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Research Article

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Enhancement of concrete performance via mixed limestone and granite powders

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Abstract:

The granite and limestone powders are commonly exploited as a replacement for cement; however, the effects of different mixing dosages of them on the mechanical properties and durability of concrete have not been scrutinized carefully. Under different environmental conditions, the compressive strength of the specimens is measured using cube compressive, splitting tensile, freeze-thaw cycles, and sulfate immersion tests. The phase composition of hydration products and microstructure is evaluated by SEM scanning analysis. The results indicate that the composite mixture of granite and limestone powders shows a complementary synergistic effect and improves the mechanical properties, freeze-thaw resistance, and sulfate erosion resistance of the concrete. The best values for the mechanical properties and freeze-thaw resistance are obtained when the dosages of granite and limestone powders in order are 10% and 5%. For the case of granite and limestone powders equal to 10% and 15%, respectively, the best sulfate erosion resistance is reported.

Keywords: granite powder, limestone powder, concrete, mechanics, durability, microstructure.

1. Introduction

Concrete is one of the most important raw materials for infrastructure construction. By taking into account green environmental protection and sustainable development, a serious transformation from classical concrete to green one is underway. Stone powder is commonly classified as waste materials produced from stone crushing as well as industrial production process[1]. Based on the available statistics, billions of tons of such materials are produced every year. In the lack of proper treatment, a large amount of stone powder is accumulated in the open air, causing severe damages to the environment. As a result, the application of waste stone powder as concrete mineral admixture cannot only solve the resulted pollution problems, but also would have important influences in promoting green and sustainable concrete[2-4]. At present, limestone and granite powders are widely exploited in concrete. The use of Portland cement containing limestone powder is a common implementation in European countries, particularly in France. The Chinese standard GB175-2007 *General Portland Cement* stipulates that the maximum dosage of limestone powder is limited to 5%[5]. Until now, researchers[1, 6-9]have carried out many studies on the mechanical properties, durability, and microstructure of concrete after the addition of granite or limestone powder separately. Nevertheless, the influences of these two kinds of commonly used stone powder compounds on the performance of concrete have not been reported systematically. In this paper, the effects of different dosages of granite and limestone powders on the mechanical properties, durability, and microstructure of concrete are going to be investigated. It is hoped that this research works would provide a solid basis for comprehensive exploitation of waste rock powder in concrete mixes shortly.

2. Experimental

2.1 Raw materials

The mixtures used were prepared with ordinary Portland cement PO 42.5 that meet the Chinese standard GB 175-2007. Granite and limestone powders, produced from stone processing enterprises (i.e., superfine limestone powder). In comparison with granite, limestone has a lower hardness, is easier to grind, and is more economical[10]. The fine aggregates are prepared from locally produced river sand, while the coarse aggregates are continuously graded gravels that meet the Chinese standard GB/T 14685—2001. To reduce water usage, high-performance naphthalene water-reducing agents are utilized, resulting in reduction of water about by 20%. The exploited laboratory tap water meets the standard JGJ63-2206. The materials properties of the concrete mix are provided in Table1 and the main chemical composition of cement, granite powder, and limestone powder are also presented in Table2.

2.2 Experimental scheme

Limestone and granite powders are replaced as a part of the cement mixture in the concrete such that the dosage of granite powder would be 10%(The current research shows that controlling the dosage of granite powder at 10% is the most beneficial to the performance of concrete[11]), and the dosages of limestone powder are 0%, 5%, 10%, 15%, and 20%. The mix ratio is made up according to C30 concrete, and group C is the reference group.The specific mix ratios for various experimentally observed groups are now given in Table 3.

The appropriate mechanical properties tests were carried out following the standard GB/T 50081-2019. The dimensions of the understudy cubical specimens are 100mm×100mm×100mm. The compressive strength and splitting tensile strength of the specimens are tested at curing ages of 7d, 14d, and 28d.

The freeze-thaw test was conducted by the quick-freezing method in accordance with GBJ 82—85. The 100mm×100mm×100mm specimens cured in 28d were immersed in water at the temperature of 20±2℃ for 4d. When the specimens are full of water, they are taken out until the water is wiped on the surface, and then they are marked and weighted. For the numbers of freeze-thaw cycles equal to 25, 50, 75, and 100 times, the specimens were taken out for conducting the compressive strength test.

The sulfate immersion test was carried out in accordance with GB/T 50082—2009. The cubic specimens subjected to standard curing at the age of 28d were immersed in the Na_2SO_4

solution of concentration 5% for 7d, 14d, and 28d, and then, they are taken out and dried by a dryer at 80℃ for 24h. Finally, the compressive strength of each specimen is measured.

The microstructure of specimens after 28 days of standard curing, 100 times freeze-thaw cycles, and 28d of 5% Na_2SO_4 solution immersion was examined by SEM scanning. By comparing the microstructure with the macro strength of concrete, the influence of the microstructure on the strength of concrete is explored, and the corresponding mechanisms are revealed.

For the sake of reducing the contingency due to existing differences between specimens, each of the above-mentioned test groups is designated for three specimens, and their average values are taken into account and reported.

