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Experimental Study on Fabrication of Environment-Friendly Concrete by Solidifying Aeolian Sand and Natural Gravel with Fly Ash-Based Geopolymer

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Abstract: To tackle the shortage of river sand resources and excessive carbon emissions in building materials, environment-friendly concrete can be fabricated by solidifying aeolian sand and natural gravel with a fly ash-based geopolymer. Aeolian sand and natural gravel are accessible building materials, but their engineering applications are largely limited by their poor properties such as high mud content, large specific surface area, and discontinuous particle size distribution. To enhance the application of this environment-friendly concrete, in this paper, 48 sets of specimens with different geopolymer dosages, curing temperatures, and curing times are studied experimentally, and quite well-strengthened geopolymer aeolian sand mortar (GAM), geopolymer aeolian sand concrete (GAC), and an appropriate dosage of the geopolymer are finally obtained. The experimental results and the failure section of the mortar specimen indicate that the fly ash geopolymer can solidify the aeolian sand and ensure the integrity and compactness of the specimen. The 28-day compressive and flexural strength of the geopolymer standard sand mortar (GSM) reached 40.5 MPa and 4.3 MPa, respectively, at a curing temperature of 60 °C when the amount of alkali activator was improved to 100%, and the 28-day compressive and flexural strength of GAM reached 33.7 MPa and 4.2 MPa, respectively, when the amount of geopolymer material was 0.75 times that of aeolian sand. A lower compressive strength of GAC was obtained following the addition of aeolian sand. The experiment results can provide a reference for aeolian sand usage and have a certain social value in environmental protection.

Keywords: aeolian sand; fly ash; geopolymer; mortar; basic mechanical properties

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1. Introduction

With the appearance of Portland cement, construction activities have used cement concrete as the core material for more than 200 years, but rapid infrastructure construction calls for a high demand of river sand and imposes serious burdens on the environment, where an alternative building resource is urgently needed [1,2]. At the same time, the mass production of cement releases almost half of global carbon dioxide emissions, which is responsible for global warming [3,4].

River sand is an essential material for the preparation of concrete, but excessive exploitation of river sand has a great impact the river ecology and water environment. Therefore, replacing river sand with aeolian sand has emerged as a solution. However, aeolian sand is formed by wind deflation and natural accumulation, mainly composed of low active silica, and its poor cohesiveness results in high porosity and deteriorates the performance of the concrete [5,6]. Nevertheless, measures have been taken to replace all or part of river sand with aeolian sand for cement concrete, but the problem of the large amount of carbon dioxide emissions still remains. Some studies [7,8] have found that adding a small or medium amount of aeolian sand during concrete preparation can improve the strength of

the concrete while adding a large amount of aeolian sand will show the opposite trend. Li et al. [9] studied the durability of aeolian sand powder concrete under the coupling effects of freeze–thaw and dry–wet conditions, and the pore characteristics, hydration products, and micro-morphology were analyzed. Dong et al. [10] conducted freeze–thaw cycle tests and a damage model study of aeolian sand light aggregate concrete; then, a constitutive model for predicting the freeze–thaw damage of light aggregate concrete with aeolian sand was established. Jiang et al. [11] produced ultra-high-performance concrete using aeolian sand instead of natural river sand; their results showed that the addition of aeolian sand can significantly improve the workability and compressive strength, but a variation in the parameter evolution law is not obvious.

In 1978, Davidovits [12] first proposed the concept of a geopolymer, which is a new member of the inorganic polymer materials. Alkali can convert a large amount of activated alumina and silicon dioxide in waste into valuable cementing substances, which finally set and harden to form an amorphous aluminosilicate gel that is similar to a zeolite structure [13,14]. Geopolymerization is a process in which chemical bonds in a substance are broken and recombined into a kind of mesh structure at the microscopic level, and the covalent bonds give it high strength and corrosion resistance, so it will not cause an "alkali–aggregate reaction" [15,16]. Some studies [17,18] reviewed the key developments in alkali-activated materials and the performances of mortar and concrete made from geopolymers that are resistant to elevated temperature.

