

Article

Influence of Rock Block Content on Mechanical Properties of Coarse-Grained Fillers Stabilized with Fiber and Geopolymer

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Abstract: This study employed fiber and geopolymer to enhance the engineering performance of coarse-grained fillers. By conducting a series of comparative mechanical tests, the ideal mass mixing ratio design of geopolymer and fiber was investigated first. Then, the influence of rock block content on the mechanical properties of coarse-grained fillers stabilized with fiber and geopolymer was explored. The deformation damage characteristics of fiber- and geopolymer-stabilized coarse-grained fillers with different rock block contents were also discussed in the final test. The results show that the ideal mass mixing ratio of geopolymer for coarse-grained filler stabilization was 15% of dry fine-grained soil in weight and the ideal dosage and length of fiber was 0.4% of dry fine-grained soil in weight and 1.2×10^{-2} m. The compressive strength of fiber- and geopolymer-stabilized coarse-grained fillers shows a tendency to increase first, then decrease, and then re-increase with the increase in rock block contents. The best compressive strength and resistance to deformation were achieved when the rock block content was 30%. The failure mode of fiber- and geopolymer-stabilized coarse-grained fillers translated from shearing slip to vertical splitting as the rock block content increased. This study can provide a reference and support for the engineering application of coarse-grained fillers stabilized with fiber and geopolymer.

Keywords: coarse-grained filler; geopolymer; basalt fiber; rock block content; mechanical properties; failure characteristic



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1. Introduction

The quality of fillers as the key factor in determining their service performance is closely related to the long-term stability of railway subgrades [1–3]. Coarse-grained filler has the characteristics of high strength and stiffness, low compressibility, etc. [4,5]. The successful construction of China's Qinghai-Tibet Railway and Harbin-Dalian High-Speed Railway has proven significant breakthroughs in the theory and engineering application of coarse-grained fillers. So, they are currently recognized as the ideal railway subgrade filler. However, since their engineering properties are significantly affected by material composition and structural effects and natural coarse-grained filler may, more or less, have some problems like poor grading and poor uniformity, many unexpected problems such as excessive deformation and frost heave frequently appear in engineering practices [6–8]. For example, 41.5% of subgrades in the Harbin-Dalian High-Speed Railway appeared to have settlement deformation larger than 0.004 m during 2012–2016, and a maximum freezing height of 0.029 m was found on the Danda Railway, which far exceeds the values specified in the current regulations from 2015–2016 [9,10]. Furthermore, the current China Code for Design of High-Speed Railway (TB 10621-2014; Code for Design of High-Speed Railway. China Railway Publishing House: Beijing, China, 2015) issued by the Ministry of Railways of the PRC has just standardized the feasibility of coarse-grained filler applied in lines with a design speed of less than 300 km/h. Their applicability with a designed speed of higher than 400 km/h or a low temperature of less than $-40\sim 50$ °C is open

to discussion [11,12]. Particularly, after many years of operation, excessive deformation and frost heave problems are continuously re-exposed. Therefore, developing excellent, grading-broad railway subgrade fillers will be an urgent key issue for China's High-Speed Railway to solve.

The utilization of inorganic cementitious materials to change the internal structure of coarse-grained fillers can effectively improve their mechanical performance and enhance their integration [13–15]. Geopolymer is a green and sustainable inorganic cementitious material that originated from the depolymerization and polymerization of active silica-aluminate in an appropriate alkaline environment [16,17]. Their raw materials can be industrial solid wastes, such as blast furnace slag, fly ash, red mud, etc. [18]. They can form amorphous gels via a dense network of covalently polymerized mineral aggregates. Since their high strength and low shrinkage can enhance the bonding among coarse-grained filler particles, no significant deformation would emerge in railway subgrade even if they were subjected to loadings transferred from the superstructure's self-weight and long-term traffic loading, and their good denseness and low thermal conductivity can improve the resistance performance of permeability and frost heave. The utilization of geopolymer-stabilized coarse-grained fillers can not only meet the demands of safety performance such as seismic resistance and durability for high-speed railway construction but can also satisfy the feasibility in terms of resource acquisition and cost control. For the investigation of geopolymer material composition, Hoy et al. [19] conducted parallel comparison tests to demonstrate the feasibility of fly ash-based geopolymer-stabilized recycled asphalt pavement as a substitute for roadbed stabilization materials. Furthermore, Yang et al. [20] carried out a series of orthogonal experiment designs to study the mechanical properties and road performance of slag-fly ash-based geopolymer-stabilized silty soil. However, although important advances have been made in the research on the physical and mechanical properties of coarse-grained fillers, research on the static mechanical properties and failure mechanism of cementitious coarse-grained fillers is very limited, especially for these geopolymer-stabilized coarse-grained fillers [13,21].