3. Results and discussion

3.1 Mechanical properties and microstructure

The compressive strength of specimens at the curing ages of 7d, 14d, and 28d has been demonstrated in Fig. 1. The obtained results indicate that the compressive strength of all specimens increases with the curing age, but different dosages of LP and GP have different influences on the compressive strength of concrete. The 28d compressive strength of G1, G2, and G3 groups was higher than that of group C about 6.0%, 16.6%, and 2.7%, respectively. In general, the strength growth rate of the first three groups is higher than that of group C in the first 7days. The results show that when the dosages of GP was 10% and the LP was lower than 10%, the composite stone powder can enhance the compressive strength of concrete, especially the early one. The research works of Yahia et al.[12]and Celik et al.[13] also revealed that the LP could raise the early compressive strength of concrete. When the dosages of GP and LP in order were 10% and 5%, the benefit of the addition of LP was more apparent. However, the compressive strength of the specimens in G4 and G5 groups at the age of 28d was significantly lower than that of group C, and neither of them reached the strength value of C30 concrete. This issue clearly indicates that when the dosages of GP and LP were 10% and more than 10%, respectively, the composite stone powder has a deterioration influence on the compressive strength.

Fig. 1. The compressive strength at different curing ages.

The results of splitting tensile strength of specimens at 7d, 14d, and 28d are presented in Fig. 2. The obtained results show that the splitting tensile strength of all specimens would grow with an increase of the curing age, and the GP and LP have a noticeable influence on the splitting tensile strength of concrete. Among various groups under consideration, the G2 and G3 performed the best, and their splitting tensile strength at 28d increased by 27.3% and 22.7% compared with that of group C. The pertinent strength of group G2 also grew about 17.4% compared with group G1; however, the splitting tensile strength of G4 and G5 groups at 28d in order was 4.5% and 13.6% lower than that of group C. This indicates that the splitting tensile strength of concrete can be improved when the dosage of both LP and GP is no more than 10%. Among different case studies, the addition of about 10% GP and 10% LP leads to a better mechanical strength compared with the single mixture with 10% GP. Further, the excessive addition of LP can degrade the splitting tensile strength of concrete.

Fig. 2. The splitting strength at different curing ages.

Fig. 3 shows the SEM scanning results of different groups of specimens at the standard curing age of 28d. As shown in Fig. 3(C), the hydration products(C-S-H:Calcium sillcate hydrate, CH:Calcium hydroxide, AFt:ettringite.) of group C are relatively dense, dominated by C-S-H gel and flake-like CH crystals. Additionally, a small amount of needle-stick AFt and some pores are clearly detectable. After the addition of GP, the stone powder began to play crucial roles in micro-filling[12, 14], crystal nucleation[15], and active effects[16, 17] , and thereby, the pores became smaller and smaller. This fact is also supported by the performed study in Ref.[18] showed that GP improves the concrete pore structure. The experimentally observed data also demonstrate that the addition of GP making the distribution of hydration products to be more uniform and the overall density of the specimens in group G1 be better than that of group C. At the same time, there is more petite CH crystal in the hydration products. This is mainly because of the fact that the active CaO and Al_2O_3 in the GP have a secondary hydration reaction with the CH crystals, which further reduces the content of CH crystal. After simultaneous addition of GP and LP, we can observe that the hydrates of group G2 are very dense and uniform, and no obvious pores and cracks can be detected, which is greatly improved the mechanical behavior of the specimens with respect to that of groups C and G1. This issue indicates that the simultaneous addition of 10% GP and 5% LP provides a concrete mix with optimal grading, and it maximizes the micro-filling, crystal nucleation, and stone powder active effects. Furthermore, some performed studies[19, 20] showed that because of the rough surface and irregular shape of the composite stone powders, the above-mentioned fact would be beneficial to enhance the absorption capacity of the cement slurry. Based on the test results for group G3, we observed the precipitation of a large amount of unhydrated LP due to the increase of the dosage of LP, and therefore, the densification of hydration products would lessen. For the groups G4 and G5, this fact is more pronounced. The C-S-H gel in hydration products would significantly lessen, the connection degree of hydration products would reduce, and a large number of pores and micro-cracks would appear throughout the specimens. This fact is mainly attributed to the replacement of the excessive cement by the addition of LP as well as the coarsing effect[16, 21, 22]. In fact, the LP itself is an inert substance[23], almost does not participate in the hydration reaction, and its micro-filling, crystal nucleation, and active effects cannot make up for the impact of a large drop in the cement hydration products. A large number of pores and micro-cracks can seriously affect the performance of concrete. Such microscopic test results are also consistent with the macroscopic mechanical properties of concrete.

Fig. 3. SEM scanning of concrete subjected to 28d standard curing.

3.2 Freeze-thaw resistance and microstructure

As one can see in Fig. 4, the compressive strength of concrete specimens decreases with the increase of freeze-thaw cycles. Among various case studies, the compressive strength loss of group G5 reduced about 50% when the number of freeze-thaw cycles was 75 times, and the specimen had arrived at the failure standard. After 100 time freeze-thaw cycles, the strength loss of the groups C-G5 was estimated to be 49.5%, 46.0%, 40.7%, 45.6%, 52.1%, and 59.9%, respectively. The freeze-thaw resistance of the G1, G2, and G3 groups was better than that of group C, and the strength loss of group G2 was reported to be the smallest one. These new findings reveal that using 10% GP and 5% LP can provide the concrete with the best freeze-thaw resistance. When the LP dosage exceeds 10%, the mechanical resistance of concrete deteriorates, chiefly related to the increase of pores and micro-cracks within the concrete specimens. Tikkkanenj et al.[24] also explained that the binding force after hydration becomes smaller when the dosage of LP is too large due to its limited vitality, which would be harmful to the freeze-thaw resistance of concrete.

Fig. 4. The compressive strength at different freeze-thaw cycles.

