Effect of Mineral Admixtures on the Performance of Ceramsite Shotcrete for High Geothermal Underground Engineering

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ABSTRACT: Ceramsite concrete is used in lining structures of underground engineering in the geothermal environment. This study, by means of mixing fly ash and silica fume, aims at diminishing the adverse effects on concrete performance caused by elevated temperature in high geothermal underground engineering. Under simulated geothermal conditions (20, 40, and 60 °C, RH ≥ 90%), it was first proposed that 15 and 5 wt % cement replacements by fly ash and silica fume, respectively, were most optimal. Then, the effect of mineral admixtures on ceramsite shotcrete performance was investigated. The results show that the mixing of fly ash and silica fume could improve ceramsite shotcrete adaptability in elevated curing temperature. Particularly for silica fume, at 40 °C curing temperature, the 28-day compressive strength and splitting tensile strength increased by 12.6 and 50.9%, respectively. The improvement effect of silica fume on permeability resistance and resistance to chloride ion permeability was higher than that of fly ash. Nevertheless, the mixing of fly ash was more effective than silica fume for reducing thermal conductivity.

1. INTRODUCTION

High geotemperature is a major challenge for modern tunnel and mine shaft construction at present and has attracted more and more attention.1−10 The elevated temperature not only deteriorates the construction environment, but also affects the strength and durability of the concrete3−7 and has an adverse effect on the lining structure.8−10

It is generally believed that elevated curing temperature leads to promotion of the development of early-age strength of concrete, as well as later-age strength when cured under the threshold temperature. However, the excessive curing temperature will result in a decrease in later-age strength compared with that of standard curing conditions.6,9,10 The fly ash and silica fume are commonly used as supplementary cementitious materials, which can display setting retardation,5 reduce the hydration heat release,14 and improve some performance such as self-shrinkage, durability, and strength of concrete.12,13 Shi et al.14 reported that the strength of high-volume fly ash concrete was improved when cured at elevated temperature, while the resistance to chloride ion permeability decreased. Deschner et al.15 believed that the pozzolanic effect of fly ash cured at elevated temperature was present in the early stage, nevertheless the elevated temperature caused the porosity of concrete to increase. The research of Bingöl and Tohumcu16 showed that the fly ash and silica fume could increase the strength of concrete with an early-age curing temperature of 50−80 °C, but the strength was all lower than that of the silica fume concrete cured at room temperature. In addition, the literature indicates that silica fume at elevated early-age curing temperature could improve the strength at all ages,17 and the durability, but the resistance to chloride ion permeability decreased at a curing temperature of 50−80 °C.18 Yan and Cui19 reported that the 35% content mineral admixtures (that is, grinding blast furnace slag, or fly ash-silica fume) promoted the later-age strength under standard curing conditions, exceeding the concrete strength of only Portland cement as a
binder. When cured at an elevated temperature of 50 °C, the concrete strength of composite binders was higher than that of the Portland cement concrete at all ages. However, from the current research situation of the concrete cured at elevated temperature, much attention has mostly been focused on ordinary aggregate concrete, including only cement, binary, or ternary mixtures as a cementitious material.

In recent years, some research studies have been carried out on performances of shotcrete and surrounding rock under simulated high geothermal environments. The experiment under a 100 °C hot-dry environment indicated that the addition of steel fibers or basalt fibers could obviously improve the concrete compressive strength and splitting tensile strength. The two kinds of strength of double mix of steel fibers and silica fume concrete decreased as silica fume had adverse effects on the mechanical properties and pore structure. Aiming at diminishing the adverse effect of the hot-humid condition (50 and 80 °C, with a relative humidity of 55%) on the concrete strength and the bond strength with the rock, steel fibers and polypropylene fibers were used as additives. For reducing thermal sensitivity, vitrified beads were added to the lining concrete. This illustrated that the combination of the vitrified beads and the fiber material could effectively reduce the loss of strength derived from the increase in curing temperature. In the simulated relatively high geothermal environment (60, 80, and 100 °C, with a relative humidity of 55%) the shear experiments on the shotcrete-rock interface were conducted by Hu et al. As the curing temperature grew, the shear properties decreased, and the peak shear stress became smaller, while microcracks of shotcrete near the contact face generated and increased because of the effect of higher temperature.