Regarding the mechanical properties of coarse-grained soils, Vallejo et al. [22] and Irfan et al. [23] pointed out that the shear strength of coarse-grained fillers was related to particle size distribution, rock block content, rock block distribution, water content, etc. Shi et al. [24,25] and Zhang et al. [3,26] pointed out that their complex material composition and random structural effects resulted in significant difficulties and discreteness in conducting indoor or in situ experiments. Kong et al. [27] studied the dynamic behavior of coarse-grained materials with different fine contents after freeze–thaw cycles under multi-stage dynamic loading and determined how to obtain statistical experimental data with more reference value. Kuenza et al. [28], Tang et al. [29], and Ding et al. [30] further indicated that when the rock block content of coarse-grained fillers was less than 25%, the influence of rock block content on the mechanical properties of coarse-grained fillers could be almost negligible because rock blocks were suspended in fine-grained soils with large spacing, few contacts, and poor interaction. As the rock block content gradually increased, the probability of interaction between rock blocks inside coarse-grained fillers increased, and their peak shear or compression strength was significantly affected due to the joint action of the soil matrix and rock blocks. When the rock block content exceeded 70%, the interior of coarse-grained fillers was mainly composed of tight-contact rock blocks that play the role of the main skeleton, and the fine-grained soil matrix filled in the gaps among rock blocks. Their macroscopic mechanical behavior thus became controlled by the biting force and friction effect among rock blocks and did not change much with the increase in rock block content. Jin et al. [13] and Sonmez et al. [31] further pointed out that the compressive strength of coarse-grained fillers could be improved with the increase in cementitious material dosage when it was not exceeding a certain amount. Xuan et al. [32] systematically presented the structural properties of cement-treated construction and demolition waste as road bases. Some research showed that as the deformation increased, micro-cracks relatively concentrated around the area of rock blocks would appear first and take on a

phenomenon of contact surface climbing and expansion, and the maximum influence range of failure bands would be approximately twice the maximum particle size inside [33,34]. All of these documented studies proved that their material composition and structural effects were very important factors in the strength formation of coarse-grained fillers, regardless of whether they were strongly cementitious or not.

This study innovatively focuses on the mechanical properties of coarse-grained fillers affected by material composition and structural effect. Basalt fiber and geopolymer were employed as stabilizers to enhance the engineering performance of coarse-grained fillers. Their ideal mass-mixing ratio design was explored through a series of indoor tests. Then, the influence of rock block content on the mechanical properties and failure mechanisms of coarse-grained fillers stabilized with fiber and geopolymer was discussed fully.

2. Materials and Methods

2.1. Testing Materials

(1) Coarse-grained filler

The coarse-grained filler samples in this study were prepared with silty soil, rock blocks, and geopolymer binder. The soil matrix used in the test was collected from a construction site in the Jiangpu Campus of Nanjing Tech University. As shown in Figure 1a, this soil's texture is grayish brown, with the majority of particles being sand and silty and a few being clay particles. Its basic physical indexes are listed in Table 1. Considering the presence of a small amount of particles with a diameter greater than 2×10^{-3} m in this natural soil, the soil was dried and passed through a 2×10^{-3} m sieve to ensure sample uniformity. The gray rock blocks were taken from Shelu Quarry, Jiangning District, Nanjing, Jiangsu Province, as shown in Figure 1b. Their texture was hard and angular, belonging to limestone. The rock blocks had a dry density of 2530 kg/m^3 and a water absorption rate of 0.63%. Considering that the maximum allowable particle size should be less than 0.2 times the specimens' diameter, the maximum size of rock blocks was limited to not exceeding 2×10^{-2} m. Namely, the size of rock blocks used in the test ranged from 2×10^{-3} m to 2×10^{-2} m.

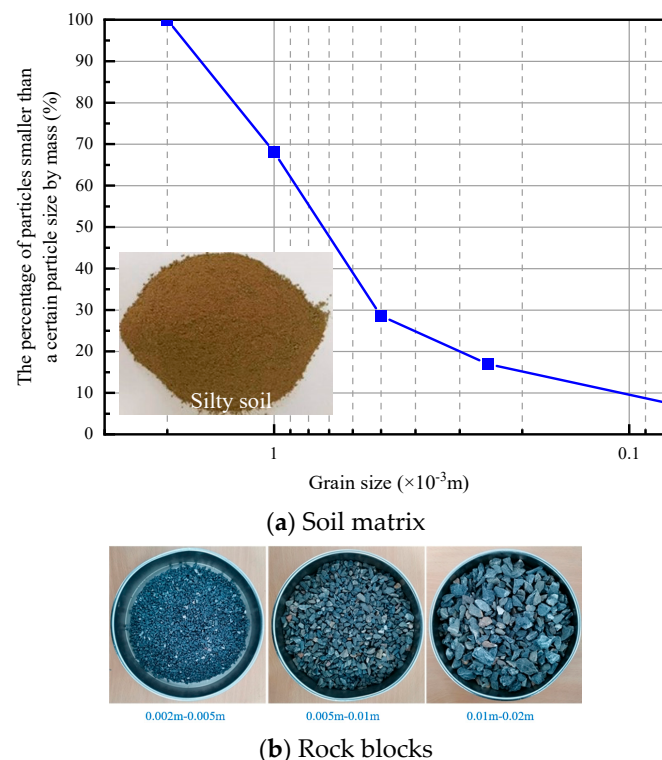
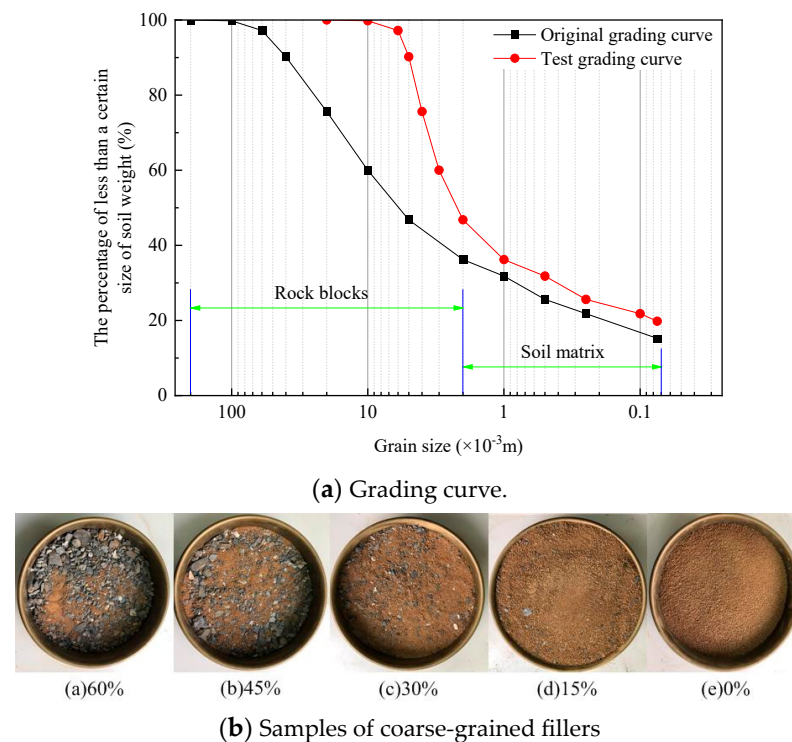