According to Fig. 5, many micro-cracks appeared within specimens of group C as the number of freeze-thaw cycles approaches 100 times. Additionally, a large number of needle-stick AFt precipitate around the cracks, which seriously affect the compressive strength of concrete. For specimens of groups G1, G2, and G3 (see their corresponding plots in Fig. 5), numerous flower-cluster C-(A)-S-H gels would be formed and arranged in a close connection. Although the resulting structure was loose, their pertinent effects on the compressive strength were less than micro-cracks and pores. This is because of the fact that when the dosage of LP is relatively small, its micro-filling effect improves the concrete densification, hinders water from entering into the concrete[25], and reduces the generated stresses from ice expansion. According to experimentally observed data, the densification of specimens of group G2 was higher than that of G1 and G3 groups. For the specimens tested in G4 and G5 groups, the reduction of cementitious materials leads to the increase of concrete pores, and the poor connectivity of each part results in grave influence on the freeze-thaw resistance.

Fig. 5. SEM scanning of concrete after 100 freeze-thaw cycles.

3.3 Sulfate erosion resistance and microstructure

Based on the plotted results in Fig. 6, the compressive strength of concrete specimens decreases with the increase of soaking time. After soaking for 28 days, the compressive strength loss of group C was about 16.1%, and that of group G1 was approximately equal to 14.3%, indicating that the addition of GP improved the sulfate erosion resistance of concrete. In fact, the incorporation of GP into the concrete mix increases its compactness. Concerning the specimens of group G2, we found that the strength loss of group G2 was significantly lower than that of the G1 and C groups due to the addition of LP. Among different groups, group G4 showed the best performance, whose compressive strength loss was only 8.9%. These investigations show that the addition of LP enhances the sulfate resistance of concrete.

Fig. 6. The compressive strength at different immersion times.

The performed study in Ref.[26] displayed that sulfate erosion is divided into ettringite and gypsum crystalline types. The crystal type of ettringite is the reaction of sulfate ions with sodium hydroxide and calcium aluminate hydrate to form the needle-like AFt precipitation, causing micro-crack and damage to the cement. The corresponding reaction equation has been provided in Eq. (1). For the gypsum crystal type, when the concentration of sulfate ions in the erosion solution is greater than 1000mg/L, AFt will also be produced plus to gypsum crystal precipitation through the chemical reaction. At this time, the volume of dihydrate gypsum formed inside the cement stone increases about 1.24 times the initial volume, causing damage to the cement stone due to excessive internal stress. The pertinent chemical reaction has been displayed by Eq. (2) .

$$3CaO\cdot Al_2O_3\cdot 12H_2O + 3Na_2SO_4 + 3Ca(OH)_2 + 19H_2O \rightarrow 3CaO\cdot Al_2O_3\cdot CaSO_4\cdot H_2O + 6NaOH \quad (1)$$

$$Ca(OH)_2 + Na_2SO_4 \rightarrow CaSO_4 + 2NaOH \; CaSO_4 + H_2O \rightarrow CaSO_4\cdot 2H_2O \quad (2)$$

Except for the cases presented in Figs. 7(C) and 7(G1), we can see obvious needle-like AFt in other cases. As it is seen in Fig. 7(C), there is almost no CH crystal, fewer hydration products, and apparent pores and micro-cracks. This indicates that CH crystal in the specimens of group C is consumed in chemical reactions with sulfate ions. The GP in specimens of group G1 plays a filling role to some extent, and its structural integrity is slightly better than that of specimens in group C. Further, the fewer amount of AFt were produced in compared with group C. This issue clearly displays that why the loss rate of the compressive strength of specimens in group G1 is lower than that of group C. Ramadji et al.[27]found that existence of GP in the concrete mix can reduce the heat of hydration and improve the resistance of the properly cured structure to the acid attack due to its low participation in the hydration reaction. The obtained results display that the addition of LP increased the amount of gypsum in the erosion products; some scholars[11, 28]believe that gypsum will cause the decalcification and softening of C-S-H gel, resulting in the loss of concrete quality and the decrease of strength. However, no clear gypsum crystals could be detected in Figs. 7(G2), (G3), and (G4). In these groups, the AFt could be observed, but its quantity and density are significantly lower than those of groups C and G1. Commonly, the structural integrity and compactness are optimized by increasing the LP's dosage. Clustered prismatic gypsum crystals as well as granular sodium sulfate crystals can be apparently observed in Fig. 7(G5). It is worth mentioning that the study of scholars in Ref.[29] revealed that the existence of sodium sulfate crystals causes concrete deterioration in sodium sulfate solutions. Actually, the combined incorporation of LP and GP improves the compactness of slurry and improves the coarsing effect caused by the excessive LP. In addition, LP can consume the Al phase in the GP and reduce the number of AFt generated by sodium sulfate. The Al_2O_3 and SiO_2 in the GP can also consume CH crystal[30, 31]. Liu et al.[32] also found that calcium carbonate in LP could react with the acid such that a higher content of that leads to the faster decrease of the concrete strength. When mixed with fly ash or silica fume, they could both react with calcium hydroxide, and C-S-H is generated. This is good for enhancing the paste's strength and weakens the degree of reactions between the hydration products and the acid. When the dosage of GP was about 10%, and the dosage of LP was lower than 15%, they result in a complementary synergistic effect and improve the sulfate resistance of concrete. The optimal effect was achieved when the dosages of GP and LP in order were set equal to 10% and 15%. When the dosage of LP is too large, the dilution effect begins to dominate[21, 22], and the complementary synergistic effect of composite stone powder begins to lose.

