The Effect of Additive ZRJ-S1 on Mechanical Properties of Portland Cement

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Received 10 December 2021; Revised 13 April 2022; Accepted 25 April 2022; Published 9 May 2022

Academic Editor: Robert Černý

Research Article

For mechanical performance perfection of cement-based material, toughening materials are often added to the cement system, such as solid particles, carbon-based material, or other inorganic/organic materials. Compared with other materials, carbon-based materials have better compatibility and are more likely to form a cross-linked network structure in the cement system, which can significantly improve the mechanical properties of cement stone. In this review, a new type carbon-based material ZRJ-S1 was used as a mechanical additive to reinforce oil well cement. In this experiment, ZRJ-S1 was explored with microlevel scale and showed the thin-layer sheet morphology. With static mechanical-strength test, ZRJ-S1 reinforced cement-based material was found with excellent mechanical improvement when 0.05 wt% ZRJ-S1 additive was used, that is, compressive strength improved to 150.9% of that of control sample, splitting tensile strength improved to 134%, and flexural strength improved to 129.2%. Furthermore, the weight percentage superiority of ZRJ-S1 was researched by dynamic stress-train mechanical test and found the mechanical elasticity improvement in which Poisson ratio improved by 74% and formed elasticity modulus reduced to 65.4% when resisting to mechanical damage. The effect of ZRJ-S1 on the microstructure of cement-based materials was studied. As a result, ZRJ-S1 was found with the bridging effect for completion of cement-based material, crack deflection effect for controlling microcrack propagation, and pulling-out effect for preventing immediate fracture of cement-based material itself. Then, using about 0.05% of ZRJ-S1 achieved the accelerating effect on hydration, the speed of the cement-based material, in which more C-S-H gel was formed. Moreover, adding of microscale ZRJ-S1 showed denser spatial microstructure and excellent control ability to pore structure of cement-based material. Micropore percentage of more than 200 nm size, which was with serious damage to mechanical performance, was decreased from 17.40 to 11.89%, and porosity of cement-based material itself decreased to 16.20%. As a result, ZRJ-S1 additive showed excellent reinforcement effect on Portland cement.

1. Introduction

Recently, the research of reinforcing the mechanical performance of cement-based material has been deeply explored. Due to multiscale characteristics of cement-based material itself, that is, differences among its macrostructure, mesostructure, and microstructure, more new kinds of reinforced cement-based material have been developed. Nasser et al. depicted that tree pruning waste could be used for mechanical performance reinforcement of cement-based materials, in which tree pruning wastes of the size of 0.425 mm to 0.850 mm were used [1], and Cai et al. described the macrocharacteristics of high-volume fly ash to cement-based materials, and found their enhancement effect to leaching resistance performance [2]; therefore, the mechanical properties of cement-based material could get improvement through the reinforced macrostructure. Also, Graham et al. [3] and Loredana et al. [4] indicated mesoscale optimization showed excellent benefits of mechanical performance. So the meso-scale structure design of cement-
based material is useful for mechanical improvement of itself. Furthermore, Gao et al. [5] and Santos et al. [6] all depicted the importance of reinforcing the microstructure of cement-based material by using microlevel carbon fiber. Besides, the acceleration of hydration process could accelerate the microstructure development of cement-based material itself, so Santos described the effect of carbonated water to cement-based material when used for carbon fiber reinforced cement-based (CFRC) materials and found optimization of microstructure when carbonation accelerated, for which the mechanical performance was further reinforced.

As a reinforcement effect to the structure of cement-based material itself, the reinforcement was associated with using of different types of materials, such as solid particles, carbon-based materials, or other inorganic/organic materials, and these materials showed different scales when added to cement-based material. First, macroscale additive, such as macrosynthetic fiber researched by Amin et al. [7], and rubber particles researched by Jun and Olivares [8, 9]. Second, mesoscale additive, such as mesoscale carbon fiber researched by Graham. Third, with scale-level control, reinforcement material could be used at microscale level, especially carbon-based material, such as graphene [10] and graphene oxide [11]. Besides, for hydration speed control of cement-based materials, other kinds of reinforcement materials could also be used due to their interaction and chemical reaction with hydrating products, such as nanosilica [12], boron nitride [13], and whisker [14].

