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The effects and optimization of additives for expansive clays under freeze–thaw conditions

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ABSTRACT

This article reports on the optimization of additives to improve the geotechnical properties of an expansive clay soil subject to freeze–thaw effect, and the effects on soil behavior are evaluated. Lime and rice husk ashes, which are waste materials, were used in stabilization, and randomly distributed fiber was used as reinforcement. The response surface methodology was used for experimental design and optimization. The ranges of additives used in the experimental design were selected as 2.0–8.0% lime, 0.0–15.0% rice husk ash, and 0.0–0.8% fiber. The experiments were conducted on both soil samples before and after freeze–thaw cycle. The non freeze–thaw subjected samples were subjected to only 28-day curing, whereas freeze–thaw subjected samples were subjected to 28-day curing followed by seven freeze–thaw cycles. At the end of these periods, unconfined compressive strength and swelling tests were conducted on the samples, the results were evaluated via response surface methodology, and scanning electron microscopy images were produced for some samples. According to the experimental results, the most influential parameter on compressive strength values in non freeze–thaw subjected samples was lime percentage, whereas it was rice husk ash percentage in freeze–thaw subjected samples. Fiber and lime were effective on axial strain value in both cases. While only the lime amount was effective on the swelling pressure values in the non freeze–thaw subjected samples, the lime and the rice husk ash amount were effective in the freeze–thaw subjected samples. In the optimization of three response variables in combination, desirability levels were 0.85 and 0.94, respectively, in non freeze–thaw subjected and freeze–thaw subjected samples. In the non freeze–thaw subjected samples, the optimum percentages for lime, rice husk ash and fiber additives were calculated as 7.39%, 5.78–5.91% and 0.8%, respectively. In the freeze–thaw subjected samples, the optimum percentages were 6.46%, 14.94–15.0% and 0.78–0.79%, respectively. The optimum rice husk ash amount increased under the freeze–thaw effect and it was especially effective, whereas the lime percentage decreased.

1. Introduction

Expansive soils can be problematic in engineering applications, depending mostly on their interactions with water. Changes in soil volume can cause very significant damage to construction works such as single-story structures, pavements and pipelines located in areas of expansive soils. Lime is mostly used as an additive to stabilize expansive soils and prevent such damage. The lime additive reacts with the soil particles, and decreases the swelling potential while increasing the strength and durability of the soil (Du et al., 1999; Guney et al., 2007; Locat et al., 1990).

Recently, a number of waste materials have been used in the stabilization of soils in order to reduce both environmental problems and the requirement for traditional additives such as lime and cement. Rice husk ash (RHA) is an agricultural residue that is one of these waste materials obtained from the outer covering of rice grains during milling process. RHA includes a huge amount of silica with high specific surface that is very suitable for activating the reaction of soil and lime (Choobbasti et al., 2010). Some researchers showed that the RHA was a promising pozzolanic materials to improve lime or cement-stabilized soils (Ali et al., 1992; Balasubramaniam et al., 1999; Basha et al., 2005; Muntohar, 2002; Rahman, 1987). Muntohar (2004) shows that the addition of 6.0% lime in combination with RHA principally has a significant effect in reducing swell and swelling pressure (Ps) of the clayey soil. Alhassan (2008) stated that the unconfined compressive strength (UCS) of the specimens increased with the addition of lime–RHA in clayey soil. While the use of lime improves the most engineering properties of clay, it brings unfavorable phenomena such as reduction in axial strain at post peak strength (ε), residual strength and plasticity of soil. In recent years, polypropylene fibers have been added into soils to improve the strength, ductility and swelling behaviors of soil (Ikizler et al., 2008; Vessely and Wu, 2002).

In cold regions, the most important factor determining the engineering behavior of fine-grained expansive soils is freeze–thaw (F–T) cycles.

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Fine-grained soils influenced by F–T cycles show changes in volume, strength and compressibility, densification, unfrozen water content, bearing capacity and microstructure (Hohmann-Porebska, 2002). During soil freezing, ice crystals of various sizes and shapes tend to segregate in soils, resulting in the formation of characteristic micro- and macro-scale structures. As a result of F–T cycles, soil behavior is fundamentally changed: crack propagation and stability failures occur following cycles of F–T (Altun et al., 2009). Recently, studies have been conducted on the use of waste materials in reducing F–T effect in clays. These studies used additives such as rapid stabilizers (Shoop et al., 2003), recycled gypsum (Ahmed and Ugai, 2011), synthetic fluid (Gullu and Hazirbaba, 2010), and lime–fly ash mixture (Soni and Jain, 2008). It was reported that these additives showed highly positive impacts on the strength of clay soils under the F–T effect. Some studies using fibers in clay soils under F–T effect reported generally increased UCS values of soils (Ghazavi and Mahya, 2010; Zaimoglu, 2010).

