LABORATORY MODEL DESIGN FOR DEEP SOIL MIXING METHOD

Scientific paper

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Abstract: One of the most critical problems in the construction sector is the inadequate bearing capacities of subsoils. To solve this problem, various soil improvement methods are employed. Soil improvement is defined as the improvement in soil properties to the desired level by using various methods when the soil is not suitable for superstructure loads. Various types of soil improvement methods exist, and their application depends on the construction site, soil properties, earthquake zone, application time, and cost. One of the most widely used methods recently is the deep soil mixing method. In this study, a laboratory-scale deep soil mixing device is first developed; subsequently, the effects of injection pressure, mixing time, and dosing parameters on application are investigated. Deep soil mixing columns are prepared using different injection pressures, mixing times, and dosages and then subjected to the unconfined compression test. Results show that the effects of injection pressure, cement dosage, and mixing time on the unconfined compressive strength of deep soil mixing samples vary based on the initial soil properties.

Keywords: Soil Improvement; deep soil mixing method; laboratory-scale device.

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1 INTRODUCTION

Owing to the increase in human population worldwide, the demand for new settlements has increased as well [1]. However, the soil conditions in areas allocated for construction may not always be appropriate, and certain phenomena can be encountered such as low soil bearing capacity, excessive settlement potential, and slope stability problems. One of the major problems in the construction sector is the insufficient soil bearing capacities of subsoils. To enable safe and economical constructions on problematic areas, appropriate foundation systems must be designed [2–4]. In this context, various soil improvement methods have been used, the selection of which can be done according to the subsoil type, earthquake zone, time, and cost [4–6]. One of the most widely used methods, in recent years, is the deep soil mixing (DSM) method [7,8]. It is a typical ground improvement method that can be used to improve the bearing capacity and stability, reduce differential settlements of foundations, and improve the shear strength of soft soils [9–12]. DSM has been investigated extensively, and its quality control and quality assurance elucidated via laboratory tests [13–20]. In addition, numerous reports regarding DSM have been published through European research programs [21, 22]. DSM involves strengthening the physical and mechanical properties of soil [23] by injecting a cement–water mixture into the soil while mixing it using blades. In Turkey, the application of DSM as a soil improvement method has increased recently [24].

During DSM, soil is mixed onsite with different binders that react chemically with groundwater. It is an in-situ admixture stabilisation method that uses cement and/or lime as binder [20]. The resulting stabilised ground material exhibits higher strength, lower permeability, and lower compressibility compared with natural soil [15,25]. Soil mixing can be performed via one of the two basic methods: dry and wet [26]. Dry soil mixing method is employed in case of saturated soils with high moisture content, such as clay or organic soils. Wet soil mixing method increases strength without relying on the natural moisture of the soil. Dry soil mixing is preferred when the natural moisture content of the soil exceeds 60%, whereas wet soil mixing is preferred when it is less than 40% [27,28]. Wet soil mixing is advantageous over other soil improvement methods; hence, it is used extensively worldwide [29].

Previous studies based on analytical and numerical methods show an increase in the soil bearing capacity and a decrease in the settlement level by DSM method at weak soil conditions. The strength characteristics of soils improved via DSM differ according to certain factors, such as the physical and chemical properties of the soil to be improved, binding material, additives, treated water, application technique, and mixing conditions [15,30]. Tests conducted on DSM columns in the soils improved using cement mixture indicate that increasing the cement content (dry weight of cement/dry weight of soil) and curing time increases the column strength [30, 31]. In addition, horizontal–vertical movements were less likely to occur in swollen soils improved via DSM than in non-improved soils [32]. DSM is also known to maintain soil displacements within the desired limit values [33–35]. Furthermore, compared to other mixing methods, DSM incurs a lower cost, increases the soil bearing capacity by a higher margin, and requires less time in application [36, 37]. It is widely used owing to its low application cost, low environmental damage, and non-requirement for water drainage [38].

