was because the doping of glass fibers enhanced the integrity of the shotcrete material. As shown in Figure 11, the glass fibers acted as reinforcing ribs inside the shotcrete material, improving the tensile strength of the shotcrete material. As the mix ratio of the glass fibers increased, there were more reinforcing ribs available inside the shotcrete material to offer support. For this reason, the mechanical performance of the shotcrete material was improved as the mix ratio of the glass fibers increased. However, at a 15‰ mix ratio of glass fibers, the peak stress decreased significantly, indicating that a higher mix ratio of the glass fibers weakened the tensile strength of the modified shotcrete material. The major reason for this deterioration was that the glass fibers stayed together as clusters due to non-uniform mixing as more glass fibers were doped. These clusters of glass fibers increased the porosity in the shotcrete material, thereby decreasing the tensile strength of the shotcrete material. According to the peak tensile strength curves in Figure 10, at glass fibers’ mix ratios of 1‰ and 10‰, the shotcrete material had the lowest and highest tensile strength values, respectively. As seen from the above, an appropriate choice of the mix ratio of glass fibers in the shotcrete material was crucial for improving the tensile strength of the shotcrete material. According to the comparison of doped and undoped shotcrete specimens, the doped shotcrete specimen still preserved part of the tensile strength after damage. At this stage, the residual tensile strength was primarily provided by the doped glass fibers in the shotcrete material.

|    |    |    |    |    |    |    |
|----|----|----|----|----|----|----|
| L1 |    | 159 | 159 | 96 | 9.7 |
| L2 | 3  | 147 |     |    |    |    |
| L3 |    | 171 |     |    |    |    |
| M1 |    | 413 |     |    |    |    |
| M2 | 5  | 311 | 333 | 3416 | 58 |
| M3 |    | 275 |     |    |    |    |
| N1 |    | 378 |     |    |    |    |
| N2 | 10 | 475 | 418 | 1712 | 41 |
| N3 |    | 401 |     |    |    |    |
| P1 |    | 58.9|     |    |    |    |
| P2 | 15 | 121 | 123 | 2957 | 54 |
| P3 |    | 192 |     |    |    |    |
According to the tensile strength values of the shotcrete material in Table 4, for doped glass fibers with a length of 3 mm, the highest average peak tensile strength of 429 kPa was reached at a mix ratio of 10‰, exceeding that of a 1‰ mix ratio by 175%. Similarly, at the doped glass fibers’ lengths of 6 and 15 mm, the peak tensile strengths of the shotcrete material were 585 and 417 kPa, respectively. These were higher than the lowest peak tensile strengths of the undoped shotcrete specimens by 37.3% and 309.8%, respectively. As expected, the doped glass fibers significantly improved the tensile strength of the shotcrete material.

3.1.2. Shear Strength

Because shear strength is also vital for the proper mechanical performance of shotcrete materials, we further studied whether the doped glass fibers also improved the shear strength.

To achieve this purpose, we doped glass fibers with a length of 6 mm and at a mix ratio of 10‰ into the shotcrete specimens; this combination ensured the highest tensile strength of 429 kPa. The shear tests were performed at three different shear angles (40°, 50° and 60°) on specimens with five different curing ages (1, 3, 7, 14, and 28 days). Figure 12 shows the curing age and shear angle effects on the shear strength of the doped shotcrete specimens.
According to the experimental results plotted in Figure 12 and listed in Table 5, the shear strength of shotcrete specimens dropped with the shear angle at any curing age. This is because, as the shear angle increased, the shear force inside the shotcrete specimen increased, leading to the shear damage of the specimen. The shear force inside the specimen was small at a small shear angle. The specimen was subject to the combined action of shear strength and compressive strength. For this reason, the larger the shear angle, the smaller the shear strength. As shown in Figure 13, at different shear angles, the orientation of crack propagation also varied. At a larger shear angle, several cracks appeared in the specimen along the shear direction. This indicated that the shear strength of the shotcrete specimen increased at a larger shear angle. Moreover, the glass fibers had a bridging effect inside the shotcrete specimen, which further enhanced the anti-shear effect in the specimen.
According to Figure 14, at different shear angles, the shear strength of the shotcrete specimens increased with the curing age and to varying degrees. At shear angles of 40°, 50°, and 60°, the peak shear strength increased by 387.3%, 611.3%, and 596.9%, respectively, compared to 1d. Thus, as the curing age increased, the shear strength of the shotcrete specimen increased most dramatically at a shear angle of 50°. In addition, as shown in Figure 14b, at a shear angle of 50°, the peak shear strength of the shotcrete specimen increased most significantly when the curing age was increased from 14 to 28 days.