As former researches, natural fibers [15], synthesized inorganic fibers [16, 17], inorganic whiskers [18–20], and nanomaterials [21] were researched for their effects on mechanical performance of Portland cement. However, there is still a lot of room for development of carbon-based materials as additives. Carbon-based materials have excellent mechanical properties, are well compounded with cement-based materials, and are easier to disperse in the matrix to form a network structure. In this review, a new type of carbon-based material is selected as an additive for cement-based materials. This material has a very small diameter and is a nanoscale material, and the definition code is ZRJ-S1. This study investigated the physicochemical effects of ZRJ-S1 on cement-based materials. The results show that ZRJ-S1 has an excellent reinforcing effect for the mechanical properties of cement. In addition, the ZRJ-S1 reinforced cement material had superior toughness performance, for which the material had improved elasticity performance. Finally, its mechanism of action was explored.

### 2. Materials and Methods

#### 2.1. Materials

Ordinary Portland oil well cement (class G) was used, and chemical composition was shown as Table 1. ZRJ-S1, a new type carbon-based material, commercial product, was used as the functional additive for cement-based materials, the material has small particle size and is more easily dispersed in cement matrix than fiber, and the physical parameters shown as in Table 2. Other relating additives were used, including fluid loss additive G33S and dispersant SXY-2 were used, commercially products (China).

#### 2.2. Specimen Preparation

##### 2.2.1. Preparation of Cement Slurry.

Dry mixing method is used to configure cement slurry, and the density is 0.44. In accordance with the Chinese standard-GB/T 19139-2012, cement samples were prepared. G33S, SXY-2, and ZRJ-S1 were mixed with concrete powders and added to the water. The formulas of sample preparation were given in Table 3. The mixing was with a low-speed agitation of 4000 r/min for no more than 15 s. Then, mixing continued, with a high-speed that increased to 12000 r/min±250 r/min for 35 ± 1 s. Before testing, all prepared samples were kept in recommended curing molds, cured at 70°C water bath for 7 days.

##### 2.2.2. Preparation Procedure of Mechanical-Strength Tests.

According to recommended GB/T 50266-99 standard, preparation procedures of mechanical-strength tests were designed. First, rectangular specimens (size as 50.8 × 50.8 × 50.8 mm³) were used for compressive-strength test, at a crosshead speed of 400 N/s; second, cylindrical specimens (size as ø50 mm × 25 mm³) were used for fracture resistance test, at a cross-velocity of 600 N/s. Third, rectangular specimens (size as 40 × 40 × 160 mm³) were used for flexural-strength test, crosshead speed was set at 0.02 mm/min, and span was 100 mm. Fourth, stress–strain response of ZRJ-S1 reinforced cement-based materials. Hardened cylindrical samples (with MgB₂O₃ 3% moustaches (Φ: 1 in. × 2 in.) were used for the mechanical triaxial rock test, and the operating procedure was the recommended Chinese standard GB/T 50266-99. On the one hand, for multicycle loading test, loading rate at 1.6 kN/min and unloading speed rate at 3.2 kN/min, test pressure of 20.7 MPa, and test temperature of 70°C; on the other hand, for stress–strain curve analysis, test pressure of 20.7 MPa, and test temperature of 70°C, with loading rate at 1.6 kN/min.

#### Table 1: Chemical components of class G oil well cement.

| Components | Wt% |
|------------|-----|
| Magnesia (MgO) | 1.42 |
| Sulphur trioxide (SO₃) | 2.52 |
| Insolubles | 0.55 |
| R₂O | 0.43 |
| C₅S | 57.33 |
| C₃A | 2.34 |
| 2 C₅A + C₅AF | 18.21 |
| Loss | 1.03 |

#### Table 2: Physical properties of ZRJ-S1 additive.

| Material | Thickness (µm) | Components |
|----------|---------------|------------|
| ZRJ-S1 | <100 | Carbon-based microsheet |

2.2. Specimen Preparation

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2.2.3. Preparation of Testing Procedures for Microstructure Analysis. As a requirement for microstructure analysis of cement-based materials, testing procedures were made. First, scanning electron microscope (SEM) was utilized, and observed samples were collected after mechanical test [22]. All samples were collected purely. Second, mercury intrusive porosimetry (MIP) was used to test the distribution of pore structure and porosity of cement-based materials. For it, cylindrical specimens (size as \( \phi 25.0 \times 40.0 \text{ mm}^3 \)) were used, and then kept in 70°C water bath, deviation as \( \pm 2^\circ \text{C} \), and cured for 7 days (atmospheric pressure). Moreover, automatic mercury porosimeter was used according to mercury porosimetry test international standard-ISO 15901-1-2016. Finally, the zeta potential of the cement slurry system was measured by a zeta potential meter. In the experiment, the zeta potential value of the cement slurry system at different times with different ZRJ-S1 additions was mainly investigated.