The aim of this study is to design a system for simulating DSM in the laboratory to facilitate extensive investigation into DSM performed worldwide. The system is developed using local resources, and the corresponding details are presented herein. Subsequently, DSM was modelled based on laboratory conditions. Additionally, the effects of parameters such as injection pressure, mixing time, and cement dosage were investigated, and the results are presented.

2 DSM CONSTRUCTION PRINCIPLES AND EQUIPMENT

In DSM, the track drill is positioned based on the determined column coordinates, and the mixer shaft reaches the desired depth by breaking the soil. A DSM column is prepared by injecting a cement–water mixture into the soil (Figures 1 and 2).

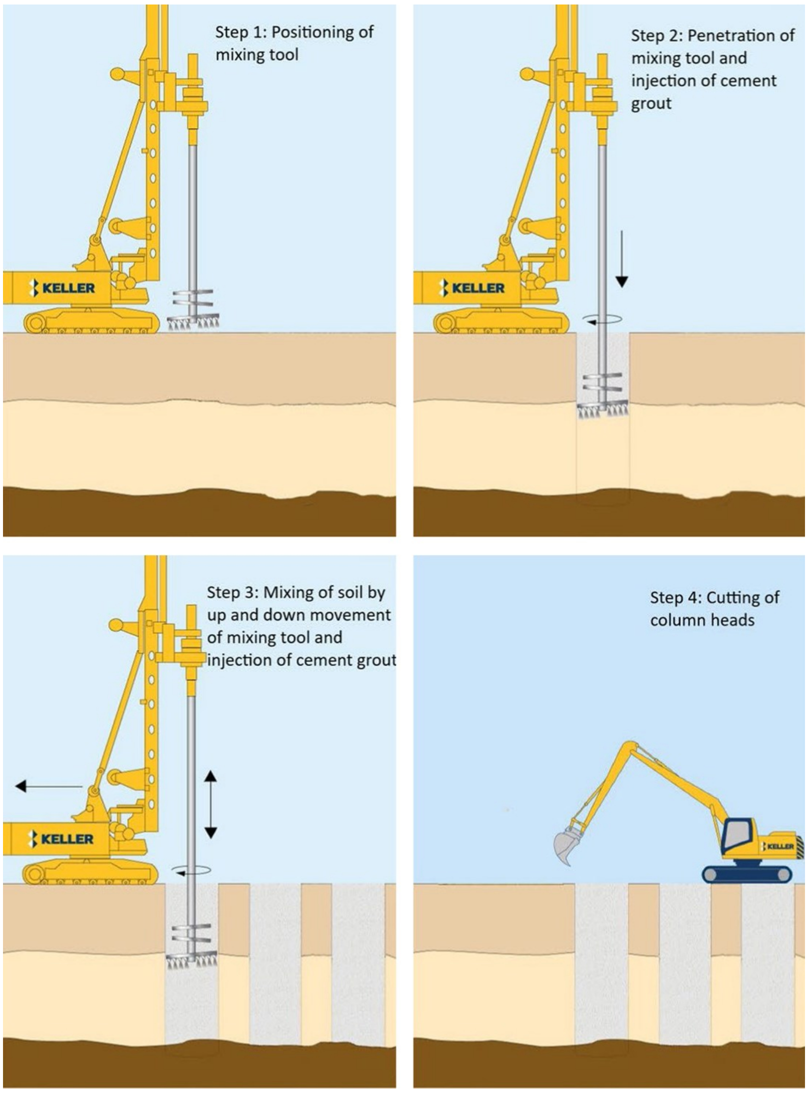

Figure 1 Application stage [39]

Figure 2 Application of wet DSM [40]

In DSM, the soil is thoroughly mixed using large-scale single or multi-axis augers to form a column or a panel of improved material by injecting the prepared mixture at the depth of improvement. The mixer shaft is pulled up from the desired depth while mixing the soil, and the mixture is injected during ascending/descending phases of the shaft, which results in its mixing with the soil [24]. Consequently, the engineering properties of the soil are improved by the increase in the soil strength and reduction in its compressibility and permeability. Previous studies indicate that the most preferred binders for the mixture are cement [41–43] and lime [44–46], although slag or other additives can be used as well. Onsite-mixed columns can be prepared singly, in groups, in single rows for walls, or in specific moulds to form cells. This process can be used to create impermeable curtain walls on coarse-grained soils, build excavation support walls, and stabilise liquefiable soil.