Fig. 7. SEM scanning of 5% Na2SO4 solution soaked for 28d.

4. Conclusion

In this study, the effects of different mixing dosages of granite and limestone powders on the mechanical properties and durability of concrete were investigated.The main obtained results from this experimental study are summarized in the following:

1) The simultaneous mix of GP and LP can improve both compressive strength and splitting tensile strength of concrete, and the best effect is reported when 10% GP and 5% LP are exploited. For such a mixing plan, the compressive strength and splitting tensile strength of the specimens at the curing age of 28d increased about 16.6% and 27.3%.

2) The combination of both GP and LP can enhance the freeze-thaw resistance of concrete, and the best effect is gained when 10% GP and 5% LP are exploited. After 100 times freeze-thaw cycles, the compressive strength loss rate of the specimens was approximately 8.8% lower than that of group C.

3) The compound mixing of 10% GP and no more than 15% LP results in an excellent synergistic effect, enhancing the sulfate erosion resistance of concrete and resolving the

problem of poor sulfate erosion resistance of LP-based concrete. Among various cases, the best results are observed for the case of 10% GP and 15% LP. After soaking in 5% Na_2SO_4 solution for 28d, the strength loss of group G4 would be 7.2% lower than that of group C.

5.Acknowledgements

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Figures

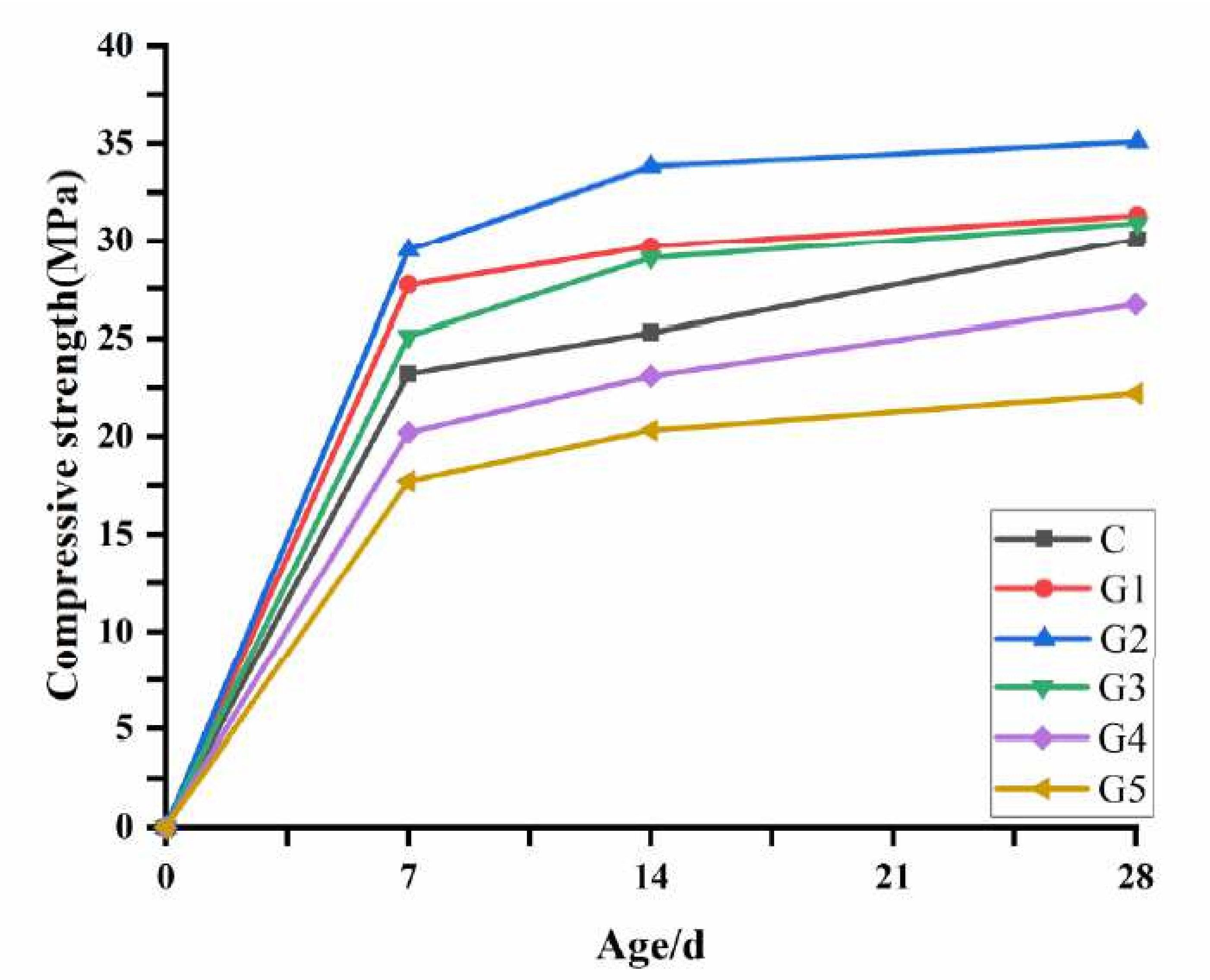

Figure 1

The compressive strength at different curing ages.