3. Results and Discussion

3.1. Characterization of ZRJ-S1 Additive. Shown in Figure 1, ZRJ-S1 showed excellent chemical reactivity. The waveband of hydroxyl group was shown at about 3400 cm\(^{-1}\). Therefore, ZRJ-S1 could accelerate the hydration rate of cement-based materials [23, 24]. In addition, wavebands at 1326.8 cm\(^{-1}\) and 1070.3 cm\(^{-1}\) were assigned to the C-OH and C-O \([25, 26]\) groups, respectively, and waveband at 1635.3 cm\(^{-1}\) was possibly the unoxidized graphitic domains (\(=\text{C-H}\)) on chemical structure of ZRJ-S1 additive \([26, 27]\).

Furthermore, for an effect on microstructure of cement-based materials, scanning electron microscope (SEM) was used for confirming its physical features, shown as Figure 2. As a result, ZRJ-S1 was found with microlevel scale, approximately 5–10 \(\mu\text{m}\). Besides, it was found with thinner microsheet characteristics; so it could be of excellent filling effect on microstructure of cement-based materials. Moreover, it could possibly apply the mechanical contribution that is similar to carbon fiber \([28, 29]\) and other microlevel reinforcement materials \([30–32]\), such as transition effect, crack deviation effect, and ripping effect.

3.2. Effect of ZRJ-S1 to Mechanical Properties of Cement-Based Material

3.2.1. Effect of Adding ZRJ-S1 Additive to Cement Slurry. The fluid characteristics of the cement sludge were tested according to the Chinese standard GB/T 19139-2012 recommended. Test results were shown in Table 4. The flow of cement sludge decreased slightly with the addition of ZRJ-S1, which shows that ZRJ-S1 has a certain thickening effect and can improve the viscosity of cement slurry system. But it will not be too thick and could still meet certain pumping conditions. Besides, there was no separated free water that could occur, in which cement slurry showed stable fluid characteristics. In addition, the addition of ZRJ-S1 has reduced the removal of cement sludge. This implied the adding of ZRJ-S1 was indirectly beneficial to the free water control of cement slurry, just as fluid loss additive, and it shows that ZRJ-S1 has a certain potential in controlling water loss in cement slurry system. In conclusion, ZRJ-S1 has no obvious side effect on the flow performance of cement slurry system.

3.2.2. Static Mechanical Test of ZRJ-S1 Reinforced Cement-Based Materials. The compressive strength of cement stone refers to the maximum stress when it bears compression failure, the tensile strength refers to the maximum stress when it bears tensile failure, and the flexural strength refers to the maximum stress when it bears bending failure. The three factors comprehensively reflect the mechanical properties of cement stone and can be used as the criterion of cementing ability. As a result, as shown in Figures 3–5, with the increase of ZRJ-S1 content, the compressive strength and tensile strength of cement set increase first and then decrease, which may be due to the fact that excessive ZRJ-S1

| Test no. | Cement (g) | G33S (wt%) | SXY-2 (wt%) | ZRJ-S1 (wt%) | Water (g) |
|---------|------------|------------|-------------|--------------|-----------|
| 1       | 800        | 2          | 2           | 0            | 352       |
| 2       | 800        | 2          | 2           | 0.01         | 352       |
| 3       | 800        | 2          | 2           | 0.03         | 352       |
| 4       | 800        | 2          | 2           | 0.05         | 352       |
| 5       | 800        | 2          | 2           | 0.07         | 352       |
| 6       | 800        | 2          | 2           | 0.09         | 352       |

Note. Wt%, percentage by weight of cement powders; Test No. 1 with no ZRJ-S1 was control sample.
Figure 2: SEM analysis of ZRJ-S1 additive.

| ZRJ-S1 dosage/wt% (BWOC) | Density (g/cm$^3$) | Fluidity (cm) | Fluid loss (mL) | Free fluid (mL) |
|--------------------------|--------------------|---------------|-----------------|-----------------|
| 0 (Control sample)       | 1.90 ± 0.01        | 24 ± 0.04     | 16.0 ± 0.3      | 0 ± 0           |
| 0.01                     | 1.90 ± 0.01        | 20 ± 0.02     | 16.0 ± 0.2      | 0 ± 0           |
| 0.03                     | 1.90 ± 0.01        | 20 ± 0.03     | 15.4 ± 0.3      | 0 ± 0           |
| 0.05                     | 1.90 ± 0.02        | 19 ± 0.02     | 15.2 ± 0.3      | 0 ± 0           |
| 0.07                     | 1.90 ± 0.01        | 18 ± 0.03     | 14.9 ± 0.2      | 0 ± 0           |
| 0.09                     | 1.90 ± 0.02        | 18 ± 0.02     | 14.8 ± 0.3      | 0 ± 0           |