3 EXPERIMENTAL STUDY

In soil improvement methods, the application parameters must be determined prior to the application of the methods. In particular, no limit or interval is defined in the regulations for parameters such as injection pressure, cement dosage, and the duration of DSM application. Depending on the field conditions, these application parameters can be applied incorrectly, resulting in both time loss and incomplete or unsatisfactory soil improvements. In this study, a device that can create deep mixing columns in the laboratory was designed, as shown in Figure 3, using which the soil improvement parameters can be identified by simulating field conditions in the laboratory.

Figure 3 Laboratory-scale DSM system

DSM and jet grouting methods can be performed at laboratory scales using this device, and pile foundations can be simulated via a simple header change. In addition, this device can be used to simulate other improvement methods, such as the stone column, with slight modifications. Furthermore, by adding different materials to the soil sample (fibre, basalt fibre, etc.), the soil behaviour can be analysed. Drawings of the designed device are shown in Figure 4.

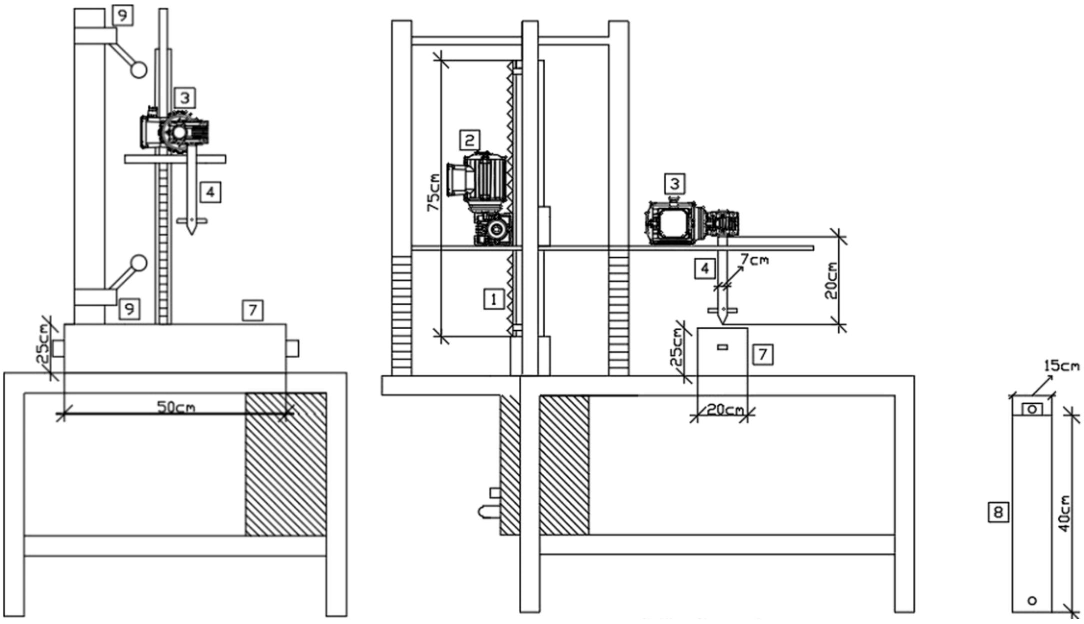

Figure 4 Test machine design drawings

A depth motor is attached onto the gear and operated by the driver. The system ascends and descends at the desired speed via the driver's manual operation. When the system realises that it has reached the lowest point, it ascends by changing the mixing direction via two switches (at the top and bottom). Once the system reaches the upper switch, it stops automatically. The mixing motor is connected to a mixer blade comprising at least two injection holes and is operated by the driver. It can rotate the helical shaft to the injection hole at the desired speed. To simulate various soil improvement methods and pile foundations, head shafts (agitator blade, injection shaft, helix shaft etc.) suitable for the mixing engine were designed. Subsequently, a cylindrical water/cement mixing chamber and a mixing vessel for placing the soil sample were built. The system is designed in Eskisehir Technical University (ESTU) so named as ESTU Laboratory Scale DSM system. The system is low maintenance and can be improved and modelled easily while being economical, with a production cost of approximately $1.900.

3.1 Soil Properties

Soil samples were obtained from various regions of Eskisehir province, Turkey. The geotechnical properties of Eskisehir soils are typically inadequate and thus require improvement to sustain superstructure loads. In particular, owing to the loose and soft structure of the soils, they are defined as poor alluvial. For this study, soil samples were obtained from Odunpazarı, Tepebaşı, and Alpu districts, all of which exhibit a high construction potential with several projects in progress therein. First, the index properties of the soil samples were determined; subsequently, their strength characteristics were determined via unconfined compression tests conducted on undisturbed samples. All tests were performed according to the ASTM standards. The index and strength properties are tabulated in Tables 1 and 2, respectively.