Previous studies have used single additives and waste materials in clay soils under F–T effect. In this case, while some soil properties may be improved, other properties may be negatively affected. The properties of the soil can be improved in a balanced manner using chemical additives such as lime and cement together with other additives. Thus, the present study investigated how the strength, ductility and swelling properties of soil under the F–T effect were changed by using the three additives in combination: lime, RHA and fiber. Moreover, no previous studies have examined the effects of RHA on the behavior of clay soils under F–T effect. The response surface methodology (RSM), which also involves optimization, was used to determine the changes. The UCS and swelling tests were conducted on non F–T subjected and F–T subjected samples by designing an experiment according to RSM. The results were evaluated by forming the most suitable models according to the RSM, and optimum additive contents were calculated. Furthermore, scanning electron microscopy images (SEM) were taken of the non F–T subjected and F–T subjected experimental samples, and structural changes in the samples were examined.

2. Materials and test procedures

2.1. Materials used

The expansive soil used in this investigation was collected from a depth of 100 m from Ermenek coal mine, in Karaman state, Turkey (Table 1). Industrial hydrated lime was used in this study. Quantitative analysis indicated that the lime contained 93% $Ca(OH)_2$ and 3% calcite. Polypropylene fiber was used for reinforcing the expansive soil specimens (Table 2).

Rice husk constitutes about 20% of the weight of rice. It contains about 50% cellulose, 25–30% lignin, and 15–20% silica. When rice-husk is burnt RHA is generated. On burning, cellulose and lignin are removed leaving behind silica ash. The combustion environment affects specific surface area, so that time, temperature and environment must be considered in the pyroprocessing of rice husks to produce ash of maximum reactivity (Bakar et al., 2010; Nehdi et al., 2003). In line with earlier observations, the analysis show that the highest amounts of amorphous silica occur in samples burnt in range of 500 °C–700 °C (Chopra et al., 1981; Ganesan et al., 2008; Mehta, 1978; Nair et al., 2008; Yu et al., 1999). The reactivity of amorphous silica is directly proportional to the specific surface area (James and Rao, 1986; Mehta, 1994).

Table 1
Index properties of the expansive soil.

Property	Value
Specific gravity	2.65
Liquid limit (%)	95.10
Plastic limit (%)	51.90
Plasticity index (%)	43.20
Shrinkage limit (%)	12.25
Optimum moisture content, OMC[a](%)	26.31
Maximum dry unit weight, ($\gamma_{d,max}$)[a] (kN/m^3)	12.75
Free swell index, FSI (%)	130
USCS classification	CH
Mineralogical composition[b]	Smectite: 92%; illite: 8%
Organic substance amount (%)	7.50

[a] Standard Proctor Test.
[b] XRD spectra.

Table 2
Properties of polypropylene fiber.

Property	Value
Fiber type	Single fiber
Length (mm)	12
Diameter (mm)	0.034
Specific gravity	0.91
Tensile strength (MPa)	500–700
Modulus of elasticity (MPa)	2800
Melting point (°C)	160
Burning point (°C)	590
Elongation at break (%)	25

In this study, the rice husks were collected from Kastamonu state, in Turkey, washed and dried. Then, the samples were burnt in a programmable temperature furnace at 650 °C over a period of 1 h (as Ganesan et al., 2008). The temperature of the furnace was increased at a rate of 10 °C/min to 650 °C. At 650 °C, the temperature was kept constant for a burning time of 1 h: under controlled condition and then cooled. In order to improve the pozzolanic behavior of these materials, RHA samples were ground by ball milling for 90 min using ceramic balls (as Salas et al., 2009). The properties of the RHA are shown in Table 3.

2.2. Sample preparation and test procedures

The various ratios of the three soil additives were determined according to RSM, as given in Table 4. Firstly, standard Proctor experiments were conducted (ASTM D698) and optimum water content (w_{opt}) values of mixtures were determined (Table 4). While lime additive was particularly effective on the w_{opt} values, the effect of the other two additives was negligible. Increased lime percentage was associated with substantially increased w_{opt} (for unstabilized clay $w_{opt} = 26.3\%$, compared with $w_{opt} = 41.3\%$ with 8% lime addition).

According to the requirements of ASTM D5102, cylindrical specimens with 38 mm diameter and 80 mm height were used for the UCS test. Then, clay, lime and RHA were thoroughly mixed in dry conditions for every combination. Water was added to the mixture according to the w_{opt} value for each mixture. Afterwards, fiber was mixed until a uniform consistency was obtained. This mixture was

Table 3
Physical and chemical properties of RHA.

Property	Value
Specific gravity	2.09
Fineness (%) (passing 45 μm)	12.3
pH	9.25
Average particle size (μm)	8.1
Specific surface area (cm^2/g)	3860
Chemical composition (%)	
Silica (SiO_2)	91.81
Alumina (Al_2O_3)	0.27
Iron oxide (Fe_2O_3)	0.19
Calcium oxide(CaO)	0.64
Potash (K_2O)	2.28
Magnesia (MgO)	0.78
Na_2O	0.09
Loss on ignition	3.94