Effects of soil grading and sand content on soil-cement properties

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Abstract: The effect of soil-cement characteristics, unconfined compressive strength (UCS), dry density, and water absorption on the soil grading and sand content of six groups (natural soil, \( \leq 2 \) mm, \( \leq 1 \) mm, \( \leq 0.5 \) mm, \( \leq 0.25 \) mm, and \( \leq 0.075 \) mm) of soil-cement block was studied. The results showed that the characteristics of soil-cement mixed with sand were influenced by soil grading. Better characteristics of soil-cement soil were obtained when the soil particle sizes of soil-cement were less than 0.075 mm of mixed sand. Every soil particle size has optimal sand content. Results showed that the optimal sand content of natural soil is 40%, whereas those of other soil particle sizes are all 55%. The results also showed that the UCS of 28-day ages is 1.79 times that of natural soil for soil-cement mixed with sand of \( \leq 0.075 \) mm particle group, whose water absorption is 50% that of natural soil as the optimal sand content. Finally, the study of clay content showed that there exists an optimal clay content for various size groups, namely, 9.12%, 7.06%, 8.08%, 9.05%, 11.36%, and 13.60% for natural soil, \( \leq 2 \) mm, \( \leq 1 \) mm, \( \leq 0.5 \) mm, \( \leq 0.25 \) mm, and \( \leq 0.075 \) mm, respectively.

1. Introduction

Soil-cement is a strengthening mixture that is made up of various materials, such as soil, cement, water, and other mixtures. In recent years, soil-cement has been widely applied in soft soil foundation treatment, highway engineering, and anti-seepage curtain and has achieved good economic and environmental benefits [1–3]. Currently, soil-cement has been widely applied in the South–North Water Transfer Project in order to deal with soft soil foundation. The principal factors, which are advantageous characteristics of soil-cement, are as follows: high strength, low compressibility, low permeability, low cost, and convenient construction.

Scientific research was carried out worldwide based on a number of engineering applications of soil-cement. Zhou et al. [4] postulated that the strength of soil-cement can be increased by 38% when 8% natural pumice was added, which is especially beneficial in anti-freezing and is suitable for use in cold regions. The mechanical properties of glass fiber and fly ash soil-cement were studied by orthogonal test [5]. The results showed that age and cement content have significant influence on the unconfined compressive strength (UCS) of soil-cement. Otherwise, we do not need to improve the UCS of soil-cement with fly ash and glass fiber. The UCS of soil-cement can be increased by 93% as 3% superfine particles were added [6]. However, this approach is applicable only to muddy soil, and the strength is not high, which can only be satisfied with the requirement of the strength of the

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modified soil generally. Adding steel fiber does not improve the UCS of soil-cement [7]. The addition of silicon powder and polypropylene fiber increases the UCS of soil-cement [8]. However, adding silicon powder to soil-cement increases soil UCS. On the other hand, this mixture is more expensive than polypropylene fiber; thus, this mixture is inappropriate in an economic sense because this will increase the cost of soil-cement. Therefore, one of the key technical problems to be solved is how to select an additive that not only meets the needs of strength but also reduces the cost of soil-cement in the current engineering.

Sand as an additive is cheap and produces better improvement effect, which caused immense attention worldwide [9–11]. However, the current studies are limited to the influences of the strength after sand mixing with soil [12, 13] using a grading (< 2 or < 0.075 mm) of the soil.

It mainly has two aspects adding an additive in soil-cement. On the one hand, additive can improve soil-cement strength by solidifying the soil-cement. On the other hand, it can fill the gap of the soil-cement to make the latter compact to enhance its strength. Therefore, reasonable grading of soil can minimize soil-cement gap, thus improving the strength of cement-soil. The influences of soil-cement strength on the soil grading and sand used as an additive have not been found in reports. Therefore, in this article, research on soil-cement characteristics was carried out for various particle sizes and grading of natural soil (≤ 5 mm, ≤ 2 mm, ≤ 1 mm, ≤ 0.5 mm, ≤ 0.25 mm, and ≤ 0.075 mm) through indoor test.

2. Experimental program

2.1 Materials

2.1.1 Cement

In this research, the composite binder, P.C32.5 cement, was employed. Hence, the cement content in the mixture is 10%. The physical properties of P.C32.5 cement are presented in Table 1.

| Specific gravity/ g/cm³ | Specific surface/ m²/kg | Initial setting time/ min | Final setting time/ min | UCS at 3days/ MPa | UCS at 3days/ MPa |
|------------------------|-------------------------|---------------------------|-------------------------|-------------------|-------------------|
| 3.02                   | 345                     | 165                       | 420                     | 17.6              | 37.2              |