Figure 1. Soil and rock blocks.

Table 1. Physical parameters of the test soil sample.

Density (kg/m ³)	Liquid Limit /%	Plastic Limit /%	Plasticity Index /%	Optimum Water Content/%	Maximum Dry Density/(kg/m ³)
2685	34	18	16	12	1700

The grading of coarse-grained fillers was designed by a combination of similar grading and equivalent substitution methods, as shown in Figure 2a. Soil particles smaller than 2×10^{-3} m remained unchanged. The size distribution of rock blocks after scaling was $(2\text{--}20) \times 10^{-3}$ m. The samples of coarse-grained fillers with different rock block contents are shown in Figure 2b.

**Figure 2.** Design of coarse-grained fillers.

(2) Geopolymer binder

The geopolymer binder used in the test was prepared by metakaolin, quicklime, and sodium silicate, and its mass ratio was 3.6:1:0.8 [35]. The metakaolin was a white powder produced by Shengyun Mining Industry Co., Ltd. in Lingshou, Shijiazhuang, China. Its specification is AS2-1250 mesh, and its specific chemical composition is listed in Table 2. The quicklime (CaO) and sodium silicate (Na₂SiO₃) were taken from the laboratory of the College of Chemical Engineering, Nanjing Tech University. Their purity was chemically pure. The water glass suspension is a well-known solution. However, the basalt fiber would be mixed with the geopolymer binder first and then mixed with the silty soil in this study. If a water glass suspension were used, it would result in an uneven distribution of fibers in the soil. Furthermore, the concentration of sodium silicate in a water glass suspension is always low. If it were used, the dosage of water glass suspension might be very high and this high dosage might result in an excessive water addition. This would lead to differences in specimen preparation. Hence, this study did not use the water glass suspension as the component of the alkali activator and instead used pure sodium silicate powder. The quicklime was a white to off-white powder and the sodium silicate was white and powdery.

Table 2. Chemical composition of metakaolin.

Chemical Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	K ₂ O	Na ₂ O	SO ₃	TiO ₂
Mass ratio/%	57.16	37.71	1.28	0.13	0.09	0.55	0.01	0.01	3.06

(3) Basalt fiber

The displacement of fiber-reinforced coarse-grained fillers can be limited by the frictional resistance or biting force between fibers and the soil matrix. So, the basalt fiber was also used to improve the performances of coarse-grained fillers. The basalt fiber was manufactured by Shanghai Chenqi Chemical Technology Co., Ltd. (Shanghai, China) and was brown and had a metallic luster, with length specifications of 3×10^{-3} m, 12×10^{-3} m, and 18×10^{-3} m. The other length specifications used in this study were all prepared based on these specifications. The performance parameters of this fiber are shown in Table 3.

Table 3. Performance parameters of basalt fiber.

Diameter / μ m	Density /(kg/m ³)	Tensile strength/Mpa	Elastic Modulus/Gpa	Ultimate Elongation/%	Acid and Alkali Resistance	Melting Point/°C
13	2650	≥ 2000	90~110	3.5	$\geq 99\%$	1250

2.2. Testing Equipment

A universal electronic microcomputer-controlling testing machine was employed for the test. This machine can realize four kinds of closed-loop control, including force, deformation, displacement, and process. The control system is designed to work at a frequency as high as 50.0 Hz and a maximum test force of 20 kN. The test speed range is $(0.001\text{--}500) \times 10^{-3}$ m/min with an accuracy of $\pm 1\%$ ($(0.001\text{--}10) \times 10^{-3}$ m/min). The accuracy of deformation measurement is $\pm 0.5\%$. The control range of constant force, deformation, and displacement is 0.2–100%FS (FS is the full scale of the machine).