![Figure 13. Comparison of specimens at different shear angles. (a) Crack at a shear angle of 40; (b) Crack at a shear angle of 50°; (c) Crack at a shear angle of 60°; (d) Specimens after shearing.](image)

| Specimen Designation | Curing Age, Days | Shear Angle, Degrees | Shear Strength, kPa | Average Shear Strength, kPa | Standard Deviation, % |
|---------------------|-----------------|----------------------|---------------------|-----------------------------|-----------------------|
| A1                  | 1               | 40                   | 766                 | 575                         | 200                   |
| A2                  |                 | 661                  |                     |                             |                       |
| A3                  |                 | 299                  |                     |                             |                       |
| A4                  | 1               | 50                   | 14                  | 186                         | 134                   |
| A5                  |                 | 202                  |                     |                             |                       |
| A6                  |                 | 342                  |                     |                             |                       |
| A7                  | 1               | 136                  |                     |                             |                       |
| A8                  |                 | 47                   | 64                  | 53                          |                       |
| A9                  |                 | 8.5                  |                     |                             |                       |
| B1                  | 3               | 596                  |                     |                             |                       |
| B2                  |                 | 691                  |                     |                             |                       |
| B3                  |                 | 537                  |                     |                             |                       |
| B4                  |                 | 335                  |                     |                             |                       |
| B5                  |                 | 334                  | 333                 | 2.9                         |                       |
| B6                  |                 | 328                  |                     |                             |                       |
|   |   |   |   |   |
|---|---|---|---|---|
| B7 | 60 | 164 | 12.7 |
| C1 | 40 | 1032 |
| C2 | 784 | 1108 | 299 |
| C3 | 1507 |
| C4 | 7 | 425 |
| C5 | 50 | 568 | 66 |
| C6 | 565 |
| C7 | 60 | 279 |
| C8 | 6 | 217 | 25 |
| C9 | 256 |
| D1 | 40 | 1854 |
| D2 | 2393 | 2066 | 234 |
| D3 | 1950 |
| D4 | 14 | 50° | 825 |
| D5 | 297 | 628 | 235 |
| D6 | 762 |
| D7 | 60 | 506 |
| D8 | 305 | 390 | 85 |
| D9 | 359 |
| E1 | 40° | 2683 |
| E2 | 2696 | 2802 | 158 |
| E3 | 3026 |
| E4 | 28 | 1025 |
| E5 | 1787 | 1323 | 332 |
| E6 | 1158 |
| E7 | 60 | 286 |
| E8 | 425 | 446 | 140 |

**Figure 14.** Average peak shear stress at different curing ages. (a) Shear angle of 40°. (b) Shear angle of 50°. (c) Shear angle of 60°.
3.2. Microstructural Characteristics

3.2.1. Microscopic Characteristics of Tensile Strength

In this section, the specimens’ microstructure was characterized by SEM to determine the mechanism by which the doped glass fibers influenced the mechanical performance of the shotcrete material. Figure 15 shows the distribution of glass fibers in the shotcrete specimens at different magnification factors under the action of tensile stresses.