Table 4: The effect of ZRJ-S1 on the performance of cement slurry.
cannot disperse well in the cement matrix and agglomeration forms defects in the matrix. However, when there is a ZRJ-S1 addition $\leq 0.05\%$, the compressive strength and tensile strength all improved. The compressive strength was increased from 16.3 MPa to 24.6 MPa, which was increased by 50.9%; the tensile strength in division increased from 2.47 MPa to 3.31 MPa, which was increased by 34.0%. In terms of flexural strength, its variation trend is roughly the same as that of compressive and tensile strength. Compared with blank group, the addition of ZRJ-S1 can significantly improve the flexural strength of cement. In conclusion, ZRJ-S1 can significantly improve the mechanical properties of cement stone, which may be because ZRJ-S1 can act as a “bridge” at the pore of cement stone. However, excessive addition may agglomerate and form defects. According to the experimental results, the optimal addition is 0.05%.

**3.3. Stress-Strain Response of ZRJ-S1 Reinforced Cement-Based Material**

**3.3.1. Effect Dynamic Multicycle Loading.** In order to further explore the influence of the variable pressure environment...
Table 5: Mechanical parameters of cycle peak (control sample).

| Cycle sample   | Cycle no. | Loading Poisson ratio | Elongation Elastic modulus (MPa) | Unloading Poisson ratio | Elastic modulus (MPa) |
|----------------|-----------|-----------------------|----------------------------------|-------------------------|-----------------------|
| Control sample | 1         | 0.34                  | 5601.6                           | 0.484                   | 2230                  |
|                | 2         | 0.546                 | 2283.3                           | 0.493                   | 1733                  |
|                | 3         | 0.547                 | 1783.2                           | 0.547                   | 1487                  |
|                | 4         | 0.58                  | 1512.4                           | 0.571                   | 1298                  |
|                | 5         | 0.612                 | 1333.7                           | 0.609                   | 1177.4                |
|                | 6         | 0.646                 | 1197.2                           | 0.612                   | 1081.7                |
|                | 7         | 0.655                 | 1098.1                           | 0.6414                  | 959                   |

Note. Loading rate at 1.6 kN/min and unloading speed rate at 3.2 kN/min, test pressure of 20.7 MPa and test temperature of 119°C.

Table 6: Mechanical parameters of cycle peak (ZRJ-S1 (0.05 wt%) reinforced).

| Cycle sample     | Cycle no. | Loading Poisson ratio | Elongation Elastic modulus (MPa) | Unloading Poisson ratio | Elastic modulus (MPa) |
|------------------|-----------|-----------------------|----------------------------------|-------------------------|-----------------------|
| ZRJ-S1 (0.05 wt%) | 1         | 0.406                 | 8625.2                           | 0.227                   | 2028.4                |
|                  | 2         | 0.256                 | 1993.9                           | 0.224                   | 1436.4                |
|                  | 3         | 0.261                 | 1469.6                           | 0.257                   | 1206.4                |
|                  | 4         | 0.277                 | 1201.2                           | 0.280                   | 1023.4                |
|                  | 5         | 0.297                 | 1081.9                           | 0.304                   | 939.9                 |
|                  | 6         | 0.328                 | 958.6                            | 0.330                   | 855.7                 |
|                  | 7         | 0.343                 | 860.3                            | 0.364                   | 808.6                 |

Note. Loading rate at 1.6 kN/min and unloading speed rate at 3.2 kN/min, test pressure of 20.7 MPa and test temperature of 119°C.