2.1.2 Sand

The fine aggregate was river sand with 1.18 of fineness modulus from Xinmi City, Henan Province. The specific gravity and bulk density are 2.68 and 1.57 g/cm³, respectively. The sand grading is shown in Fig. 1.
2.1.3 Soil
The soil was silty clay with a density of 2.64 g/cm$^3$ from Xinzheng City of China. The liquid limit and plastic limit are 25.41% and 11.38%, respectively. The soils were smashed to pass a 5 mm sieve in the laboratory. Given that most of the soils taken from the sites contained a large amount of water, they were dried in natural condition until the weight was constant. Then, the soils were divided into six groups by the soil mesh, were passed through sieve No. 500 (500 mm), and marked as natural soil group. Subsequently, soil particles were crushed by a crusher and divided into five grades. The soil particles that passed through sieves No. 200 (2 mm), No. 100 (1 mm), No. 50 (0.5 mm), No. 25 (0.25 mm), and No 7.5 (0.075 mm) were labeled as S500, S200, S100, S50, S25, and S7.5, respectively (GB/T50123-1999).

The soil was divided into different particles by LS13320 laser granulometer produced by Netherlands, which are made up of light workbench and different processing module (Universal Liquid Module, Aqueous Liquid Module, Tomado Dry Power System and Micro Liquid Module, etc.). Based on the principle of light scattering, statistical size distribution of particles which were suspended in liquid or powder was measured. Universal Liquid Module was used in this study, the experimental process are as follows: Specimens were firstly added in water channel after the instrument running. After specimens were scattered in water channel and passed to the light workbench by the pipe (Fig. 2), it was measured in the light workbench. Lastly, the output was gained automatically at the end of test. These grading are also shown in Fig. 1.

![Fig. 2 Laser granulometer](image)

2.2 Experimental research
Compaction (light) experiments were performed on soil-cement, which is made up of 10% cement content and 90% soil. The relationship between water content and dry density is shown in Fig. 3.

![Fig. 3 Compacting curves of different particle sizes of the soil](image)

The compaction experiment results show that the optimal soil moisture content is approximately
11.3% for the soil-cement of S500, S200, and S100. The optimal soil moisture content is about 13.6% for S50, S25, and S7.5. Using the methods described above, the best experiment plan can be achieved for soil-cement.

Therefore, the optimal water content is 11.3% for S500, S200, and S100, whereas the optimal water content is 13.6% for S50, S25, and S7.5. The specimens were made in cube for S500, S200, S100, S50, S25, and S7.5, with 10% cement content, in which sand content is respectively 0%, 20%, 40%, 55%, 65%, and 75% (in mass); experiment parameters are shown in Table 2.

| groups  | S500 | S200 | S100 | S50 | S25 | S7.5 |
|---------|------|------|------|-----|-----|------|
| Water content (%) | 11.3 | 11.3 | 11.3 | 13.6 | 13.6 | 13.6 |
| Cement content (%) | 10 | 10 | 10 | 10 | 10 | 10 |
| Sand content (%) | 0, 20, 40, 55, 65, 75 | 0, 20, 40, 55, 65, 75 | 0, 20, 40, 55, 65, 75 | 0, 20, 40, 55, 65, 75 | 0, 20, 40, 55, 65, 75 | 0, 20, 40, 55, 65, 75 |

As soon as the mixing was finished, soil-cement mixtures were poured fully into a mould with 70.7 mm³. The specimens were stored in the curing room at 20±2 °C and 60±5% relative humidity and demolded after 48 h. After demolding, the specimens were stored in the curing room up to 7 and 28 days. Unconfined compressive strengths of soil-cement were tested with a microcomputer-controlled electric hydraulic universal testing machine (max measuring range of 30t). The loading rate is 2 mm/min.

3. Results and discussion

3.1 Sand content

As shown in Fig. 4, at 28 days, soil-cement specimens showed that UCSs were 5.25, 5.18, 5.21, 5.45, 4.85, and 4.52 MPa for natural soil, S200, S100, S50, S25, and S7.5 groups respectively, when soil-cement was mixed without sand. This finding indicates that UCS also gradually reduced with the decrease of particle sizes. The smaller the soil particle size is, the more the soil particles tend to be homogeneous and thus the grading becomes worse. With the increase of sand, the UCS for soil-cement of each group first increases and then decreases. Therefore, this value is an optimal value of sand content.

![Fig. 4 Relationship between UCS and sand content](image-url)

The optimal sand content of natural soil is different from other groups at the peak value of UCS. The optimal sand content of the natural soil is 40%, whereas the optimal sand contents for S200, S100, S50, S25, and S7.5 are all 55%. At 28 days, soil-cement specimens showed that UCSs were 6.21, 7.22, 7.98, 8.45, 9.87, and 11.12 MPa for natural soil, S200, S100, S50, S25, and S7.5 groups, respectively, in optimal sand content cases.

With other things being equal, with the increase of sand content, the smaller the particle sizes and the more the UCS increases.
The relationship between the ratios of UCS and sand content is shown in Fig. 5 (the ratios of UCS at 28 days for various groups between sand content of 20%–75% and 0). With increase of sand content, the ratio of UCS changes from 1.2 to 2.5. The ratio of UCS has more variation for the S7.5 group, which is 2.5 without sand. The specimens in descending order are as follows: S25, S50, S100, S200. Natural soil (S500) also changes a little, and the ratio of UCS is 1.2 without sand.