Table 1 Index properties of soil samples

Sample Areas	Granulometric Content (%)			Atterberg Limits (%)			Water Content (%)	Unit Weight (gr/cm^3)
	Gravel	Sand	Silt & Clay	LL	PL	PI	ω	γ
Odunpazarı	27.40	37.20	35.40	28.6	15.3	13.3	12.60	2.07
Tepebaşı	2.89	60.83	36.28	37.0	20.0	17.0	24.17	1.93
Alpu	0	72.54	27.46	48.0	22.0	26.0	18.00	1.81

Table 2 Strength properties of soil samples

Sample Areas	Fracture Stress (kgf/cm²)	Fracture Stress (N/mm²)	Subgrade Reaction (t/m³)
Odunpazarı	1.94	0.19	1250
Tepebaşı	1.44	0.14	1100
Alpu	1.16	0.11	1000

3.2 DSM Sample Preparation

Although the parameters of 100 bar injection pressure, 450 kg/m³ cement dosage, and 20 min duration of DSM application were used in Eskisehir province to create field deep mixing columns with a diameter of 70 cm and length of 800 cm, the initial experimental values were selected by considering a scale factor for laboratory conditions. In the laboratory, DSM columns with a diameter of 7.0 cm and a length of 14.0 cm were prepared using the designed DSM device. First, the soil samples were placed loosely and fully saturated in the moulds without compression, considering the necessity for improvement. Subsequently, DSM columns were created using the designed DSM device. The created DSM samples were subjected to the unconfined compression test. All the DSM column samples were cured for 7 days. Meanwhile, the sample skins were fixed to minimise roughness. All the tests were repeated three times, and the average result of the unconfined compression test was obtained.

4 TEST RESULTS AND ANALYSIS

The experimental results show that the injection pressure, cement dosage, and mixing time affected the soil strength during DSM. The results were interpreted based on the initial unconfined compression test results. As the actual soil and the reconstructed laboratory samples differed significantly, only results from the unconfined compression test were compared.

4.1 Injection Pressure

The injection pressure was adjusted with a barometer, which was connected to the output of the compressor. Although the injection pressure ranges from 10 to 100 bars in field applications, injection pressures of 0.21, 0.41, and 0.62 N/mm² were applied in this study considering the laboratory scale factor when creating the DSM samples. Other parameters were maintained constant for all samples (cement dosage: 350 kg/m³, mixing time: 45 s). Various DSM columns were created by changing the injection pressure, and they were subjected to loading in the unconfined compression device. The results are presented in Figure 5.