A fly ash-based geopolymer prepared with a slag powder as the binder had ideal workability, setting time, and compressive strength under normal temperature curing conditions [19]. The autogenous and drying shrinkage of alkali-activated fly ash pastes was associated with different contents of a sodium silicate solution [20]. Pavithra et al. [21] developed a design methodology for geopolymer concrete, mainly focused on achieving better compressive strength in an economical way for different alkaline solution-to-binder proportions. The different durabilities of alkali excitation materials were attributed to the different raw materials that formed the different components but were generally higher than those of common cement-based materials [22]. The interface mechanism, splitting characteristics, and microstructure of fiber-reinforced cement-solidified aeolian sand were experimentally assessed [23,24]. Agrawal et al. [25,26] examined the effectiveness of geopolymer fly ash sand as a replacement for natural river sand in concrete using industrial-grade sodium silicate and sodium hydroxide and then studied the mechanical properties and durability of geopolymer fly ash sand concrete. Alkaline substances were found to be able to activate aeolian sand powder [27], and geopolymer mortar was found to have different porosities, densities, and water absorption rates at different sodium hydroxide concentrations, curing times, and temperatures [28–30].

Using a geopolymer and fine particles to stabilize aeolian sand and soil was found to effectively improve the cyclic loading capacity, but the cumulative axial strain of the mixture increases at the same time [31,32]. Some scholars [33–35] have experimentally studied the application of polymer-stabilized aeolian sand based on a fly ash and slag-to-pavement base and showed that its carbon emissions are lower than those of cement.

Cement was used as the cementing material in early research on solidifying aeolian sand while reinforcing fibers were added. A geopolymer was used to stimulate the active ingredients in industrial waste [36–38] and was shown to rapidly form early strength and strong deformation resistance [39–41], together with excellent cohesive abilities and frictional properties [42–44]. In this paper, a fly ash-based geopolymer was used in a large number of tests to solidify aeolian sand and to achieve high strength in specimens. The research has a certain economic and social value in the use of aeolian sand in building materials for construction. Under the premise of a low concrete strength, concrete is prepared using the fly ash-based geopolymer to solidify aeolian sand to reduce the cost of river sand mining and transportation and to protect the river ecology and water environment, which are beneficial to environmental protection.

2. Materials

2.1. Aeolian Sand and Natural Gravel

Aeolian sand was taken from the edge of the Taklimakan desert; its particle composition is an important characteristic, and its chemical composition is silica. Its particle composition affects its physical properties, and its surface characteristics affect its combination with water. The mineral composition and content of the aeolian sand were obtained by X-ray diffraction analysis, shown in Table 1; the aeolian sand grading is drawn in Figure 1; and its fineness modulus and mud content were calculated. The particle size distribution is shown in Figure 2. The fineness modulus of the aeolian sand is small, and the sand particles are uniform but poorly graded. The fineness modulus of the aeolian sand is calculated as M = 0.5, while the standard sand is about 3.0, which indicates that the aeolian sand belongs to ultra-fine sand.

Table 1. Aeolian sand mineral composition and content table.

Mineral Composition	Quartz	Microcline Feldspar	Orthoclase	Sodium Feldspar	Illite	Chlorite	Calcite
Value (% by weight)	49.63	—	8.76	31.36	6.07	3.59	0.59

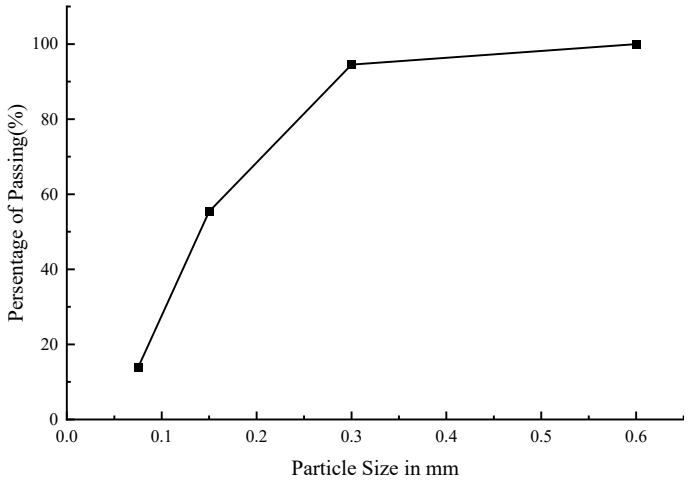


Figure 1. Gradation of aeolian sand.