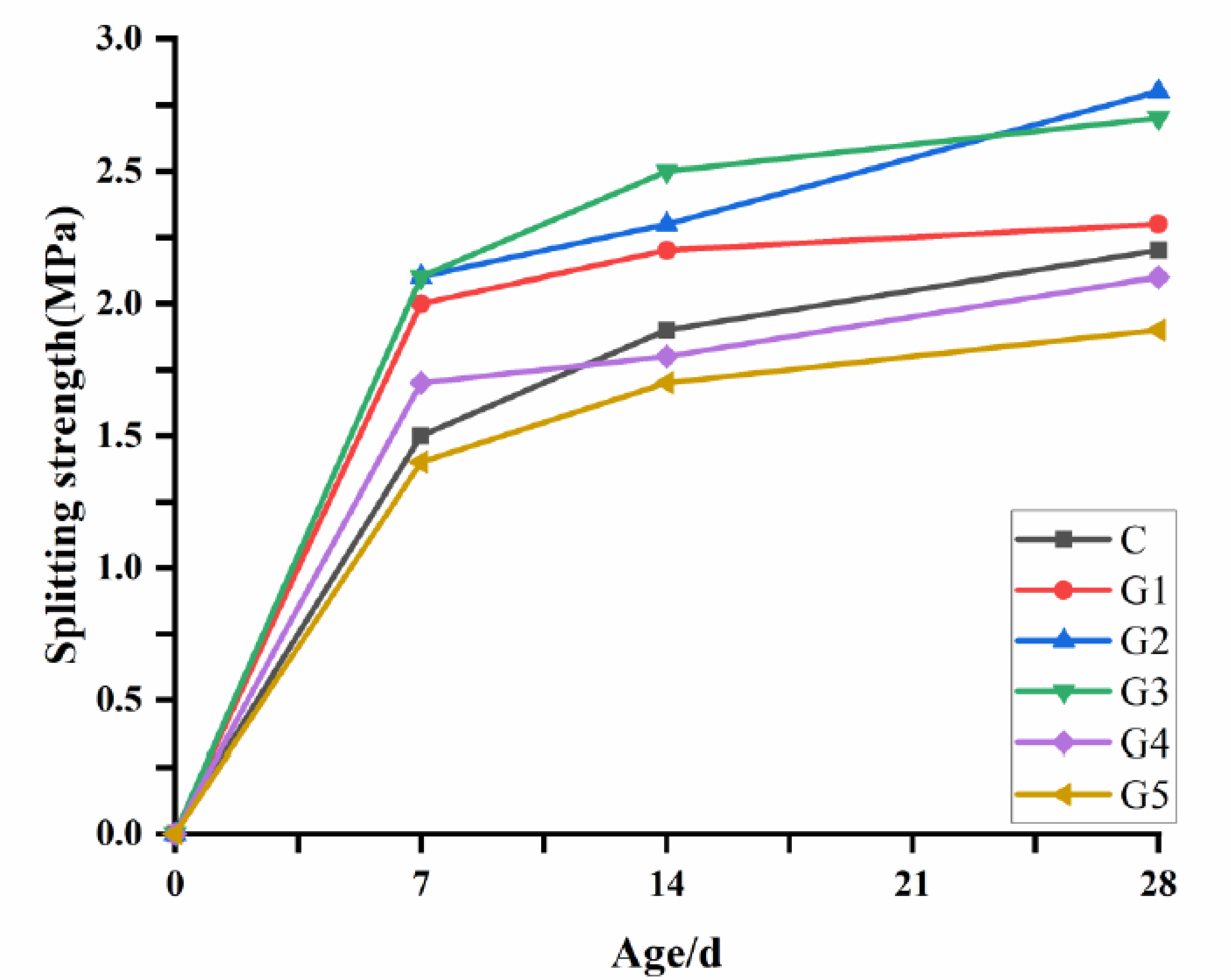

Figure 2

The splitting strength at different curing ages.