**Figure 15.** Matrix–glass fiber adhesion features during tensile tests under different magnifications. (a) Blank control; (b) Overall distribution of glass fibers×40; (c) ×80; (d) ×500; (e) ×1000; (f) ×3000.
As shown in Figure 15, the undoped shotcrete specimens (blank control group) had a smooth surface and higher integrity. When no glass fibers were doped, the shotcrete material withstood the tensile force from the outside entirely by itself. Notably, the shotcrete material generally had low tensile and shear strengths. Therefore, the undoped shotcrete material was weak in the face of the external tensile force. Doping glass fibers into shotcrete material can overcome this defect. Its application prospects appear to be promising in the engineering sector.

Figure 15 shows the microscopic structure of the glass-doped shotcrete material. It appears that doping glass fibers changed the spatial structure inside the shotcrete specimen. The doped glass fibers in the shotcrete specimens were intertwined with each other. These fibers formed the skeleton of the shotcrete specimen, enhancing the integrity of the shotcrete material. As shown in Figure 15c,d, under the magnification factors of 80× and 500×, fly ash particles were embedded into the aeolian sand particles, partially filling pores in the shotcrete specimens. This microstructure was conducive to stress transfer in specimens, improving their mechanical strength. In addition, the aeolian sand particles had a larger size, thus facilitating the hydration of fly ash and cement embedded into the aeolian sand particles. As shown in Figure 15e,f, at magnification factors of 1000× and 3000×, glass fibers were surrounded by many spherical and crystal particles. The spherical particles were the silicic acid compounds produced by the hydration reaction of fly ash and cement. The glass fibers were tightly enveloped by the shotcrete material particles, fixing particles of different components and improving the tensile strength of the shotcrete material.

3.2.2. Microscopic Characteristics of Shear Strength

In this section, SEM was employed to verify the influence mechanism of the doped glass fibers on the shear strength of the shotcrete specimens on the microscopic scale. We also analyzed the adhesion features between the matrix and glass fibers in the shotcrete specimens. Figure 16 shows the distribution of fibers in the shotcrete specimens at different magnification factors.
As shown in Figure 16a, microscopic particles were attached to the surface of the undoped shotcrete specimens, promoting their failure even under small loads. The glass fibers became oblique under the shear force in the glass fiber-doped shotcrete specimens (Figure 16b). This was mainly because the shotcrete material and the glass fibers worked synergistically to resist the external shear force at the initial stage. After the shotcrete material was damaged, only the glass fibers were left to resist the external force. Thus, after the specimen was damaged, the glass fibers inside the shotcrete material underwent oblique damage under shearing. In addition, the glass fibers exerted an anti-shear effect in the opposite direction under the shear force, thus inhibiting the deformation and failure of the shotcrete material. Consequently, the mechanical performance of the doped shotcrete specimens was improved, and the shotcreting effect was optimized.

At a magnification factor of 40×, the overall attachment of the glass fibers in the shotcrete specimens was able to be visualized. The fibers were embedded within the shotcrete material, enhancing the integrity of specimens. When the shotcrete material adheres to the surrounding rocks or the roadway floor, the glass fibers in the shotcrete material will improve the adhesion and strength of the contact surface. At magnification factors of 500×, 1000×, and 1500×, the distribution of glass fibers within the shotcrete material was able to be visualized. The shotcrete material densely enveloped the glass fibers. In addition, the fly ash exerted an alkali activation effect, enhancing the hydration of cement and quicklime, and improving the mechanical performance of the shotcrete material.
4. Discussion

4.1. Elaboration of a Mechanical Model of Glass Fibers’ Effect

The influence laws of the doped glass fibers on the tensile and shear strengths of the shotcrete material were analyzed at both the macroscopic and microscopic scales. We tentatively explained the influence mechanism of the glass fibers in the shotcrete material based on the macroscopic mechanical behavior. In addition, the effect of doped glass fibers on the shotcrete material was verified microscopically using SEM. We constructed a 2D simplified mechanical model of the glass fibers distributed in the shotcrete material based on the influence mechanism of the doped glass fibers on the mechanical performance of the shotcrete material, as shown in Figure 17.