3.3.2. Triaxial Stress–Strain Curve Analysis. In order to explore the influence of the cement stone on the formation confining pressure, it is necessary to carry out a triaxial stress test on it. According to the results of triaxial stress–strain curve and related mechanical parameters (Figure 8 and Table 7), ZRJ-S1 reinforcement-based material showed better resistance to the outside pressure, in which material showed a lower elastic modulus of 6940.2 MPa to resist the outside pressure. The modification that was caused to the cement-based materials itself underwent a longer period to reach strain limit of 1.07% rather than 0.9% so that the bigger stress 28.5 MPa was formed. All samples showed a certain level of toughness behavior, and stress–strain curve was formed into a bigger area integral of 28 when ZRJ-S1 additive was added, plus the increase of Poisson ratio value from 0.230 to 0.132, so ZRJ-S1-reinforced cement-based material got an excellent toughness improvement.
Table 7: Mechanical parameters of cement-based material under stress–strain loading.

| Test no.                  | Elasticity modulus (MPa) | Poisson ratio  | Stress value (MPa) | Strain value (%) | Area integral |
|---------------------------|--------------------------|----------------|--------------------|------------------|---------------|
| Control sample            | 10619.5 ± 0.3            | 0.132 ± 0.06   | 24 ± 0.1           | 0.9 ± 0.02       | 14 ± 0.02     |
| ZRJ-S1-(0.05 wt%) reinforced sample | 6940.2 ± 0.1            | 0.23 ± 0.04    | 28.5 ± 0.1         | 1.07 ± 0.01      | 28 ± 0.01     |

Note. Test pressure of 20.7 MPa and test temperature of 119°C, with loading rate at 1.6 kN/min.

Figure 9: Mechanical contribution of ZRJ-S1 additive to cement-based materials.
3.4. Reinforcement Mechanism of ZRJ-S1 to Cement-Based Materials

3.4.1. SEM Analysis. As shown in Figure 9, ZRJ-S1 additive was relatively dispersed within cement-based material. The aggregated ZRJ-S1 microsheets were relatively dispersed when added to cement-based materials, and each microsheet was spatially distributed along different direction. According to the bigger increase in mechanical tests, the reinforcement effect of ZRJ-S1 additive was confirmed. When added in cement slurry, ZRJ-S1 additive got the contact with components within cement slurry, such as K+, Na+, Ca2+, OH−, SO3− [33]. All these components that dissolved in water were formed into electrolyte solution, which could possibly form the electrochemical atmosphere to impose the stable dispersion and physical peeling of aggregated ZRJ-S1 additives [34, 35].

Furthermore, as ZRJ-S1 was added, it was formed into the particle of dispersion phase. When under certain loading, ZRJ-S1 additive was transformed into the new stress concentration point to resist the mechanical effect of possible loading [36].

As shown in Figure 9, the naked ZRJ-S1 additive was embedded within cement-based material. On the one hand, the microsheet was uniformly vertically inserted on the interface so that the length of microcrack could be limited and the crack propagation trend could be interdicted on the part of the interface, which was similar to the function of a carbon fiber [37–40], but on a bigger area rather than some point or line part. On the other hand, ZRJ-S1 microsheet was embedded parallel to the observed interface, for which the depth of microcrack vertical to interface could be directly interdicted [37–40]. Also, the adding of ZRJ-S1 caused the filling effect to microstructure of cement-based material. As a result, as inferred, the possible reasons for reinforcement behaviors of ZRJ-S1 to cement-based materials, similar to carbon fibers, the ZRJ-S1 additive could be used as mechanically functional additive for cementitious material.

3.4.2. MPI Analysis. When ZRJ-S1 additive was added, the microstructure of cement-based materials showed better improvement as shown in Table 8, mercury intrusion porosimetry test result. In the experiment, with 0.05 wt% ZRJ-S1 additive added, micropores (size as ≤20 nm) increased from 13.32% to 14.40%, micropores (size as 20–50 nm) decreased from 43.98% to 27.50%, micropores (size as 50 to 200 nm) increased from 25.30% to 11.89%, and the overall porosity of cement-based material decreased from 17.02% to 16.24%. So when ZRJ-S1 was added, size distribution of micropores was optimized, as the percentage value decreased in micropore from size 20–50 nm and size as ≥200 nm. Though there is a relative increase in the amount of micropores (size as 50–200 nm), and the overall decrease of porosity indicated the improvement in the pore structure of cement-based materials [41–44]. Indirectly, the optimization of pore structure was beneficial for the improvement of mechanical performance because of the potential damage reduction due to imperfection weakening of pore structure.