Basing on the reinforcement mechanism of soil-cement, we determined that the soil is a mixing system that is composed of soil particles of different composition. The strength of the soil is mainly decided by the connection strength between soil particles. When sand is added to soil-cement, whose particles are fairly small, then cement is seen as a cementing material and sand as an aggregate. Cement was formed by sand particles as the center through cement hydration and hardening. The soil particles are surrounded to form a stable structure. Thus, the strength of soil-cement mixing sand is enhanced. However, if the soil particles are too large, such as natural soil, the soil particle content of the groups with size of more than 0.25 mm is 40%, and the soil particle content of the groups with size of more than 0.25 mm is about 35%. Therefore, a large gap exists between sand and soil of soil-cement. Therefore, soil-cement is imperfect and has low strength increase.

![Fig. 5 Histograms between the ratio of UCS and sand content](image)

3.2 Clay content

Clay content is one of the important parameters of soil-cement properties. The relationship between UCS and clay content is shown in Fig. 6. With the increase of clay content, UCS first increases and then decreases. Optimal clay content values were found at the peak value of UCS, which are 9.12%, 7.06%, 8.08%, 9.05%, 11.36%, and 13.60% for S500, S200, S100, S50, S25, and S7.5, respectively, changing from 7%–13.6%. Therefore, with the decrease of the soil particle sizes, the optimal value of clay content tends to increase, and UCS increases gradually.
Fig. 6 Relationships between UCS and clay content

3.3 Dry density
Fig. 7 describes the relationship between dry density and sand content. With increase of sand content, the dry density of various groups first increases and then decreases. The optimal value of sand content results in a dry density max value. The optimal value of natural soil is 40%, whereas that of other groups is 55%, which is similar to the change of UCS.

As seen from the change of dry density of various groups, with increase of sand content, the dry density of natural soil changes a little, and dry density increases from 17.53 to 18.39. As sand content changes from 0% to 40%, dry density increased by 4.9%. Significant change is found in group S7.5 in various groups. Specifically, the dry density increases from 17.43 to 19.41. As sand content changes from 0% to 55%, dry density increased by 11.4%. As seen from the change of soil particle sizes, group S7.5 is 1.06 of natural soil for dry density, which is the optimal value of sand content cases. This finding shows that with the increase of sand content, the smaller the particle sizes, the better the grading of sand mixing with soil and the greater the compactness. Dry density and UCS reach the maximum at the same time. Moreover, the relationship between dry density and UCS is shown in Fig. 8. The correlation of both is larger, with the correlation coefficient between 0.859 and 0.986. The value becomes closer to 1.0 with the decrease of soil particle sizes. Therefore, after mixing sand in soil-cement, the better the grading of the mixture, the larger the value of dry density and UCS.
3.4 Water absorption

Another parameter that can be used to determine the property of soil-cement is water absorption. The higher the water absorption was, the larger the void of soil-cement was. The greater the imperfection was, the lower the strength of soil-cement was. On the contrary, the lower the water absorption was, the smaller the void of soil-cement was. The greater the perfection, the higher the strength of soil-cement. After 28 days curing, all the specimens were tested by immersing them in water for 24 h and drying them in an oven. The results of water absorption and sand content are depicted in Fig. 9.

Similar to the relationship between strength and sand content, water absorption also showed the best values at the optimal sand content (i.e., 20.1%, 16.65%, 15.35%, 13.41%, 11.23%, and 10.05% for natural soil, S200, S100, S50, S25, and S7.5, respectively). Therefore, dry density and UCS of soil-cement were enhanced when mixed with sand, whereas water absorption of soil-cement was reduced. Consequently, the mechanical properties of soil-cement increased. As seen from water absorption of various soil-cement groups, the water absorption value of group S7.5 is half of that of the natural soil group, but it still showed better properties.

UCS, dry density, and water absorption can be obtained in perfect soil-cement properties for fine particles compared with coarse particles.

4. Conclusions

Based on the experimental researches of soil-cement characteristics for groups particle sizes (natural soil, ≤ 2 mm, ≤ 1 mm, ≤ 0.5 mm, ≤ 0.25 mm and ≤ 0.075 mm), which are UCS, dry density and water absorption, the associated conclusions can be obtained:
1. The UCS of various groups soil-cement first increases and then decreases with increase of sand content, there is an optimal sand content.
2. Clay content is one of important factors influencing UCS of soil-cement mixing sand, in various groups soil-cement, group S7.5 showed optimal properties, whose clay content is 13.6%.
3. There is a strong relationship between UCS and dry density, and the correlation coefficient is from 0.859 to 0.986.

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Conflict of Interest:
The authors confirm that this article content has no conflict of interest.

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