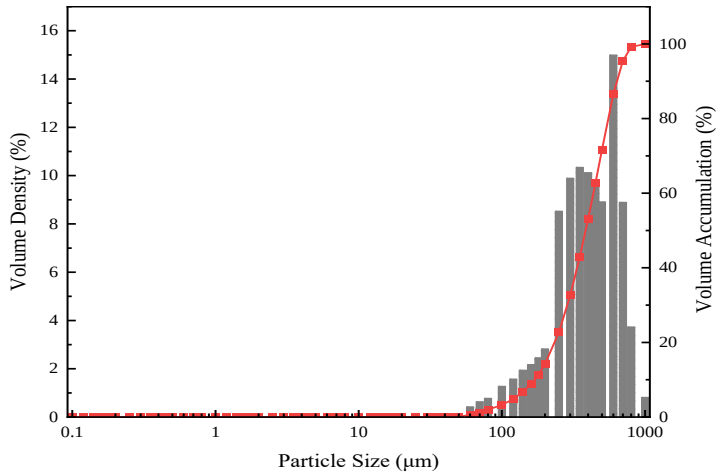


Figure 2. Size distribution curve of the aeolian sand particles.

The natural gravel was taken from a highway construction site which contains gravel, sand, and clay; its chemical composition is silica, which is the same as standard sand (Xiamen Aisio Co., Ltd., Shanghai, China), and its gradation was continuous with a mud content of 2.8%. The natural gravel gradation is drawn in Figure 3. As is known to us, the mud content is over the limit for concrete preparation; however, it is suitable for confirming the curing effect of the fly ash-based geopolymer on fine powders.

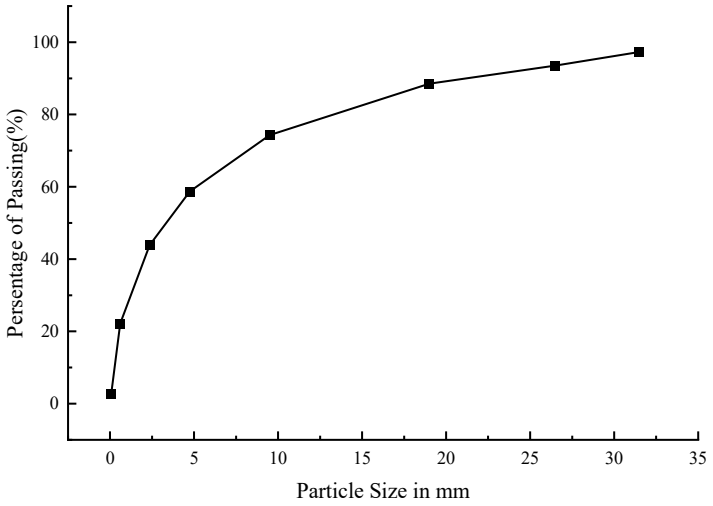


Figure 3. Gradation of the natural gravel.

2.2. The Characterization of the Fly Ash

F-grade fly ash is an industrial waste generated after coal combustion in thermal power plants; its fineness is of the second order, and the physical and chemical properties are shown in Table 2 below.

Table 2. Chemical composition of the fly ash.

Specifications	Color	Loss of Ignition	SiO_2	$SiO_2 + Al_2O_3 + Fe_2O_3$	CaO	MgO	TiO_2	MnO	Others
Observations	Light Grey	2.85%	57.4%	88.66%	5.21%	1.63%	1.18%	0.24%	0.23%

2.3. Preparation of the Alkali Activator

The flake sodium hydroxide was slowly placed in water, and uniformly and slowly stirred at the same time to prepare the sodium hydroxide solution with a concentration of 8 mol/L. After cooling, the sodium hydroxide solution was evenly mixed and stirred with water in a glass with the modulus of 1.5 at a ratio of 1:2; finally, the mixed solution was left until it became static, cooled, sealed, and stored for use. The sodium hydroxide properties are listed in Table 3.

Table 3. Properties of the sodium hydroxide.

Properties	Molecular Weight	Sodium Hydroxide (Purity)	Na_2CO_3	Nitrate
Value	40	99%	0.01%	0.01%

3. Methodology

3.1. Standard-Consistency Geopolymer Mortar Alkali Activator Dosage and Setting Time Test

According to the test procedure for the water consumption of standard-consistency cement to determine the dosage of alkali activator in the fly ash geopolymer mortar, its

initial setting time and final setting time were measured. When the dosage of the alkali activator was 95.5 g, the distance between the standard consistency test rod and the base plate of the Vicat apparatus was 6.1 mm. In accordance with the standard regulations, the amount of alkali activator at a standard consistency was 19.1%, and the initial coagulation time was 13 min when the coagulation needle was sunken 4 mm away from the bottom plate, and the final coagulation time was 23 min when the specimen reached the final coagulation state.