2.3. Testing Scheme

This study aimed to enhance the engineering performance of coarse-grained fillers with fiber and geopolymer and discover the influence of material composition and structural effects on their mechanical properties and deformation damage characteristics. Considering that the cementation effect of geopolymer binders on coarse-grained fillers mainly contributed to the stabilization of the fine-grained soil matrix, a series of compression tests on silty soil stabilized with the fiber and geopolymer were conducted first to explore their ideal mixing ratio design, and then a series of mechanical tests on coarse-grained fillers stabilized with fiber and geopolymer were carried out to investigate the influence of rock block content on their strength performance and failure mechanisms. The whole testing scheme was divided into two parts, as follows:

(1) Tests for the mixing ratio design of silty soil stabilized with fiber and geopolymer.

Generally, the mechanical performance improvement of geotechnical media is positively related to the dosage of cementitious materials [36]. However, many studies have also indicated that the strength of cemented soil did not always grow with the dosage of cement when it reached a certain level. The geopolymer binder is a new development in the trend of inorganic cement. It may have a captivating effect on soil stabilization and the same development trend with an increase in dosage. Therefore, cylindrical silty soil specimens stabilized with different mass mixing ratios of the geopolymer were prepared to investigate the optimum dosage of geopolymer for silty soil stabilization (Test I). Considering that basalt fibers can further improve the strength properties of geopolymer-stabilized silty soil, specimens with different fiber mixing ratios and fiber lengths were prepared to investigate the optimal mixing design (Test II and Test III). Three specimens were prepared

as parallel controls for each case to ensure the reliability of the experimental data. The detailed experimental schemes are listed in Table 4.

Table 4. Detailed experimental design for silty soil stabilized with fiber and geopolymer.

Steps	The Ratio of Geopolymer (%)	The Ratio of Basalt Fiber (%)	Lengths of Basalt Fiber (m)	Initial Water Content (%)	Curing Temperature (°C)	Curing Age (d)
I	10, 12, 14, 15, 16, 18	-	-	14	20	7
II	15	0.2, 0.3, 0.4, 0.5	1.2×10^{-2}	14	20	7
III	15	0.4	9×10^{-3} , 1.2×10^{-2} , 1.5×10^{-2} , 1.8×10^{-2}	14	20	7

(2) Tests for the influence of rock block content on the strength performance and failure mechanisms of coarse-grained fillers stabilized with fiber and geopolymer.

The influence of material composition and structural effects on the mechanical properties of coarse-grained fillers stabilized with fiber and geopolymer is ultimately controlled by the content of fiber, geopolymer, and rock blocks. Since the contributions of the fiber and geopolymer to their mechanical performance improvement were more prone to the soil matrix, the dosages of geopolymer and fiber were determined dynamically by the relative proportion of the fine-grained soil matrix to coarse-grained fillers in mass [8]. Namely, their mixing ratios were constantly relative to the soil matrix. To clarify the influence of rock block content on the strength performance and failure mechanisms of coarse-grained fillers stabilized with fiber and geopolymer, cylindrical specimens of coarse-grained fillers stabilized with fiber and geopolymer were prepared with various rock block contents (Test IV). The detailed experimental schemes are listed in Table 5.

Table 5. Detailed experimental design for coarse-grained fillers stabilized with fiber and geopolymer.

Steps	The Content of Rock Block (%)	The Ratio of Geopolymer (%)	The Ratio of Basalt Fiber (%)	Lengths of Basalt Fiber (m)	Initial Water Content (%)	Curing Temperature (°C)	Curing Age (d)
IV	0, 10, 20, 30, 40, 50, 60	15	0.4	1.2×10^{-2}	15	20	7

2.4. Specimen Preparation

The prepared specimens of fiber- and geopolymer-stabilized coarse-grained fillers with different rock block contents are shown in Figure 3.

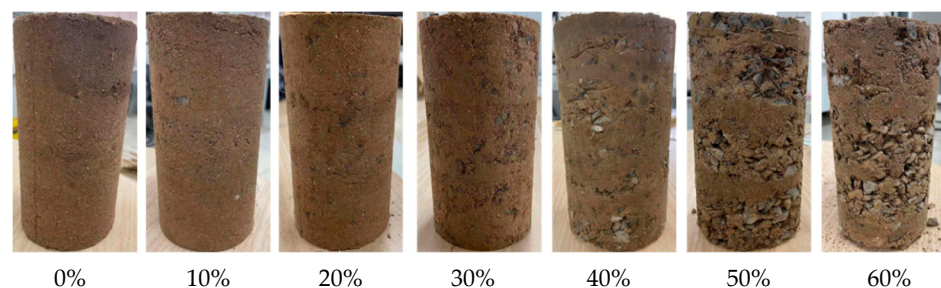


Figure 3. Specimens of fiber- and geopolymer-stabilized coarse-grained fillers with different rock block contents.

The stratified hammering method was used for specimen preparation. When preparing the fiber- and geopolymer-stabilized silty soil specimens, the required mass of silty soil, basalt fiber, and geopolymer binder was first calculated based on the dry density and

volume of the sample and then they were weighed and mixed fully. Considering that it was difficult for fibers to disperse in wet silty soil, the basalt fiber was mixed with the geopolymer binder first and then they were mixed with the silty soil. The water was determined by the optimum water content of the silty soil, which was increased by 2–3% to take into account the possible loss of water during the sampling. The water was added to the mixture of silty soil, fiber, and geopolymer binder several times and blended thoroughly. Then, these wet mixtures were poured into a cylindrical cast iron mold with the same sizes as the specimen size of 39.1 mm in diameter and 80 mm in height four times and compacted. The surface of each compacted layer was scraped before repouring the mixture into the next layer to ensure a better connection between the layers. The preparation procedure of fiber- and geopolymer-stabilized coarse-grained filler specimens was the same as the silty soil specimens overall. The one difference is that the required mass of silty soil, rock blocks, basalt fiber, and geopolymer binder was calculated based on the dry density and volume of the sample first and then weighed and mixed fully, and an additional amount of water as 1% of the dry rock blocks was considered, except for the silty soil achieving the optimum water content since the rock mass might absorb water from the soil matrix. The other difference is the sizes of fiber- and geopolymer-stabilized coarse-grained filler specimens, which were 100 mm in diameter and 200 mm in height. When specimens were prepared, all of them were numbered and placed in a curing box with constant temperature and humidity for 24 h, and then they were removed from the mold and continuously cured under the same conditions until the target age was reached.