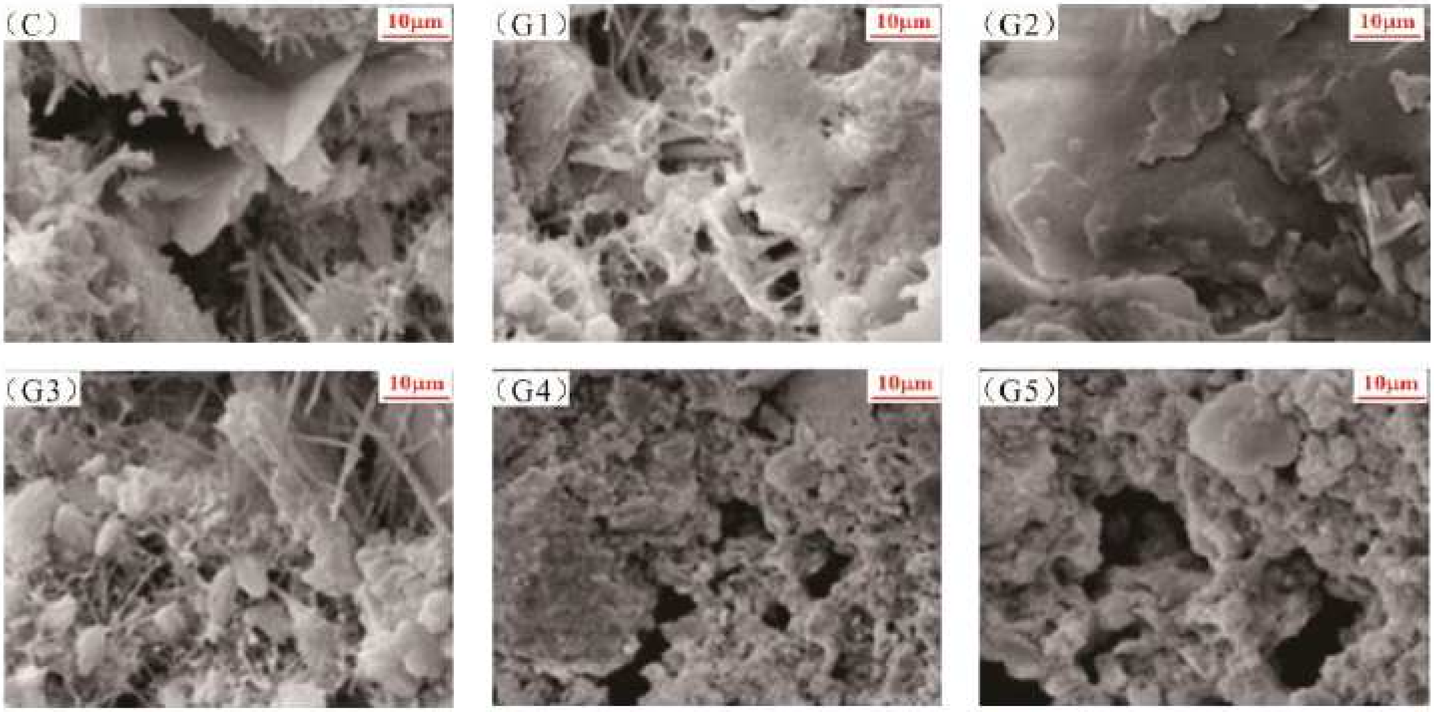

Figure 3

SEM scanning of concrete subjected to 28d standard curing.

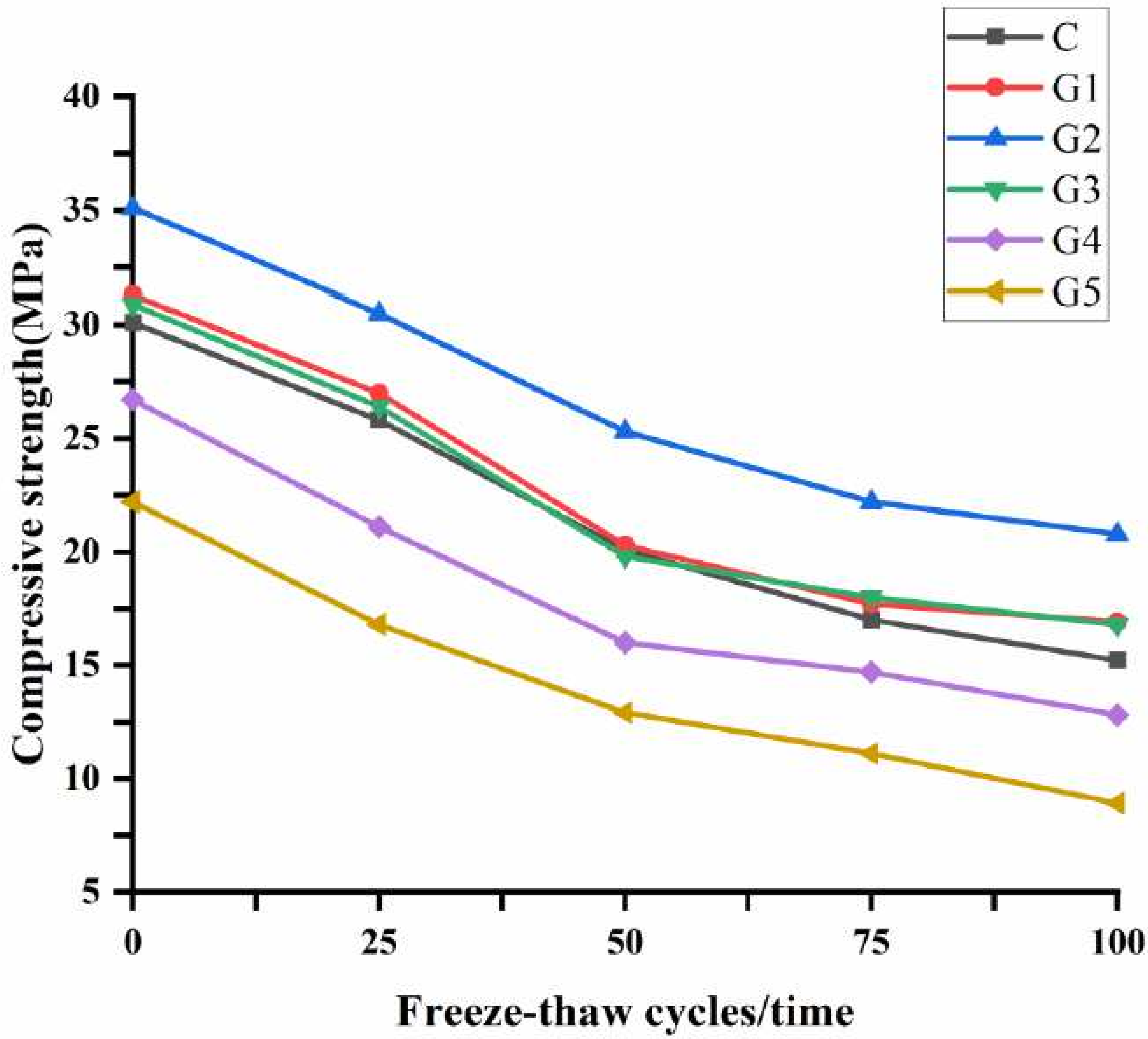

Figure 4

The compressive strength at different freeze-thaw cycles.