3.2. Experiment on the Fly Ash Geopolymer Mortar

The mortar test is the basis of concrete preparation, so a fly ash geopolymer test was carried out according to the cement mortar test specification: standard sand and aeolian sand were used as raw materials; fly ash and alkali activator were used as the cementing material; and the amount of alkali activator and curing temperature were variables, in which the GSM was the control group for comparatively analyzing the consolidation effect of the fly ash-based geopolymer and obtaining the best amount of the geopolymer.

Due to the fine particles of the aeolian sand, which exceeds the maximum soil content stipulated for aggregates used in concrete preparation, the dosage of the fly ash and alkali activator was doubled to obtain GAM with sufficient strength. The amount of test materials in each group is shown in Table 4. The mortar specimens were made using a single metal triple mold with the size of 40 mm × 40 mm × 160 mm after vibration. The curing times of each group of specimens were 3 days, 7 days, and 28 days, and the curing temperatures were 20 °C, 40 °C, and 60 °C, as shown in Tables 5–7. The results of the flexural strength test and the compressive strength test were determined by taking the average of the three samples and six samples, respectively, and the experimental process of the geopolymer mortar is shown in Figure 4.

Table 4. Mixture proportion of the mortars.

Specimens	Alkali Activator Content (%)	Mortar Material Consumption (g)			
		Standard Sand	Aeolian Sand	Fly Ash	Alkali Activator
GSM-40	40	1350	-	450	90
GSM-60	60	1350	-	450	135
GSM-80	80	1350	-	450	180
GSM-100	100	1350	-	450	225
GAM-80	80	-	1350	450	180
GAM-100	100	-	1350	450	225
GAM-150	150	-	1350	675	337.5
GAM-200	200	-	1350	900	450

Table 5. The specimens prepared with 40% and 60% alkali activator dosages and different curing processes.

Specimens	Curing Time (d)	Curing Temperature (°C)	Specimens	Curing Time (d)	Curing Temperature (°C)
GSM-40	3	20	GSM-60	3	20
GSM-40	7	20	GSM-60	7	20
GSM-40	28	20	GSM-60	28	20
GSM-40	3	40	GSM-60	3	40
GSM-40	7	40	GSM-60	7	40
GSM-40	28	40	GSM-60	28	40
GSM-40	3	60	GSM-60	3	60
GSM-40	7	60	GSM-60	7	60
GSM-40	28	60	GSM-60	28	60

Table 6. The specimens prepared with 80% and 100% alkali activator dosages and different curing processes.

Specimens	Curing Time (d)	Curing Temperature (°C)	Specimens	Curing Time (d)	Curing Temperature (°C)
GSM-80	3	40	GAM-80	3	40
GSM-80	7	40	GAM-80	7	40
GSM-80	28	40	GAM-80	28	40
GSM-80	3	60	GAM-80	3	60
GSM-80	7	60	GAM-80	7	60
GSM-80	28	60	GAM-80	28	60
GSM-100	3	40	GAM-100	3	40
GSM-100	7	40	GAM-100	7	40
GSM-100	28	40	GAM-100	28	40
GSM-100	3	60	GAM-100	3	60
GSM-100	7	60	GAM-100	7	60
GSM-100	28	60	GAM-100	28	60

Table 7. The specimens prepared with 150% and 200% alkali activator dosages and different curing processes.

Specimens	Curing Time (d)	Curing Temperature (°C)	Specimens	Curing Time (d)	Curing Temperature (°C)
GAM-150	3	60	GAM-200	3	60
GAM-150	7	60	GAM-200	7	60
GAM-150	28	60	GAM-200	28	60

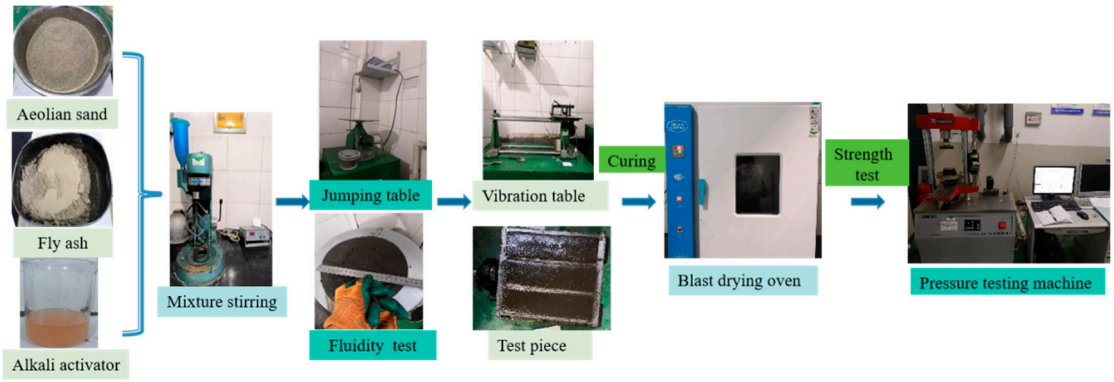


Figure 4. Geopolymer mortar experiment process.