As mentioned above, at elevated curing temperature, the current research on the effect of mineral admixture focuses mostly on ordinary aggregate concrete. More attention was paid to mechanical properties, bonding strength, and pore structure, while little attention was paid to durability. Furthermore, little research on ceramsite concrete has been reported. The ceramsite concrete used as a lining material possesses the characteristics of light weight and thermal insulation, which can alleviate the construction difficulty brought by a high geothermal environment and reduce the refrigeration cost. The strength of ceramsite concrete is a little lower than that of the ordinary aggregate concrete, which nevertheless, still meets the demand for the shotcrete lining structure. As it has a good application prospect for shotcrete lining, it is necessary to find suitable methods to improve its performance in high geothermal underground engineering.

This research was conducted against the background of the Gaoligong tunnel on Dali-Ruili Railway, and the temperature varies from 19.4 to 40.6 °C along the tunnel line according to geological exploration. Based on this, to improve the strength and durability the mineral admixtures were mixed into the ceramsite concrete that was cured at temperatures of 20, 40, and 60 °C. The improvement effect was finally explored. This paper could provide a theoretical basis and reference for ceramsite shotcrete used as a supporting material in high geothermal underground engineering.

2. RESULTS AND DISCUSSION

2.1. Optimization Experiment of the Fly Ash Content.
The concrete of 10, 15, and 20 wt% cement replacements by fly ash was fabricated at 20, 40, and 60 °C curing temperatures. The compressive strengths and the slump indicating fluidity of the concrete mixture are shown in Table 1.

| content of fly ash | curing temperature (°C) | $\sigma_{28d}$ (MPa) | $\sigma_{60d}$ (MPa) | slump (mm) |
|--------------------|-------------------------|---------------------|---------------------|------------|
| none               | 20                      | 17.1                | 26.0                | 130        |
|                    | 40                      | 19.3                | 24.6                |            |
|                    | 60                      | 13.3                | 16.2                |            |
| 10 wt%             | 20                      | 19.7                | 24.5                | 145        |
|                    | 40                      | 19.8                | 26.7                |            |
|                    | 60                      | 16.5                | 17.5                |            |
| 15 wt%             | 20                      | 20.5                | 25.9                | 150        |
|                    | 40                      | 20.4                | 26.2                |            |
|                    | 60                      | 15.0                | 19.0                |            |
| 20 wt%             | 20                      | 16.7                | 25.4                | 150        |
|                    | 40                      | 17.3                | 26.3                |            |
|                    | 60                      | 16.1                | 18.8                |            |

When no mineral admixtures were added, the 28-day compressive strength of ceramsite concrete cured at elevated temperature was lower than that cured at 20 °C. When cured at 40 and 60 °C, the compressive strength of the concrete mixed with any content of fly ash was higher than that with only cement. After adding fly ash, the compressive strength of ceramsite concrete cured at 40 °C was higher than that cured at 20 °C. This is consistent with the previous literature on cement mortar. However, the compressive strength cured at 60 °C was lower than that cured at 20 °C, indicating that a threshold existed in the range of 40–60 °C. As shown in Figure 1, it could be further found that as the content of fly ash ranges between 10% and 20 wt%, the 28-day compressive strengths cured at 40 °C were close. When the content of fly ash was 15 wt%, the improvement in 28-day compressive strength was the highest at 60 °C curing temperature and increased by 17.3% compared with the concrete of the basic mix proportion.

Moreover, it could be observed that the early-age compressive strength in general was higher when the fly ash content was 15 wt%, and the 28-day compressive strength was not much different from that of the content of 20 wt%. In addition, it could be seen that the mixing of fly ash was beneficial to improve the fluidity, as well as the workability of the ceramsite concrete mixture, by virtue of its smooth spherical surface. Taking into account the early- and later-age
comprressive strength, and the workability, the 15 wt % fly ash was used for the next experiment.

2.2. Optimization Experiment of the Silica Fume Content. The substitution rates of silica fume for cement were 3, 5, and 7 wt %. The 3-day and 28-day compressive strength and the slump are shown in Table 2. Similar to fly ash, at the higher curing temperature, such as at 60 °C, the compressive strength of ceramsite concrete was more suitable for further experiment.

2.3. Comprehensive Experiments of Mixing Mineral Admixtures. To further explore the effect of mineral admixtures on the performance of the ceramsite concrete at elevated curing temperatures, the studies on the ceramsite concrete containing 15 wt % fly ash, 5 wt % silica fume, or both the preceding items were fully conducted. The strength, permeability resistance, resistance to chloride ion permeability, and thermal conductivity were obtained.