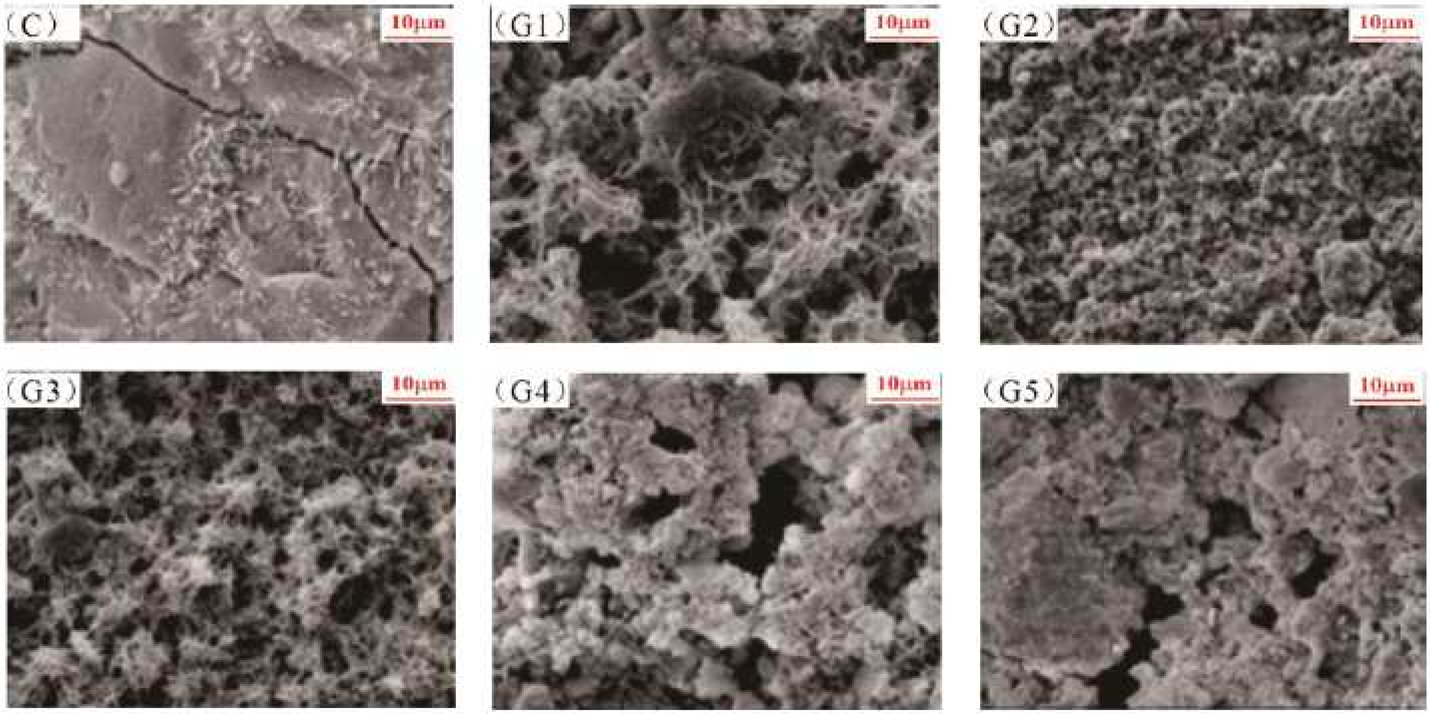

Figure 5

SEM scanning of concrete after 100 freeze-thaw cycles.