3.3. Fluidity Test

Under the condition of a low water–binder ratio, the fluidity of the aeolian sand mortar was not satisfied, so an appropriate amount of water needed be added, obtained through a test. Each group of mortars needed to be tested on the jump table until their fluidity reached 20 cm ± 1. After several tests, the water requirement to meet the fluidity requirements was finally determined, as shown in Table 8.

Table 8. Water requirement of the specimens.

Specimens	GSM-40	GSM-60	GSM-80	GSM-100	GAM-80	GAM-100	GAM-150	GAM-200
Water/g	110	55	20	0	155	105	0	0

3.4. Experiment on the Fly Ash Geopolymer Aeolian Sand Concrete

According to the general regulations on the design of a concrete mix ratio, the mix ratio of fly ash geopolymer aeolian sand concrete C30 with natural gravel as the aggregate was designed and calculated; then, the basic mechanical properties were measured; and finally, the failure form and strength formation mechanism were analyzed. Aeolian sand concrete with aeolian sand contents of 0%, 20%, 40%, and 60% was prepared using the interpolation method by replacing the fine aggregate with another aggregate of the same quality; the alkali activator was slowly and evenly added to the dry mixed aggregate after the fly ash particles, the aeolian sand and natural gravel were distributed in the same way, and then, the specimens were placed in an oven for curing at 60 °C for 3 days and then cured at room temperature until the strength test age later. The results of the compressive strength test were determined based on the average of three samples. The mixture proportion of the fly ash geopolymer aeolian sand concrete is shown in Table 9.

Table 9. Mixture proportions of the fly ash geopolymer aeolian sand concrete.

Specimens	Aeolian Sand Content (%)	GAM Material Consumption (kg/m^3)				
		Coarse Aggregate	Fine Aggregate	Aeolian Sand	Fly Ash	Alkali Activator
GAC-0	0	706	1058	0	690	345
GAC-20	20	706	846.4	211.6	690	345
GAC-40	40	706	634.8	423.2	690	345
GAC-60	60	706	423.2	634.8	690	345

4. Results and Discussion

4.1. The Experimental Results of GSM with Alkaline Activator Dosages of 40% and 60%

As can be seen from Figures 5 and 6, the strength of the specimen increased with the curing time, which indicates that the alkali activator and fly ash continuously reacted to form geopolymer-solidified standard sand. However, the strength of the mortar specimens with 40% and 60% alkali activator content was low due to some of the fly ash not participating in the reaction and the amount of geopolymer being insufficient; the pores in the structure left by the evaporation of water were not conducive to strength formation.

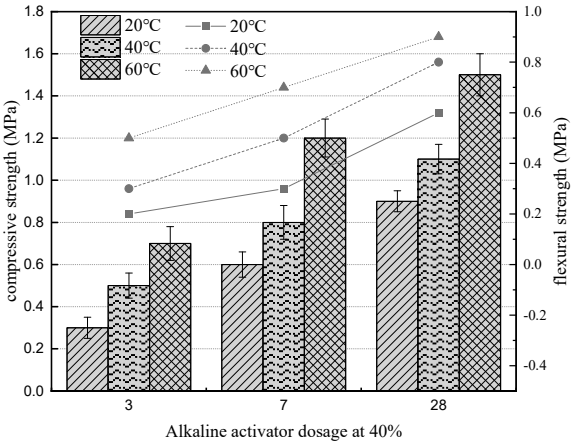


Figure 5. The strength of GSM with an alkaline activator dosage of 40%.