2.3.1. Compressive Strength. The compressive strengths of the ceramsite concrete are shown in Table 3, and the compressive strength variation of each mix proportion is illustrated by the experiment. That is to say, the elevated curing temperature played a certain role in promoting the pozzolanic effect of the fly ash. When cured at 60 °C, the compressive strengths before 1-day age were slightly lower than those of the basic mix proportion group, and the 28-day compressive strength was close. At all ages, the compressive strengths of fly ash concrete cured at 40 °C were higher than that of the basic mix proportion group, indicating that the elevated curing temperature played a certain role in promoting the pozzolanic effect of the fly ash. When cured at 60 °C, the compressive strengths before 1-day age were slightly lower than those of the basic mix proportion group, whereas when curing was continued to 3-day age they became higher than the latter. At 20 °C curing temperature, the fly ash generally had a physical filling effect in concrete at the early age, and its pozzolanic effect had not yet been exerted. Along with the growth of age, the pozzolanic effect conducted to a certain degree of enhancement of compressive strength, which was illustrated by the experiment. That is to say, the elevated temperature curing made the pozzolanic effect of fly ash appear in advance. Similarly, Deschner et al. showed that the pozzolanic effect of fly ash appeared at 1-day age when cured at 50 °C. Furthermore, according to this experiment, the promoting function of the fly ash pozzolanic effect did not escalate linearly with the elevating temperature, but instead a temperature threshold existed. It could also be observed that the 1-day compressive strength of the fly ash concrete cured at 40 °C was higher than that of the basic mix proportion group, but that cured at 60 °C was relatively lower. In addition, when cured at 60 °C, the compressive strengths after 3-day age were lower than the other curing temperatures. The reason should be related to the uneven distribution of hydration products at higher curing temperature, and further the early disorder distribution hydration products had certain hindrance to the hydration reaction in the middle-later curing age, which was analogous to the ordinary concrete and hardened cement paste. Furthermore, the water evaporation became faster at elevated curing temperature, such as at 60 °C, which was disadvantageous to the hydration degree.

Compared with fly ash, the promoting effect of silica fume on the compressive strength of ceramsite concrete was more obvious. This could be explained that the silica fume possessed more pozzolanic activity and a more obvious thermal activation effect. Moreover, the silica fume with a smaller particle size consistently dropping because the particles of silica fume were relatively thin. Hence, it is necessary to add more water reducing agent to increase the fluidity.

However, the later-age compressive strength gradually improved as the content of silica fume increased. This was based on taking into account the workability, early compressive strength, and economic factor that the 5 wt % silica fume content was more suitable for further experiment.

The substitution rates of silica fume for cement were 3, 5, and 7 wt %, the 3-day and 28-day compressive strengths before 1-day age were slightly lower than those of the basic mix proportion group, and the 28-day compressive strength was close. At all ages, the compressive strengths of fly ash concrete cured at 40 °C were higher than that of the basic mix proportion group, indicating that the elevated curing temperature played a certain role in promoting the pozzolanic effect of the fly ash. When cured at 60 °C, the compressive strengths before 1-day age were slightly lower than those of the basic mix proportion group, whereas when curing was continued to 3-day age they became higher than the latter. At 20 °C curing temperature, the fly ash generally had a physical filling effect in concrete at the early age, and its pozzolanic effect had not yet been exerted. Along with the growth of age, the pozzolanic effect conducted to a certain degree of enhancement of compressive strength, which was illustrated by the experiment. That is to say, the elevated temperature curing made the pozzolanic effect of fly ash appear in advance. Similarly, Deschner et al. showed that the pozzolanic effect of fly ash appeared at 1-day age when cured at 50 °C. Furthermore, according to this experiment, the promoting function of the fly ash pozzolanic effect did not escalate linearly with the elevating temperature, but instead a temperature threshold existed. It could also be observed that the 1-day compressive strength of the fly ash concrete cured at 40 °C was higher than that of the basic mix proportion group, but that cured at 60 °C was relatively lower. In addition, when cured at 60 °C, the compressive strengths after 3-day age were lower than the other curing temperatures. The reason should be related to the uneven distribution of hydration products at higher curing temperature, and further the early disorder distribution hydration products had certain hindrance to the hydration reaction in the middle-later curing age, which was analogous to the ordinary concrete and hardened cement paste. Furthermore, the water evaporation became faster at elevated curing temperature, such as at 60 °C, which was disadvantageous to the hydration degree.