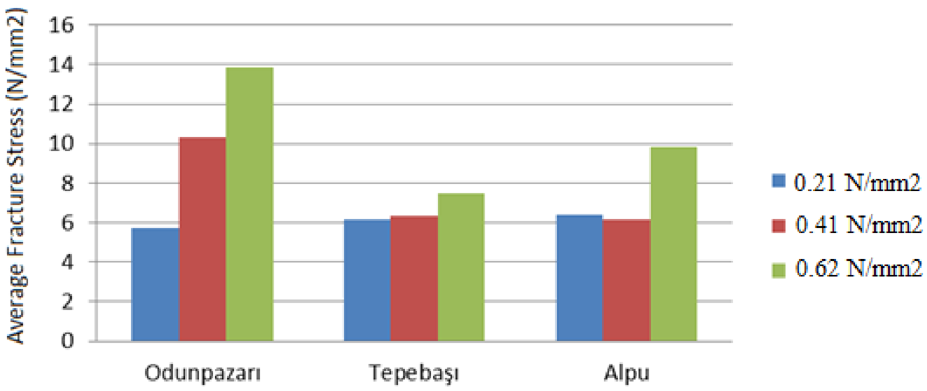

Figure 5 Effect of injection pressure

The DSM column samples exhibit a higher fracture stress than the soil in the initial condition. The initial fracture stresses were 0.19, 0.13, and 0.11 N/mm², for the soil samples from the three regions, whereas the fracture stresses of the DSM column samples were between 5.74 and 13.90 N/mm². The test results show that the initial injection pressure affects the fracture stress of the DSM samples. Therefore, adequate injection pressure should be applied to achieve high strength in the applications.

4.2 Cement Dosage

Cement dosage refers to the amount of cement [kg] added to a unit volume of soil [m³]. To determine the effect of dosing, dosages of 100 kg/m³ (2 kg of cement and 5 kg of water), 350 kg/m³ (7.0 kg of cement and 5 kg of water), and 500 kg/m³ (10 kg of cement and 5 kg of water) were used to prepare the DSM columns. Other parameters were maintained constant for all samples (injection pressure: 0.62 N/mm²; mixing time: 45 s). The DSM column samples were then subjected to the unconfined compression test. The results are presented in Figure 6.

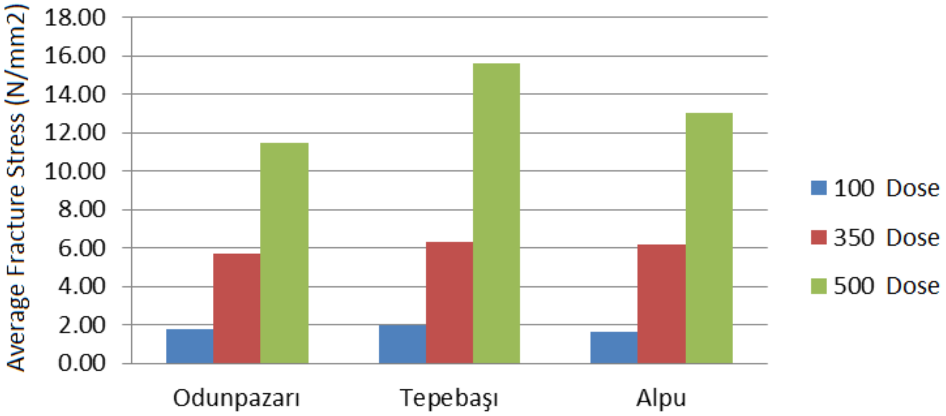

Figure 6 Effect of cement dosage

The DSM column samples exhibit a higher fracture stress as compared with the soil in the initial condition. The initial fracture stresses were 0.19, 0.13, and 0.11 N/mm², respectively, for the soil samples from the three regions, whereas the fracture stresses of the DSM column samples were between 1.75 and 15.59 N/mm². The test results show that the cement dosage affects the fracture stress of the DSM samples. Therefore, adequate cement dosage should be applied to achieve high strength in the applications.