3. Results and Discussion

3.1. The Optimum Dosage of Geopolymer for Silty Soil Stabilization

Figure 4 shows the stress–strain curves and unconfined compressive performance of silty soil stabilized with different dosages of the geopolymer. The error values given in this study were all standard deviations and were calculated using the following formula:

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n}} \quad (1)$$

It could be found that the unconfined compressive strength and tangential elastic modulus of geopolymer-stabilized silty soil increased first and then decreased with the increasing dosage of geopolymer. The peak compressive strength of geopolymer-stabilized silty soils reached 306.2 kPa when the dosage of the geopolymer was 15%. Therefore, this mixing ratio was the optimum dosage of the geopolymer for silty soil stabilization. The reason their compressive strength and elastic modulus increased first and then decreased might be that when the dosage of geopolymer was less than 15%, the polymerization products of the geopolymer binder could, on the one hand, improve the contact among soil particles and fill the micro pores in silty soils, making their structure more dense and stable, while on the other hand, their three-dimensional cemented network structure formed by the polymerization reaction could also improve the integrity of the soil. So, the higher the dosage of the geopolymer, the better the unconfined compressive strength of geopolymer-stabilized silty soils. However, it should be known that the increase in the dosage of the geopolymer for soil stabilization would also increase the quicklime content. Many studies have pointed out that quicklime was the culprit causing the shrinkage and cracking of cemented soils locally. So, excessive quicklime content would be bound to decrease the overall integrity of geopolymer-stabilized silty soils and decrease their strength performance. When the dosage of geopolymer was greater than 15%, the positive contribution of the geopolymer to the strength improvement of silty soils might weaken behind the adverse effects of quicklime. So, the compressive strength and tangential elastic modulus of geopolymer-stabilized silty soil decreased. To sum up, the optimal mass mixing ratio of geopolymer in silty soil stabilization should be 15%.

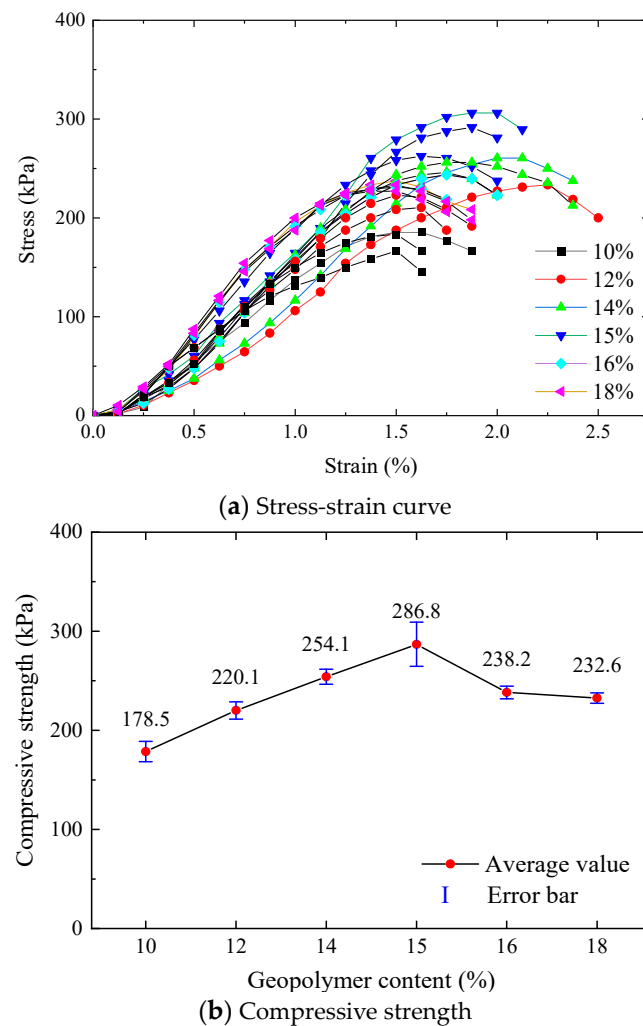


Figure 4. Unconfined compressive performance of geopolymer-stabilized silty soils.