![Figure 17. Mechanical model of fibers’ effect on the strength of specimens. (a) Before fractur. (b) After fracturing. (c) A single fiber.](image)

Figure 17 illustrates the proposed 2D simplified mechanical model of the glass fibers distributed in the shotcrete specimens. The situations before and after fracturing are depicted in Figure 17a,b, respectively. As shown in Figure 17a, the glass fibers were distributed in a disorderly manner inside the shotcrete material. The oblique angles between the glass fibers varied. As shown in Figure 17b, after cracks appeared in the shotcrete material under the external force, the fissures in the shotcrete material were filled by glass fibers. It was thus demonstrated that glass fibers had a bridging effect inside the shotcrete material.

When constructing the simplified 2D model, we randomly chose a single glass fiber among the disordered glass fibers for the analysis. Figure 17c shows the mechanical model of a single glass fiber, where the embedment length in the shotcrete material is $l$; the vertical angle with respect to the horizontal plane is $\theta$; the fracture width in the shotcrete material is $u$; and the stress acting on the shotcrete material is $\sigma$. The relationship between the stress acting on the shotcrete material and each parameter of the glass fibers was established. Then, the influence mechanism of the doped glass fibers on the mechanical performance of the shotcrete material was analyzed quantitatively.
4.2. Mechanism of Doped Glass Fibers’ Effect on the Mechanical Performance of Shotcrete Specimens

We further quantitatively explored the influence of glass fibers on the shotcrete materials’ mechanical performance. Figure 18a shows a simplified diagram of the stress–strain state of a single fiber, which was used to quantify the glass fibers’ effect on the shotcrete material’s mechanical performance via the mechanical analysis diagram plotted in Figure 18b.

![Figure 18a](image)

**Figure 18.** Microscopic features of fibers distributed in the shotcrete specimen. (a) Stress–strain state of a single fiber. (b) Mechanical performance parameters, \( \sigma \): tensile stress; \( L_f \): Fiber length; \( l \): Embedment length; \( u \): crack width.

According to the simplified mechanical model depicted in Figure 17, the stress–strain curves can be subdivided into two stages: (i) before the matrix fracture and (ii) after single or multiple fractures in the shotcrete specimens [32]. Before the failure of the shotcrete specimens, the external load acting on them was jointly borne by the shotcrete matrix and the glass fibers, and the stress–strain relationship can be described as follows:

\[
\sigma(u) = \sigma_m(u) + \sigma_f(u)
\]  
(1)
where $\sigma(u)$ is the compound stress of the shotcrete material, MPa; $\sigma_u(u)$ is the maximum tensile stress that can be borne by the shotcrete material itself, MPa; $\sigma_f(u)$ is the maximum stress that can be withstood by the glass fibers, MPa.

The maximum stress $\sigma_m(u)$ that the shotcrete material can withstand is given below:

$$\sigma_m(u) = \begin{cases} f_t \left[ 1.2x - 0.2x^6 \right], & x \leq 1 \\ f_t \left[ \frac{x}{\alpha(x-1)^{1/3} + x} \right], & x \geq 1 \end{cases}$$

(2)

where $f_t$ is the peak uniaxial tensile strength of the shotcrete material; $\varepsilon_{f,p}$ is the strain corresponding to the peak uniaxial tensile strength of the shotcrete material; $u_{f,p}$ is the displacement corresponding to the peak uniaxial tensile strength of the shotcrete material; $\alpha$ is the shape parameter of the stress-strain curve.