4.3 Mixing Time

Mixing time values of 30, 45, and 60 s were selected to determine the effect of mixing time on DSM column samples prepared in the laboratory. Other parameters were maintained constant for all the samples (injection pressure: 90 psi; cement dosage: 500 kg/m³). The DSM columns were then subjected to loading in the unconfined compression test, and the results are presented in Figure 7.

The DSM column samples exhibit a higher fracture stress as compared with the soil in the initial condition. The initial soil fracture stresses were 0.19, 0.13, and 0.11 N/mm², respectively, for the soil samples from the three regions, whereas the fracture stresses of the DSM column samples were between 5.71 and 20.39 N/mm². Based on literature review, mixing time is an important parameter for ensuring homogeneous columns and insufficient mixing does not result in the complete breakdown of the soil structure [24]. The test results show that the mixing time affects the fracture stress of the DSM samples. Therefore, adequate mixing time should be applied to achieve high strength in the applications.

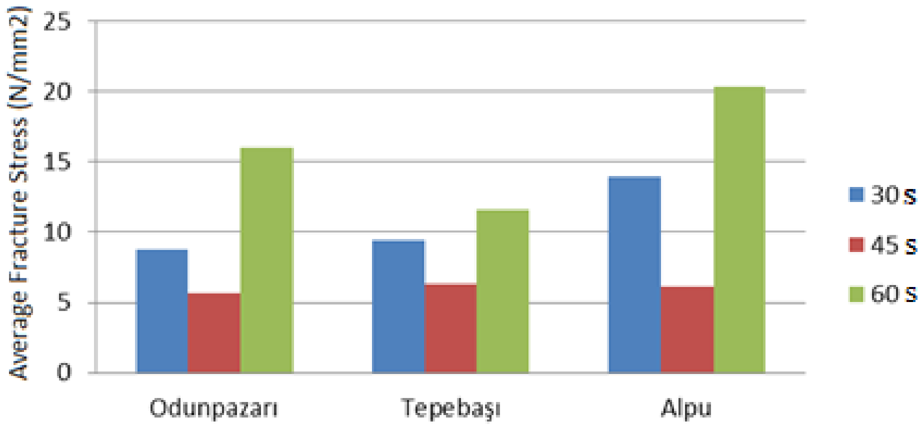

Figure 7 Effect of mixing time

5 CONCLUSIONS

DSM is a soil improvement method that is applied worldwide. A laboratory-scale DSM device was designed and built in this study, which can facilitate investigations in DSM by researchers from developing countries. In this study, an unconfined compression test was conducted for calibration in the laboratory. Other soil properties (i.e. density, compressibility, other shear strength parameters, soil fabric) should be verified, field tests performed, and model tests applied. The developed test device is economical and can be improved and modelled easily; therefore, various soil improvement methods can be simulated in laboratory conditions using this device. This study shows that test devices can be designed and manufactured based on the scientific rules and theories using local resources.

The experimental results showed that the effects of injection pressure, cement dosage, and mixing time on the DSM samples varied depending on the initial soil properties. As shown in Figs. 5–7, the effects on various DSM samples are different as the properties of original soils are different. Therefore, the application parameters for DSM should be determined based on the initial soil properties. In particular, the injection pressure, cement dosage, and mixing time should be determined appropriately prior to the application of DSM. Furthermore, test results can be affected by the roughness of the sample skin and the curing time during sample preparation in the laboratory. Additionally, the field soil behaviour can be affected by in situ stresses and other conditions. Therefore, laboratory samples should be prepared meticulously, and the scale factor considered. This study was performed using soil samples obtained from specific regions. In future studies, the experiments should be repeated on soils exhibiting different properties.

Acknowledgments

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