Compared with fly ash, the promoting effect of silica fume on the compressive strength of ceramsite concrete was more obvious. This could be explained that the silica fume possessed more pozzolanic activity and a more obvious thermal activation effect. Moreover, the silica fume with a smaller particle size

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**Table 2. Performance of the Ceramsite Concrete with Different Contents of Silica Fume**

| content of silica fume | curing temperature (°C) | 3d/ cp / MPa | 28d/ cp / MPa | slump/mm |
|------------------------|-------------------------|--------------|--------------|---------|
| none                   | 20          | 17.1         | 26.0         | 130     |
|                        | 40          | 19.3         | 24.6         |         |
|                        | 60          | 13.3         | 16.2         |         |
| 3 wt %                 | 20          | 22.9         | 26.2         | 115     |
|                        | 40          | 25.7         | 26.5         |         |
|                        | 60          | 16.9         | 19.6         |         |
| 5 wt %                 | 20          | 22.8         | 26.0         | 115     |
|                        | 40          | 25.0         | 27.7         |         |
|                        | 60          | 20.8         | 21.4         |         |
| 7 wt %                 | 20          | 22.3         | 27.3         | 110     |
|                        | 40          | 22.3         | 28.0         |         |
|                        | 60          | 19.3         | 23.5         |         |

Note: To ensure the workability of concrete, when the contents of silica fume were 3, 5, and 7 wt %, on the basis of the basic mix proportion the water reducing agent was increased by 0.1, 0.2, and 0.3 wt % of the cementitious material, respectively.

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![Figure 2. Improvement effect of silica fume on compressive strength of ceramsite concrete.](image-url)
could not only exert the pozzolanic effect but also fill the internal pores of the concrete, resulting in the increase of the compressive strength evidently. Even at room temperature, the pozzolanic effect of the silica fume could be expressed at 1-day age. Hence, the overall compressive strengths of the silica fume concrete were greater than the basic mix proportion group and the fly ash group at different curing temperatures. With the increase in curing temperature, the 7-h and 1-day compressive strengths of silica fume concrete increased observably. Nevertheless, at 3-day age the compressive strengths cured at 60 °C dropped below that at 40 °C, and even further below that at 20 °C. The slow-growing compressive strengths of middle-later age should also be related to a looser microstructure.

The compressive strengths of the comixing group were higher than that of the basic mix proportion group in the middle-later curing age. The most favorable curing temperature for compressive strength was 40 °C, coinciding with the fly ash group and the silica fume group. In addition, the compressive strengths of the comixing group were somewhere between the fly ash group and the silica fume group. Moreover, the later-age compressive strengths were closer to the silica fume group. At each of the curing temperatures, there was no additive effect of the fly ash group and the silica fume group. This could be ascribed to the less content of cement applied in the cementitious material and then led to the limited hydration product-calcium hydroxide, which could be used in the secondary hydration reaction. That is, the mineral admixtures could not yet fully exert their potential activity effect.

2.3.2. Splitting Tensile Strength. The splitting tensile strengths of each ceramsite concrete group are shown in Table 4. For the basic mix proportion group, the splitting tensile strength gradually decreased as the curing temperature increased, which was consistent with the variation trend of compressive strength. This should be attributed to the disordered overlap of hydration products at elevated curing temperatures, resulting in higher porosity in the concrete microstructure.

Compared with the basic mix proportion group, the splitting tensile strengths of fly ash concrete increased by 10.4, 46.4, and 27.3% at 20, 40, and 60 °C curing temperatures, respectively. The splitting tensile strength reached the highest level of 1.64 MPa at 40 °C and fell to the lowest value of 1.12 MPa at 60 °C. Compared with the basic mix proportion group, at 20, 40, and 60 °C curing temperatures the growth rates were 11.1, 50.9, and 53.4%, respectively. It presented the same variation trend with the fly ash group, and the promoting effect was slightly higher. The splitting tensile strength of the comixing group also achieved the highest value of 1.81 MPa at 40 °C and increased by 20, 61.6, and 39.8%, respectively. The splitting tensile strengths of comixing group concrete at 20 and 40 °C curing temperatures were higher than those of the single mixing groups. That is, comixing fly ash and silica fume was conducive to improve the toughness of ceramsite concrete.