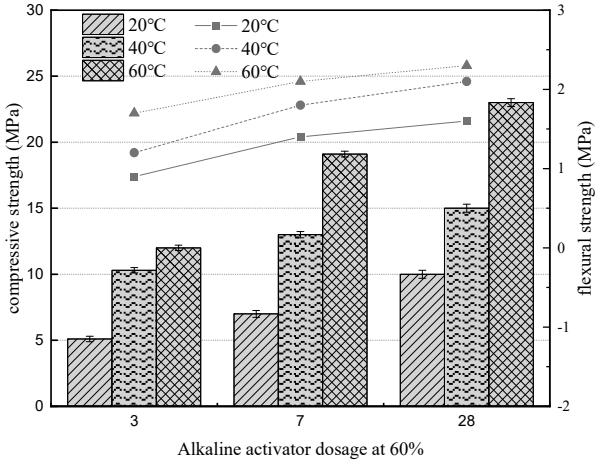


Figure 6. The strength of GSM with an alkaline activator dosage of 60%.

4.2. The Experimental Results of Mortars with Alkaline Activator Dosages of 80% and 100%

As we can see from Figures 7–10, the strength of the specimen was significantly improved; under the same curing conditions, the strength of the specimen with 100% dosage was higher than 80%, which means that the degree of chemical reaction was deepened with the increased dosage of the alkaline activator, and the active substance in the fly ash participated in the reaction to a large extent. The strength disparity between the 100% and 80% specimens with standard sand gradually reduces with the increase in curing time. The compressive strength and flexural strength of GSM for 28 days at 60 °C reached 40.5 MPa and 4.3 MPa, respectively. A large proportion of the strength of the specimen under a curing temperature of 60 °C is higher than that at 40 °C, which indicates that the temperature is proportional to the strength of the specimen and indirectly proves that geopolymer materials can adapt to high-temperature environments [17,18]. At the same time, the strength of specimens with large amount of the alkali activator was much higher than that of the specimen with a low amount of alkali activator. It can be seen from Figure 11a,b that there was enough cementing substance in the specimen to compact the internal structure. It was observed that the strength at 7 days reached more than 85% of the strength at 28 days because the geopolymer material's strength increased rapidly early on. However, the compressive strength and flexural strength of GAM at 60 °C for 28 days reached 6.5 MPa and 2.3 MPa, respectively, which demonstrates that geopolymer production is not enough to effectively consolidate the aeolian sand particles because the aeolian sand has a large specific surface area. Therefore, using more fly ash and the alkali activator was considered to generate a sufficiently gelatinous material.

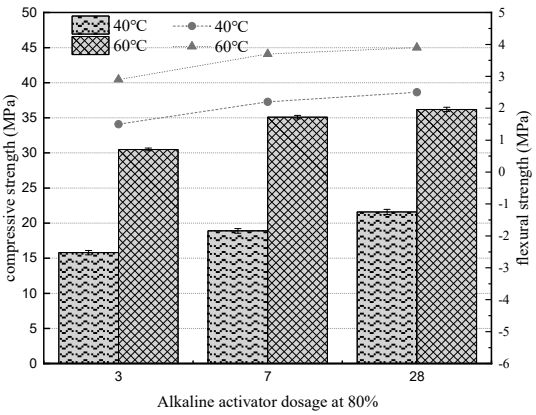


Figure 7. The strength of GSM with an alkaline activator dosage of 80%.

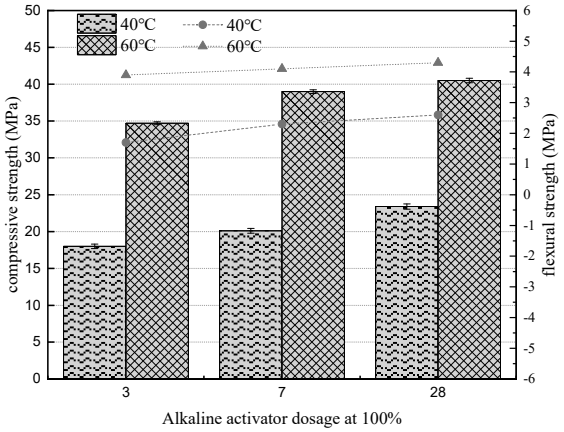


Figure 8. The strength of GSM with an alkaline activator dosage of 100%.

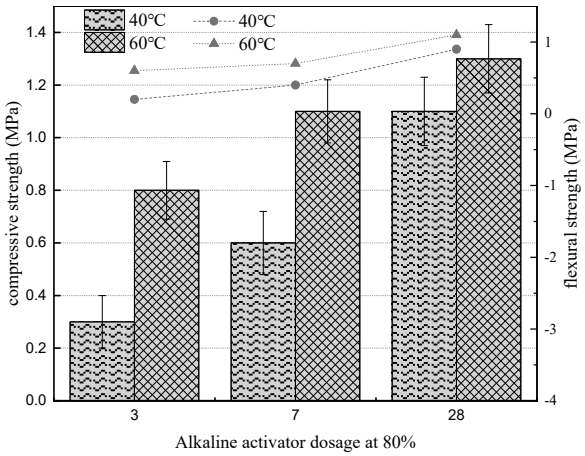


Figure 9. The strength of GAM with an alkaline activator dosage of 80%.