3.2. The Optimum Mixing Design of Fiber for Silty Soil Stabilization

Figure 5a presents the unconfined compressive strength of geopolymer-stabilized silty soils with different dosages of basalt fiber. It could be observed that the unconfined compressive strength of fiber- and geopolymer-stabilized silty soils increased first and then decreased with the increasing dosage of fibers. When the dosage of basalt fibers was low, the sparse distribution of basalt fibers made it difficult to improve the mechanical properties of geopolymer-stabilized silty soil. As the dosage of fiber increased, the geopolymer-stabilized silty soil particles tightly wrapped the fibers after hardening and shrinking, generating a strong frictional effect at the interface between them, and the random distribution of these fibers enhanced the integrity of the soil and restrained the deformation of the soil, thereby improving the strength of the soil to a certain extent. When the dosage of fiber was greater than 0.4%, the agglomeration effect of fiber bundles was enlarged, which was not only inconducive to the mixing and shaping of geopolymer-stabilized silty soils but also may have decreased the restraining effect of fibers on the soil due to the large number of basalt fibers distributed along the failure surface locally when they were excessive. The weak contacts among fibers could have caused the discontinuity in microstructure, thereby leading to a decrease in the strength of the failure surface. Therefore, the dosage of fiber should be controlled within a certain range. According to the testing results shown in Figure 5a, when the dosage of fiber was 0.4%, the maximum unconfined compressive strength of fiber- and geopolymer-stabilized silty soils was achieved. So, the optimum dosage of fiber for soil stabilization should be 0.4%.

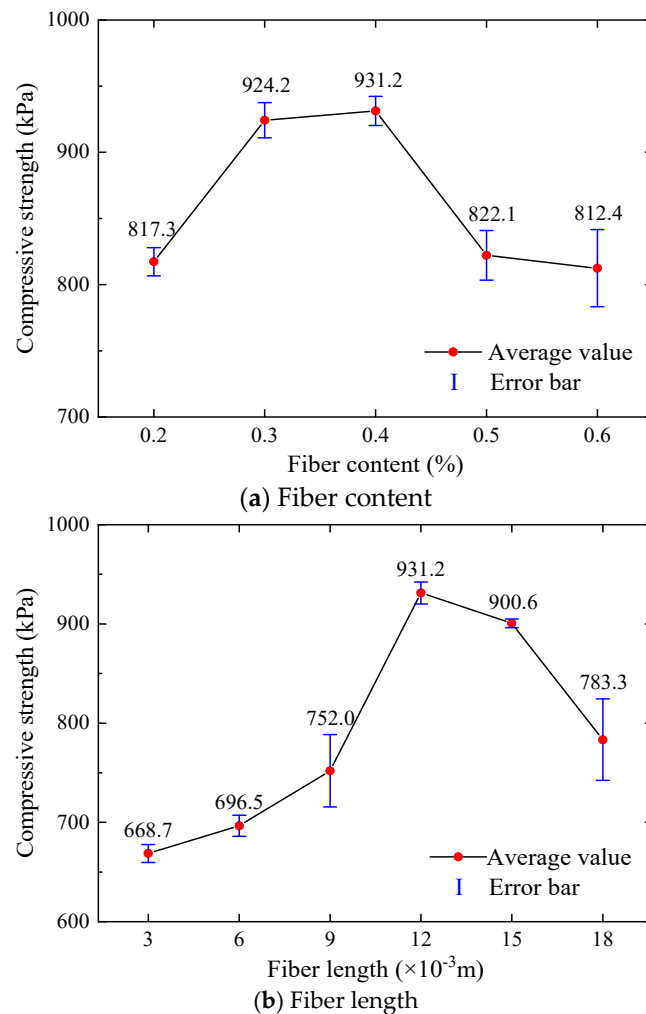


Figure 5. Unconfined compressive strength of fiber- and geopolymer-stabilized silty soils with different fiber contents and lengths.

Figure 5b presents the unconfined compressive strength of geopolymer-stabilized silty soils with different lengths of basalt fiber. It could be observed that the unconfined compressive strength of fiber- and geopolymer-stabilized silty soils increased first and then decreased with the increasing length of fiber bundles. This variation might be because when the length of fiber bundles was too short, the fibers embedded in the soil would not be able to bear more loads and could not effectively improve the strength performance of the soil. When the length of the fiber bundles was too long, these fiber bundles were more likely to entangle with each other and form agglomerations. These agglomerations led to an uneven distribution of fibers in geopolymer-stabilized silty soils, occupying a certain space in the soil, thereby resulting in an increase in the distance between soil particles and a decrease in bonding strength. Therefore, the bearing capacity of geopolymer-stabilized silty soil did not increase or even decrease when the fiber length exceeded a certain level. According to the testing results, the maximum unconfined compressive strength of fiber- and geopolymer-stabilized silty soils was achieved when the length of fiber was 12 mm. So, the optimum length of fiber for stabilized soil should be 12 mm.

3.3. The Influence of Rock Block Content on the Compressive Strength of Coarse-Grained Fillers Stabilized with Fiber and Geopolymer