From the above presentation, it could be known that the improvement effect of silica fume on the splitting tensile strength was superior to that of fly ash, in accordance with the compressive strength. This would be attributed to the better
pozzolanic activity, superior filling effect, and more obvious thermal activation effect of silica fume, as it was easier for smaller ones to fill void and bring the concrete denser microstructure and interfacial transition zone. In addition, the content of the active ingredients of silica fume was above 90%, sparking off adequate secondary hydration reactions.

In the case of 20 and 40 °C curing temperatures, the secondary hydration reaction brought by the mineral admixtures could diminish the pore size and porosity, resulting in an improved interfacial transition zone through replacement of the preferentially oriented Ca(OH)₂ crystals by C=S−H gel. Furthermore, the densification of the interfacial transition zone was more obvious because of the filling effect of extra mixing mineral admixtures. Thereby, the comixing concrete splitting tensile strengths closely connected with the densification of the interfacial transition zone were higher than the single mixing group. Moreover, the combined cementitious materials were more active at elevated temperatures, so a higher splitting tensile strength was obtained at 40 °C compared with 20 °C. When the curing temperature was as high as 60 °C, the splitting tensile strength dropped on account of the poor uniformity of internal microstructure of the concrete and the insufficient secondary hydration reaction as a consequence of more water evaporation.

2.3.3. Antipermeability. The permeability resistance and resistance to chloride ion permeability were investigated and are presented in Table 5. For the permeability resistance case,

In the case of the basic mix proportion and the fly ash concrete, the maximum seepage pressure of 3.1 MPa was reached only as the concrete cured at 20 °C. However, the seepage pressure for the silica fume group and the comixing group could achieve the maximum at three curing temperatures. At elevated curing temperature, the fine silica fume particles and its secondary hydration reaction products had a good filling effect on the micropores appearing inside the concrete microstructure and improved the internal pore structure and the interfacial transition zone. Hence, the higher permeability resistance of the silica fume concrete over the fly ash concrete was obtained, consistent with previous literature.28,30 However, the permeability resistance of the comixing ceramsite concrete cured at elevated temperature, similar to the variation trend of the 28-day compressive strength, was lower than that of the silica fume group.

For the resistance to chloride ion permeability, the improvement effect of the fly ash was obvious, and the improvement degree stemming from the silica fume was further superior to the fly ash. Moreover, there was an additive effect for the mineral materials. That is, the results of the comixing group were the best at all curing temperatures, and compared with those of the basic mix proportion group, the electric flux decreased 46 and 38% at 40 and 60 °C curing temperatures, respectively. The reasons for the above phenomenon were the physical adsorption of Cl⁻ by the mineral admixtures, as well as the aluminate contained in the mineral admixtures combining with Cl⁻ to form Friedel's salt. At the same time, the secondary hydration products of mineral admixtures and cements also had physical adsorption and chemical solidification effects on Cl⁻, thereby hindering the diffusion of Cl⁻.31,33

2.3.4. Thermal Conductivity. The thermal conductivities of ceramsite concrete, shown in Table 6, are between 0.35 and 0.5 W/(m K), which possess good thermal insulation performance compared with ordinary concrete (thermal conductivity of about 1.5 W/(m K)). The increase in internal porosity in ceramsite concrete at elevated curing temperature also affected the thermal conductivity, which manifested a decrease as curing temperature increased. In the case of the fly ash group, the thermal conductivity decreased compared with that of the basic mix proportion at each curing temperature, as the fly ash had a better effect on reducing thermal conductivity.34 Nevertheless, the thermal conductivity increased slightly when silica fume was mixed, the reason would lie in the denser microstructure of ceramsite concrete. This agreed well with the increasing strengths relating to the compactness of concrete. The findings of the comixing of fly ash and silica fume group concurred with the strengths and the permeability resistance were somewhere between the fly ash group and the silica fume group, inclining to the former.