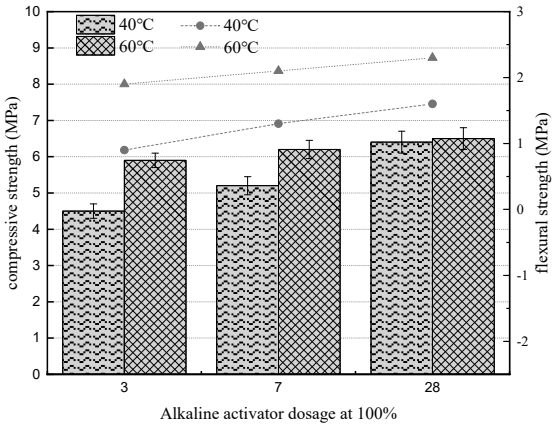


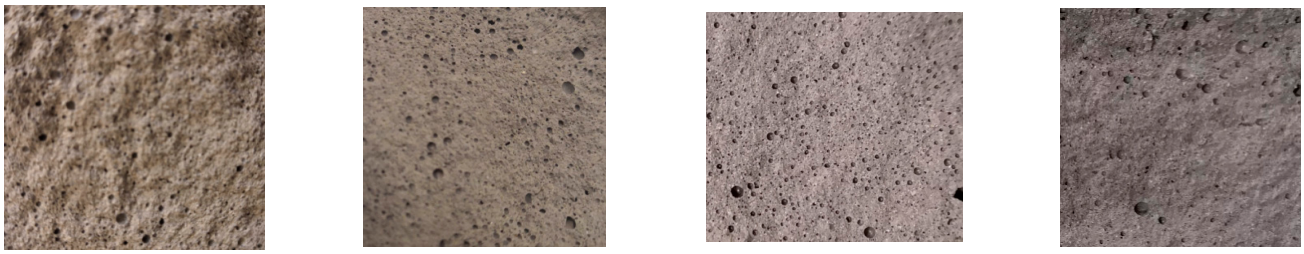
Figure 10. The strength of GAM with an alkaline activator dosage of 100%.

4.3. The Experimental Result of GAM with Double the Alkaline Activator Dosage

As can be seen from Figure 12, the bending strength and compressive strength of the specimens with a 150% dosage of the geopolymer material reached 4.2 MPa and 33.7 MPa in 28 days, respectively, which clarifies that the cementitious material is sufficient to make the aeolian sand particles form a compact structure. The strength of the specimens with a 200% dosage of the geopolymer material was slightly lower and depended on how well the aeolian sand combined with the geopolymer material. When the amount of alkali excitation is sufficient to fully activate the silicon oxides in the aeolian sand and fly ash [27],

enough amorphous aluminosilicate gel [12] will be produced as time goes on and enables all aggregates to be tightly bonded together to form a strong structure.

A few small differences from the pictures in Figure 11c,d can be seen; the amount of cementing material produced is relatively excessive in GAM-200, which accounts for the slightly better fluidity, but the insufficient aggregate and unbalanced specification made the strength decrease.



(**a**) GSM-80 (**b**) GSM-100 (**c**) GAM-150 (**d**) GAM-200

Figure 11. Damaged cross-sections of GSM and GAM.

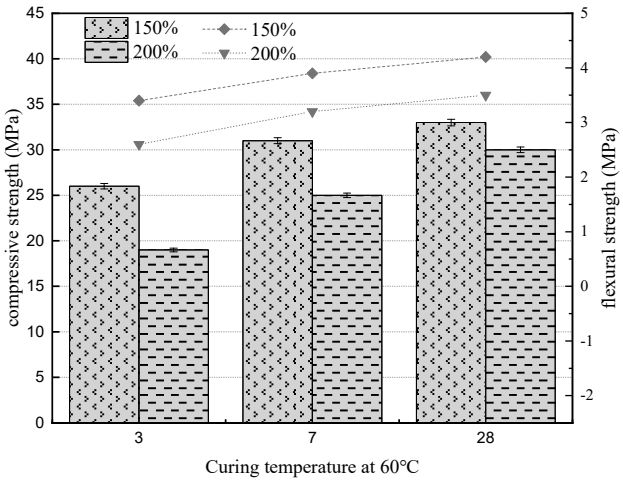


Figure 12. The strength of GAM with double the alkaline activator dosage.