Figure 6 demonstrates the stress–strain curves and unconfined compressive strength of coarse-grained fillers stabilized with fiber and geopolymer with different rock block contents. It was found that the compressive strength of coarse-grained fillers stabilized

with fiber and geopolymer showed a tendency to increase first, then decrease, and then increase. Their strength seemed to be mainly affected by the joint action of the soil matrix, rock blocks, and the cementitious interface between them. When the rock block content increased from 0% to 30%, the compressive strength of coarse-grained fillers stabilized with fiber and geopolymer increased continuously, which indicated that the increase in rock block content would enhance the skeleton effect of the inner structure and the ability of resistance to failure. When the rock block content increased from 30% to 40%, the compressive strength did not increase but rather decreased significantly, which might be due to the increase in the number of weak contact surfaces in cementitious coarse-grained fillers caused by the significant interaction between the soil matrix and rock blocks. When the rock block content further increased, the occlusal contacts between rock blocks became the primary bearers of loads. The strong biting force among rock blocks and the constraint effect of the cementitious soil matrix and fibers significantly strangled the shearing slip damage of cementitious coarse-grained fillers. So, the compressive strength of fiber- and geopolymer-stabilized coarse-grained fillers with a high rock block content reappeared to show an increasing trend. This conclusion is consistent with the research findings of Wang et al. [37] and Xu et al. [38]. Their maximum compressive strength of fiber- and geopolymer-stabilized coarse-grained fillers with a rock block content of 60% still did not exceed the value when the rock block content was 30%, indicating that the best compressive strength of fiber- and geopolymer-stabilized coarse-grained fillers would be achieved when the rock block content was at that level.

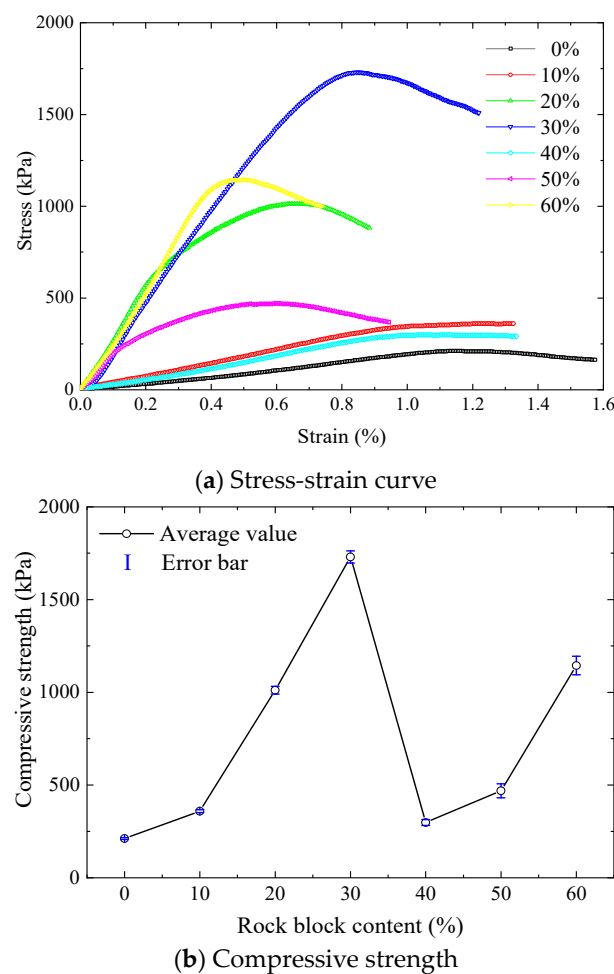


Figure 6. Unconfined compressive performance of coarse-grained fillers stabilized with fiber and geopolymer.

3.4. The Influence of Rock Block Content on the Elastic Modulus of Coarse-Grained Fillers Stabilized with Fiber and Geopolymer

Figure 7 illustrates the elastic modulus of coarse-grained fillers stabilized with fiber and geopolymer with different rock block contents. It could be found that the elastic modulus of coarse-grained fillers stabilized with fiber and geopolymer similarly showed a tendency to increase firstly, then decrease, and then increase. When the rock block content was less than 10%, there was only a slight increase in the elastic modulus. When the rock block content increased to 20%, a rapid increase in elastic modulus appeared. The reason for this change might be that the contributors of elastic modulus included both the soil matrix and rock blocks. When the rock block content reached a certain level, their particle contacts of “soil grains to soil grains” at a low rock block content turned into “soil grains to rock blocks” [33,34]. The high stiffness of rock blocks began to provide a more and more marked contribution to the anti-deformation performance improvement of fiber- and geopolymer-stabilized coarse-grained fillers, thereby resulting in a significant increase in the elastic modulus. However, this growth trend had not been sustained consistently as the rock block content further increased. Since the cementitious fiber-reinforced soil matrix was relatively more easily damaged with a relatively high rock block content, their contribution might be gradually weakened. It is well known that the utilization of inorganic cementitious materials might enhance the brittleness of soils stabilized by them [39]. Once the rock block content exceeded 30%, the thinned soil matrix was more likely to undergo brittle failure. So, their elastic modulus decreased rapidly. Of course, this failure also led to the particle contacts of “soil grains to rock blocks” turning into “rock blocks to rock blocks”. With the increase in rock block content, there were more and more instances of “rock blocks to rock blocks” contact. The high stiffness of rock blocks and the stronger and stronger occlusal contacts among rock blocks could be the primary contributors to resisting deformation [33]. So, the elastic modulus of coarse-grained fillers stabilized with fiber and geopolymer increased again with the rock block content. On the whole, the anti-deformation performance of fiber- and geopolymer-stabilized coarse-grained fillers was determined by the synergy of the soil matrix, rock blocks, and the cementitious interface between them, and since the stiffness of rock blocks was higher than that of the soil matrix, the elastic modulus of fiber- and geopolymer-stabilized coarse-grained fillers with a high rock block content was greater than that at a low level.