3. CONCLUSIONS

- The mixing of fly ash and silica fume into ceramsite shotcrete had a certain effect on alleviating the later-age compressive strength reduction issued by elevated temperature. The 15 and 5 wt % cement replacements by fly ash and silica fume were recognized more suitable, respectively.
- For the optimum content, binary or ternary blended cementitious materials all could improve compressive strengths. Moreover, the improvement effect of silica

### Table 5. Antipermeability of Ceramsite Concrete Containing Different Mineral Admixtures

| group                  | permeability resistance | curing temperature (°C) | seepage water pressure/MPa | seepage water height/mm | electric flux/C |
|------------------------|-------------------------|-------------------------|----------------------------|-------------------------|-----------------|
| basic mix proportion   |                         | 20, 3.1                 | 40                         | 2042                    |
|                        |                         | 40, 2.5                 | 2107                       |
|                        |                         | 60, 1.9                 | 2125                       |
| 15 wt % fly ash        |                         | 20, >3.1, 30           | 1749                       |
|                        |                         | 40, 2.8                 | 1799                       |
|                        |                         | 60, 2.0                 | 1825                       |
| 5 wt % silica fume     |                         | 20, >3.1, 30           | 1385                       |
|                        |                         | 40, >3.1, 60           | 1406                       |
|                        |                         | 60, >3.1, 95           | 1623                       |
| comixing of fly ash    |                         | 20, >3.1, 20           | 1125                       |
| and silica fume        |                         | 40, >3.1, 80           | 1132                       |
|                        |                         | 60, >3.1, 105          | 1323                       |

“Note: The permeability resistance test set the maximum seepage pressure to 3.1 MPa, and the seepage height was tested after the setting pressure was reached.

whereas the seepage pressure remained constant, the penetrating depth was measured. Whatever mix proportion the ceramsite concrete was of, its resistance to chloride ion permeability and permeability resistance were gradually decreased as curing temperature increased. At this point, the mechanism study on ordinary concrete could be used for reference. This could be explained from the reduction of the hydration reaction degree and internal compactness because of rapid generated and disordered distribution of early hydration product at elevated curing temperature, and this could be observed in scanning electron microscopy (SEM) photographs in Figure 4.
fume was more obvious. However, it was the existing temperature threshold, and the later-age compressive strengths cured at 60 °C dropped below 20 °C. The improvement effect of comixing on splitting tensile strength cured at 40 and 60 °C was more obvious, increasing by 61.6 and 39.8% over the basic mix proportion group, respectively.

- The increase in curing temperature led to a decrease in permeability resistance and resistance to chloride ion permeability of ceramsite shotcrete, whereas they would be greatly improved when mixing fly ash and/or silica fume. The improvement effect of silica fume was higher than that of fly ash. As for the comixing group, its resistance to chloride ion permeability was most prominent stemming from physical adsorption and chemical solidification.
- The thermal conductivity of ceramsite shotcrete decreased at elevated curing temperature, and it further declined when mixing fly ash, while it slightly ascended when mixing silica fume because of denser microstructure of concrete.

4. MATERIALS AND METHODS

4.1. Experimental Materials. Ordinary Portland cement (OPC) with a 28-day compressive strength of 42.5 MPa was used in this study, with the specific parameters shown in Table 7. The secondary fly ash produced by Jiaozuo Power Plant was adopted, with its microstructure photographs in Figure 5 and composition shown in Table 8. The silica fume was Luoyang Laifu 95 grade, with its microstructure photographs in Figure 6.

### Table 6. Thermal Conductivity of Ceramsite Concrete Containing Different Mineral Admixtures

| group number                     | curing temperature (°C) | thermal conductivity/W · (m · K) |
|----------------------------------|-------------------------|---------------------------------|
| basic mix proportion             | 20                      | 0.460                           |
|                                  | 40                      | 0.431                           |
|                                  | 60                      | 0.402                           |
| 15 wt % fly ash                  | 20                      | 0.403                           |
|                                  | 40                      | 0.401                           |
|                                  | 60                      | 0.353                           |
| 5 wt % silica fume               | 20                      | 0.464                           |
|                                  | 40                      | 0.464                           |
|                                  | 60                      | 0.405                           |
| co-mixing of fly ash and silica  | 20                      | 0.402                           |
| fume                             | 40                      | 0.418                           |
|                                  | 60                      | 0.368                           |