4.4. The Experimental Result of the Fly Ash Geopolymer Aeolian Sand Concrete

It can be seen from Figure 13 that the 28-day compressive strength of GAC-20 is 33.4 MPa, which meets the design strength requirements, and its 7-day compressive strength improvement is more than 87%; meanwhile, the damage pattern diagram of GAC shown in Figure 14 verified that the surface cracks of GAC-20 are finer than others and the internal structure is relatively dense, so using a small amount of aeolian sand as a fine aggregate to prepare concrete can slightly increase the compressive strength. Due to the addition of too much aeolian sand, the internal particles of GAC-60 could not be tightly combined and quickly decomposed under the action of force. The strength of concrete with aeolian sand increases first and then decreases with the amount of aeolian sand [7,8], so the optimum amount of aeolian sand corresponding to the maximum strength of concrete needed to be obtained.

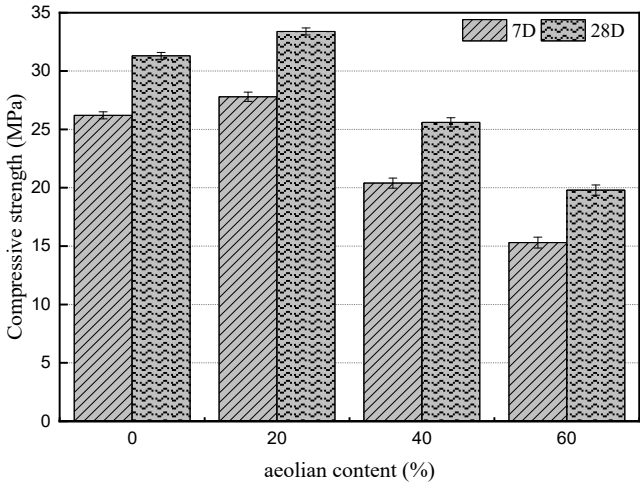


Figure 13. The compressive strength of GAC.



(**a**) GAC-0 (**b**) GAC-20 (**c**) GAC-40 (**d**) GAC-60

Figure 14. Damage pattern diagrams of GAC.

5. Conclusions

The experiments in this paper cover the mechanical tests of environment-friendly concrete with the application of aeolian sand and a fly ash-based geopolymer. A standard-consistency geopolymer mortar alkali activator dosage and setting time test was carried out first. Then, high strength GAM and a suitable cement–sand ratio were obtained. Finally, the strengthened GAC C30 was prepared, and the damage patterns of the mortar and concrete were compared and analyzed. Based on the results, the following conclusions can be drawn:

1. The optimum material ratio for preparing GSM with high strength was obtained. Given that the amount of geopolymer material was 0.5 times that of standard sand, the specimen with the largest 28-day compressive strength and flexural strength reached 40.5 MPa and 4.3 MPa, respectively, when the amount of alkali activator was improved to 100%.
2. A full aeolian sand mortar test without standard sand is rare, and the test results show high strength, which indicates that the geopolymer material is very effective in activating the active silicon oxide in aeolian sand and the resulting oligomer will eventually dehydrate and polymerize into a three-dimensional network structure. The most suitable ratio of GAM was achieved when the amount of geopolymer material was 0.75 times that of aeolian sand, and the corresponding 28-day flexural strength and compressive strength reached 4.2 MPa and 33.7 MPa, respectively, indicating that the fly ash-based geopolymer can effectively consolidate the aeolian sand and facilitate GAM internal compaction.
3. It is observed that the damaged surfaces of GSM-100 and GAM-150 are flatter and denser than those of the others, demonstrating that the aggregates are effectively bound together by the fly ash-based geopolymer, suggesting that with an appropriate amount of the geopolymer, the aeolian sand particles will be dissolved individually rather than encapsulated in clusters.

4. From 0% to 60%, the GAC with a content of 20% aeolian sand shows the best mechanical properties, with its 28-day compressive strength reaching 33.4 MPa. It provides a proper reference for the dosage of aeolian sand as a fine aggregate in environment-friendly concrete. The test results also show the compatibility of geopolymer materials with soil-containing materials that do not meet the requirements of the code.

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