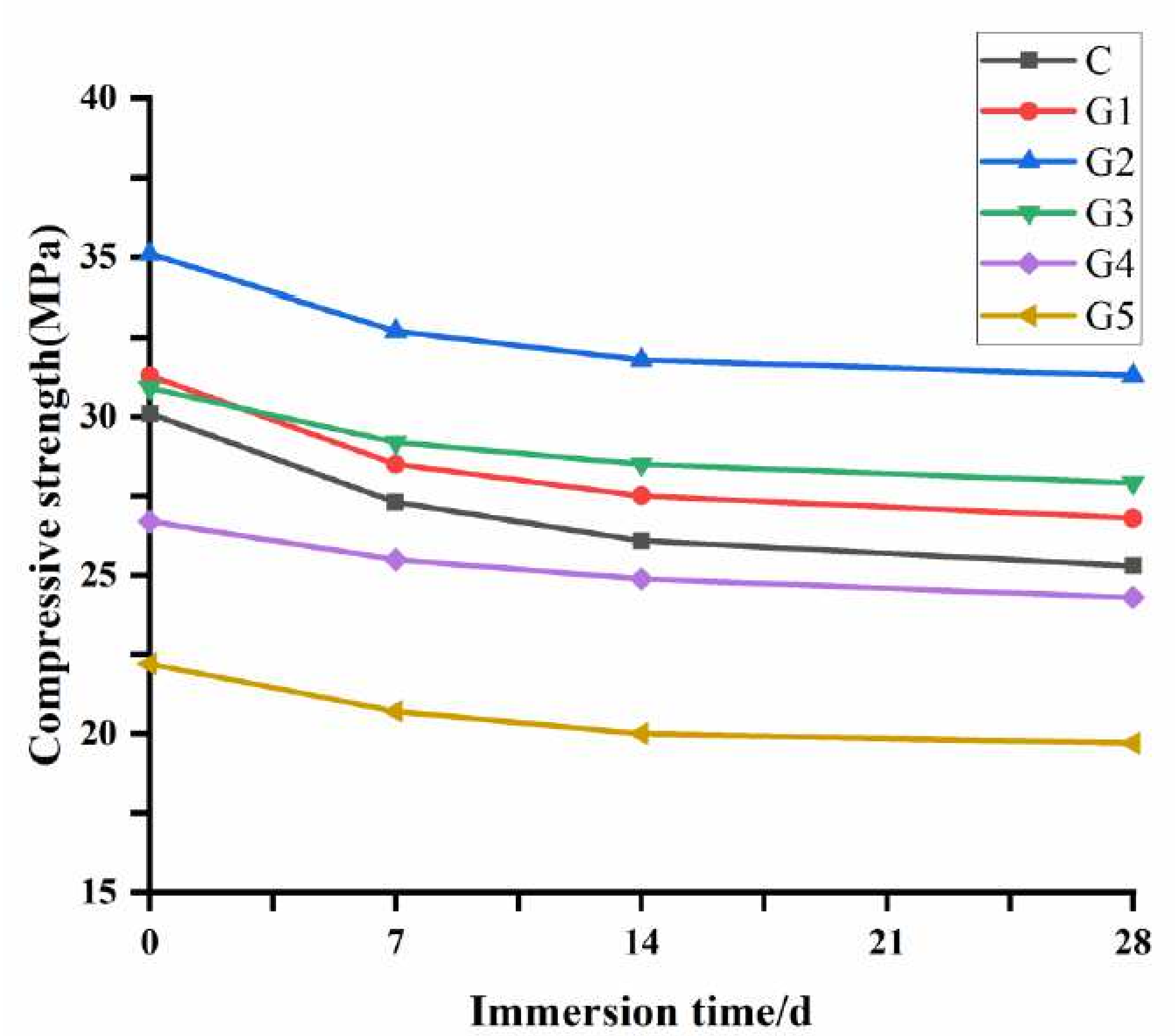

Figure 6

The compressive strength at different immersion times.

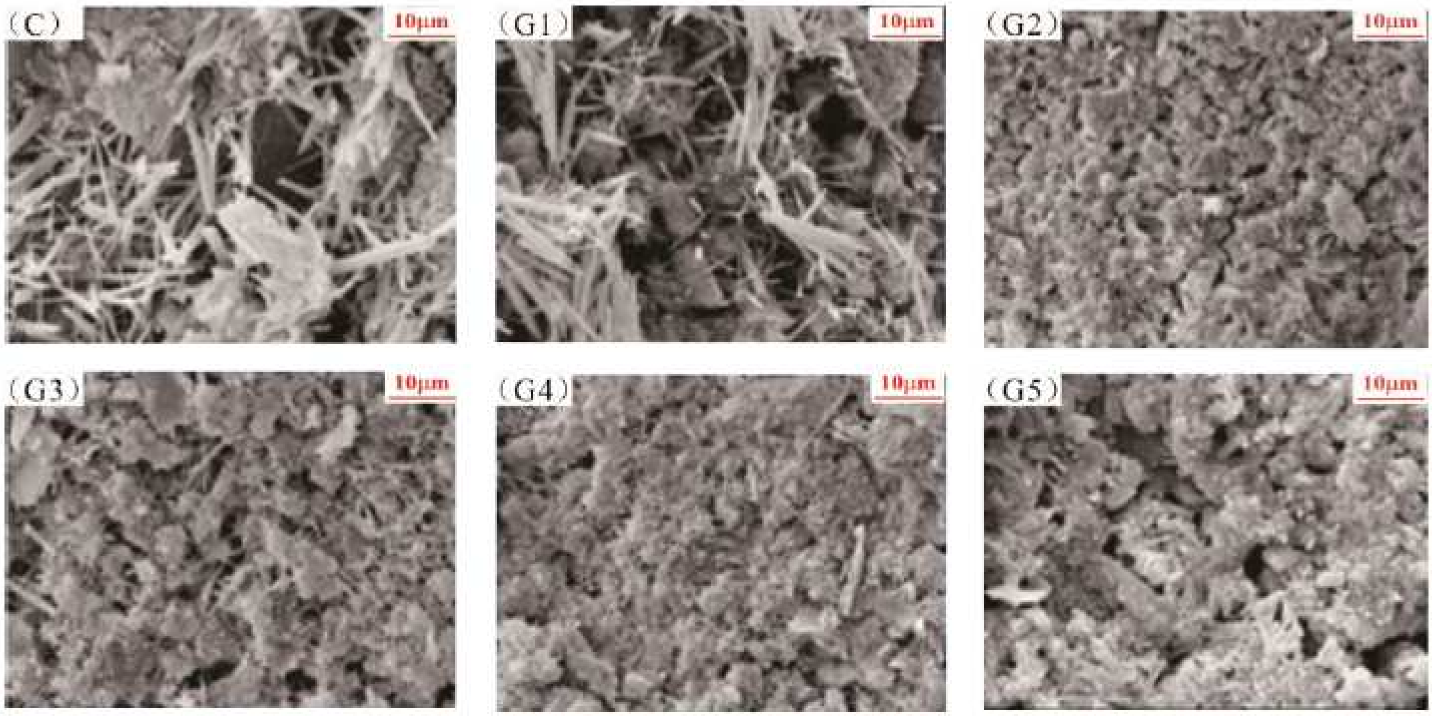

Figure 7

SEM scanning of 5% Na2SO4 solution soaked for 28d.

Supplementary Files

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- Tables9.21.pdf