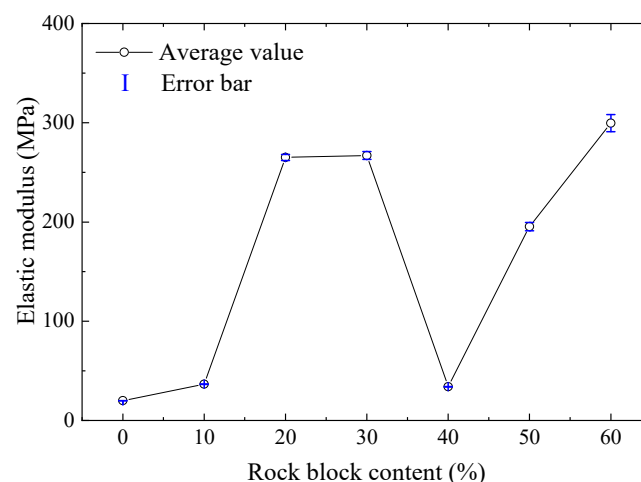


Figure 7. Anti-deformation performance of fiber- and geopolymer-stabilized coarse-grained fillers.

3.5. The Influence of Rock Block Content on the Failure Characteristics of Coarse-Grained Fillers Stabilized with Fiber and Geopolymer

Figure 8 represents the failure characteristics of fiber- and geopolymer-stabilized coarse-grained fillers with different rock block contents. It could be observed that with the increase in axial strain, the initial cracks gradually spread outward along the interfaces

between the soil matrix and rock blocks first and then developed in the cementitious soil matrix. When these cracks crossed, connected, and penetrated through the whole specimen, the specimen underwent an ultimate shear failure and was accompanied by a significant increase in volume. On the whole, with the increase in rock block content, the shear expansion effect was gradually amplified, and the damage pattern of these cementitious coarse-grained fillers changed from shearing slip failure to vertical splitting failure [8,9]. The higher the rock block content was, the easier the cracks initialized and expanded at the interfaces between the soil matrix and rock blocks. The strong biting force among rock blocks and the constraint effect of the cementitious soil matrix and fibers hindered micro-cracks from developing into larger cracks. So, the specimens were more fragmented when they failed.

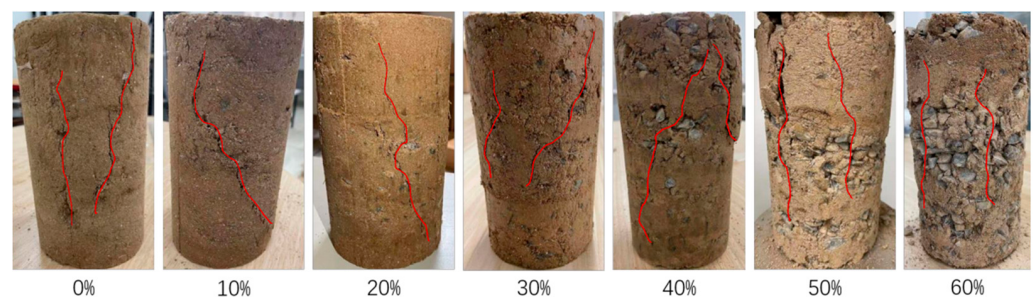


Figure 8. Failure characteristics of fiber- and geopolymer-stabilized coarse-grained fillers with different rock block contents (Red lines are cracks when specimens failed).

To sum up, the optimum mix proportion of coarse-grained fillers stabilized with fiber and geopolymer is shown in Table 6.

Table 6. Optimal ratio of materials.

Items	The Content of Rock Blocks (%)	The Ratio of Geopolymer (%)	The Ratio of Basalt Fiber (%)	Lengths of Basalt Fiber (m)
Values	30	15	0.4	1.2×10^{-2}

4. Conclusions

The mechanical performance and failure characteristics of coarse-grained filled stabilized with fiber and geopolymer were significantly related to their material composition and structural effect. This study first conducted a series of indoor tests to investigate the ideal mass mixing ratio design for silty soil stabilization and then discussed the influence of rock block content on their mechanical properties and failure mechanisms. The main conclusions obtained are as follows:

- (1) The ideal mass mixing ratio of geopolymer for coarse-grained filler stabilization was 15% of dry fine-grained soil in weight, and the ideal dosage and length of fiber was 0.4% of dry fine-grained soil in weight and 1.2×10^{-2} m.
- (2) The compressive strength of coarse-grained filled stabilized with fiber and geopolymer showed a tendency to increase first, then decrease, and then increase again with the increase in rock block content. Their best compressive strength and resistance to deformation were achieved when the rock block content was 30%.
- (3) The strength performance of coarse-grained filled stabilized with fiber and geopolymer was mainly affected by the joint action of the soil matrix, rock blocks, and the cementitious interface between them. Their ability to resist deformation was controlled by the synergy of these three.
- (4) The initial cracks gradually spread outward along the interfaces between the soil matrix and rock blocks first and then penetrated through the whole specimen. The

- failure pattern of fiber- and geopolymer-stabilized coarse-grained fillers changed from shearing slip failure to vertical splitting failure with the increase in rock block content.
- (5) Although this study investigated the macroscopic mechanical properties of fiber- and geopolymer-stabilized coarse-grained fillers using a series of indoor tests and can provide a reference for their engineering application and broaden the scope of filler demand, their intrinsic enhancement mechanism and destructive mechanism were still not able to be fully disclosed by objective experimental evidence. Further research on fiber- and geopolymer-stabilized coarse-grained fillers considered from a microscopic point of view is very necessary in the future.

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