The glass fibers have a bridging effect in the shotcrete material. The bridging stress exerted by the glass fibers is given below:

$$\sigma_f(u) = \frac{V_f}{A_f} \int P(l, \theta, u) P(\theta) P(l) dl d\theta$$

(3)

where $V_f$ is the volume content of fibers; $A_f$ is the cross-sectional area of a single fiber; $P(l, \theta)$ is the stress-displacement function of the fiber; $P(l)$ and $P(\theta)$ are the fiber embedment length and angle distribution functions, respectively. The bridging stress exerted by the glass fibers in the shotcrete material was calculated according to the distribution of the glass fibers in the shotcrete material and the functional relationship between the two:

$$\sigma(u) = \sigma_m(u) + \sigma_f(u) = \frac{V_f}{A_f} \int P(l, \theta, u) P(\theta) P(l) dl d\theta + \begin{cases} f_t \left[ 1.2x - 0.2x^6 \right], & x \leq 1 \\ f_t \left[ \frac{x}{\alpha(x-1)^{1/3} + x} \right], & x \geq 1 \end{cases}$$

(4)

According to Formula (1), the compound stress of the shotcrete material was the sum of the stress borne by the shotcrete material itself and the bridging stress exerted by the glass fibers. Formulas (2) and (3) were substituted into (1) to determine the relationship of the compound stress in the doped shotcrete material versus the fiber embedment length, embedment angle, and cross-sectional area. The functional relationship thus derived lays the basis for a quantitative investigation of the effect of doped glass fibers on the mechanical performance of the shotcrete material.

5. Conclusions

We studied the effect of doped glass fibers on the tensile and shear strengths of the shotcrete specimens with various mix ratios, fiber lengths, and curing ages. The macroscopic mechanical behavior of doped specimens was analyzed at the microscopic scale using SEM. We also constructed a 2D simplified mechanical model of the influence mechanism of the doped glass fibers on the mechanical performance of the shotcrete material. The relationship between the compound stress of the shotcrete specimens and the doped glass fibers was established. The following conclusions were drawn:

(1) The physical properties of the glass fiber-doped shotcrete material were tested, including the particle size and EDS analyses of aeolian sand and fly ash raw materials. The main chemical compositions of cement and fly ash were determined.

(2) The tensile and shear strengths of the shotcrete materials varied significantly after their doping by glass fibers with different lengths and different mix ratios. At the doped glass fibers’ length of 3 mm, the highest tensile strength of 429 kPa was...
reached at a mix ratio of 10‰, exceeding that of a 1‰ mix ratio by 175%. Similarly, at the doped glass fibers’ lengths of 6 and 15 mm, the peak tensile strengths of the shotcrete material were 585 and 417 kPa, respectively. These were higher than the lowest peak tensile strengths of the undoped shotcrete specimens by 37.3% and 309.8%, respectively. Moreover, at a shear angle of 50°, the mechanical performance of the fiber-doped shotcrete material increased continuously as the curing age increased. The shear strength increased most dramatically as the curing age increased from 14 to 28 d.

(3) The microstructure of the doped shotcrete specimens was observed by SEM. It was found that the doped glass fibers in the shotcrete specimens were intertwined with each other. The fly ash particles were embedded into the aeolian sand particles, partially filling the pores in shotcrete specimens. This microstructure was conducive to stress transfer within the specimens, improving the shotcrete specimens’ mechanical strength. The glass fibers were tightly enveloped by the shotcrete material particles, connecting the particles of different components into a whole, thus improving the mechanical strength of the shotcrete material.

(4) A 2D simplified mechanical model was constructed for the glass fibers distributed within the shotcrete material. The compound stress of the shotcrete material was the sum of stresses borne by the shotcrete material itself and the bridging stresses exerted by the glass fibers. We also established the relationships of the compound stress in the doped shotcrete material versus fiber embedment length, embedment angle, and cross-sectional area. The functional relationships thus derived lay the basis for a quantitative assessment of the doped glass fibers’ effect on the mechanical performance of shotcrete materials.

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