3.4.3. FTIR Analysis. The infrared spectrum test results of different ZRJ-S1 contents are shown in Figure 10. First, when compared with control sample (0 wt% ZRJ-S1 additive added), according to absorption peak at 3400 cm−1 that represented −OH of Ca(OH)2 [45, 46], ZRJ-S1 showed excellent accelerating effect to hydration process by reacting with Ca(OH)2, and more AFm was formed. It was similar to the effect of nano-SiO2, which can react with Ca(OH)2 and contribute to an increase in the amount of C-S-H [47]. So wavebands are associated with the presence of AFm at approximately 1640 cm−1 (τ2, H2O) and 3425 cm−1 (v1 and v3, H2O) appeared [45]. Second, as ZRJ-S1 was added, the acceleration effect of C-S-H gel formation was a fact based on the wavebands at approximately 990 cm−1 that represented C-S-H gel [45, 46]. This has been beneficial for the development of mechanical performance [48]. When ZRJ-S1 content

| ZRJ-S1 (wt%) | Pore size distribution (nm) | Porosity (%) |
|--------------|----------------------------|--------------|
|              | ≤20 | 20–50 | 50–200 | ≥200       |
| 0            | 13.32 | 43.98 | 25.30 | 17.40 | 17.02 |
| 0.03         | 13.43 | 42.53 | 27.50 | 16.54 | 16.72 |
| 0.05         | 14.40 | 40.25 | 33.46 | 11.89 | 16.24 |
| 0.07         | 14.27 | 37.84 | 35.36 | 12.53 | 16.45 |

Table 8: Pore size distribution (%) and porosity (%).
increased to 0.07 wt%, more hydration products were formed, according to waveband at 650 cm\(^{-1}\) that represented sulfate ions (\(\text{SO}_4^{2-}\)) \[49\], an increasing sharp waveband of \(\nu_{\text{OH/C-H}}\) at 3643 cm\(^{-1}\) and waveband of C-S-H gel. However, it has hampered the normal process of hydrating cementitious materials that calcite impurity far more possibly formed, and the carbonate ion detected at wavebands at 720 cm\(^{-1}\) (\(\nu_4, \text{CO}_3\)) and 1406 cm\(^{-1}\) (\(\nu_6, \text{CO}_3\)), which was presented as the contaminant in the gypsum. Combined with mechanical test results (Figures 3–5), 0.05 wt% content of ZRJ-S1 additive was possibly a better choice for class G Portland oil well cement.

Besides, the hydration acceleration may be the indirect reason for the microstructure optimization of cement-based materials.

3.4.4. ZETA Potential Analysis. ZETA potential test results of different cement slurry systems are shown in Table 9. With cement dry ash added to water, cement slurry showed an average ZETA potential value of -914.1 mV, and it was decreased to \(-1429.1\) mV when fluid loss additive and dispersant added. And ZRJ-S1 also caused the decrease of average ZETA potential value, decreased from -914.1 mV to -1182.7 mV when 0.05 wt% added.

However, when adding ZRJ-S1 combined with G33S and SXY-2, average ZETA potential value of cement slurry showed an increase, increased from -1429.1 mV to -1325.8 mV by 0.05 wt% added. Depicted in Figure 11, ZETA potential value of cement slurry showed a dynamic decrease within 5 minutes, and it could indirectly reflect the electrochemical interaction among ZRJ-S1 additives and components of cement slurry, and possibly caused hydration products of positive charge that sharply improved, and when 0.07 wt% ZRJ-S1 additive was added, cement slurry showed a relatively equivalent average ZETA potential value, so more adding of ZRJ-S1 may be of no use to change the charge properties of cement slurry.

4. Conclusion

(1) As a type of inorganic carbon-based material, ZRJ-S1 showed excellent physicochemical effect to cementitious materials. With the addition of the ZRJ-S1 microfoil, the mechanical efficiency of the cement material was further enhanced.

(2) Once the ZRJ-S1 was added, the cement-based material demonstrated excellent microstructure optimization. As a result, micropores (size as \(\gtrsim 200\) nm) decreased from 17.40% to 11.89% and the porosity of cement-based material was decreased from 17.02 to 16.24%, so that pore structure of cement-based material was well optimized and mechanical properties were indirectly reinforced.

(3) Furthermore, the adding of ZRJ-S1 contributed to the acceleration of hydration speed, for which the microstructure of cement-based material was further reinforced for more C-S-H gel formed and more Ca(OH)\(_2\) transformed. The key to improving the mechanical properties of cement-based materials is that it promotes the formation of AFm phase.

(4) As a whole, ZRJ-S1 reinforced cement-based material showed improved mechanical strength compared to control sample; compressive strength improved to 150.9% of that of control sample, splitting tensile strength improved to 134%, and flexural strength improved to 129.2%. Furthermore, ZRJ-S1 contributed to the better toughness behaviors of cement-based material, such as the Poisson ratio value reached to 0.230.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.
Acknowledgments

The authors would like to acknowledge the financial support by the National Science and Technology Major Project of China (2017ZX05049005-006).

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