### Table 7. Composition and Physical Properties of Cement

| chemical composition (%)         | OPC          |
|----------------------------------|--------------|
| calcium oxide (CaO)              | 57.9         |
| silicon dioxide (SiO₂)           | 23.7         |
| aluminum oxide (Al₂O₃)           | 7.4          |
| ferric oxide (Fe₂O₃)             | 1.9          |
| sulfur trioxide (SO₃)            | 2.64         |
| magnesium oxide (MgO)            | 2.04         |
| potassium oxide (K₂O)            | 0.63         |
| sodium oxide (Na₂O)              | 0.31         |
| loss on ignition                 | 3.36         |
| physical properties              | OPC          |
| fineness                         | 358 m²/kg    |
| initial setting time             | 175 min      |
| final setting time               | 220 min      |
| 3-day mortar compressive strength| 28.8 MPa     |
| 3-day mortar rupture strength    | 5.7 MPa      |

### Table 8. Composition of Fly Ash

| chemical composition (%)         | fly ash      |
|----------------------------------|--------------|
| silicon dioxide (SiO₂)           | 51.2         |
| aluminum oxide (Al₂O₃)           | 35.8         |
| calcium oxide (CaO)              | 2.8          |
| ferric oxide (Fe₂O₃)             | 3.9          |
| sulfur trioxide (SO₃)            | 1.0          |
| magnesium oxide (MgO)            | 1.4          |
| sodium oxide (Na₂O)              | 0.7          |
| potassium oxide (K₂O)            | 1.4          |
| titanium dioxide (TiO₂)          | 1.1          |
Table 9. Composition of Silica Fume

| chemical composition (%) | silica fume |
|--------------------------|------------|
| silicon dioxide (SiO₂)   | 96.1       |
| aluminum oxide (Al₂O₃)   | 0.9        |
| calcium oxide (CaO)      | 0.7        |
| ferric oxide (Fe₂O₃)     | 0.4        |
| sulfur trioxide (SO₃)    | 0.7        |
| magnesium oxide (MgO)    | 0.6        |
| sodium oxide (Na₂O)      | 0.1        |
| potassium oxide (K₂O)    | 0.3        |

The gravel-shale ceramsite, with the diameter ranging from 5 to 15 mm, the bulk density of 710 kg/m³, 1 h water absorption less than 11.5%, was used as a coarse aggregate. The MY-1 high-performance polycarboxylic superplasticizer provided by Henan Meiya Ltd. was used as a water reducing agent, and the N2 nonalkali type accelerating agent produced by Jiangsu Subote Ltd. was applied to speed up the concrete to harden.

4.2. Experimental Methods. The temperature adjustable curing box (relative humidity ≥ 90%) was used to maintain 40 and 60 °C for simulating the high geothermal environment. The 20 °C curing in the standard curing box was conducted as comparison.

To explore the effect of fly ash and silica fume on the mechanical properties of ceramsite concrete at elevated curing temperature, the basic mix proportion in this study was set up first in accordance with a previous experiment as shown in Table 10. On this basis, the fly ash was mixed into the concrete mixture by replacing 10, 15, and 20 wt % cement. For silica fume, the content of 3, 5, and 7 wt % was set to replace cement in consideration of the workability of the concrete mixture. According to the content of silica fume, the quality of the water reducing agent increased by 0.1, 0.2, and 0.3 wt % of the cementitious material, respectively, based on the basic mix proportion. The concrete sample was cured at the corresponding temperature conditions to a certain age. The 3-day and 28-day compressive strengths were tested. Then the optimum content of fly ash and silica fume could be determined. Subsequent experiments of single or comixing of fly ash and silica fume were carried out, and the compressive strength, durability, and thermal insulation were comprehensively investigated.

The 28-day water permeability resistance (the HS-4S permeability instrument from Wuxi Jianyi Co., Ltd., gradual increasing pressure method, and the highest pressure set at 3.1 MPa) was detected. The 28-day resistance to chloride ion permeability was investigated by the electric flux (the NJ-DTL electric flux meter from Beijing Naijuweiye Technology Co., Ltd.) according to ASTM C1202-12.35 That is, the less the electric flux passed through in 6 h, the better the resistance to chloride ion permeability was. In addition, the thermal insulation performance (the DRL-III thermal conductivity tester from Hunan Xiangke Co., Ltd., using the slice 200 mm × 200 mm × 10 mm concrete specimen, drying the specimen before test) was analyzed.

Table 10. Basic Mix Proportion of Ceramsite Concrete

| water–cement ratio | cement/kg·m⁻³ | sand ratio/% | water reducing agent/kg·m⁻³ | accelerating agent/kg·m⁻³ |
|--------------------|---------------|-------------|-----------------------------|---------------------------|
| 0.39               | 460           | 52          | 4.14                        | 18.4                      |
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