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Research paper

Optimization of carpet waste fibers and steel slag particles to reinforce expansive soil using response surface methodology

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ABSTRACT

Expansive soils exhibit great volume change with any moisture variation. In this paper, using carpet waste fibers and steel slag as an environmental friendly additives were taken into account to overcome the swelling and weakness of the expansive soil. Response surface methodology (RSM) was employed to design the experiments, evaluate the results and finally optimize the content of slag-fiber mixture for achieving appropriate values of swell percent, swelling pressure and unconfined compressive strength (UCS). Three independent variables including slag content (0–25% by dry weight of the soil), carpet waste fiber (0.2–3% by dry weight of the soil) and aspect ratio of fibers L/d (5–45) were considered and transformed to coded value, and a second-order polynomial regression equation was then derived to predict responses. The percentage contribution, validity of model and significance of independent variables and their interaction were assessed by analysis of variance (ANOVA). The optimum values of three independent variables was suggested as 14% slag and 0.78% fiber with fiber aspect ratio of 45 to improve swell percent, swelling pressure and UCS 89%, 84%, and 111%, respectively. The results showed that both chemical modification and mechanical reinforcement by adding fibers and slag are efficient methods to improve general properties of expansive clayey soil.

1. Introduction

Expansive soils contain montmorillonite clay usually exhibit great volume change with any moisture variation. This feature causes limitations and high risks for constructing dams, highways and other engineering structures on such soils. The estimated damage cost caused by expansive soil exceeds 15 billion dollars in the US annually (Al-Rawas and Goosen, 2006).

A common technique to overcome the swelling and weakness of the expansive soils is to stabilize them by using appropriate additives (Modarres and Nosoudy, 2015; Saride et al., 2013; Yilmaz and Civelekoglu, 2009). Steel slag which is an industrial by-product from iron and steel manufacturing factories proposes light pozzolanic activity, ionic exchanges and flocculation properties. Therefore, slag is one of the additives that would be useful in this way (Goodarzi and Salimi, 2015; Manso et al., 2013).

Slag particles have been recently studied by the purpose of swell suppression and strength enhancement of lime treated clays (Celik and Nalbantoglu, 2013; Wild et al., 1998). The results illustrated that use of slag reduces plasticity and swell potential (from 8% to 1%), meanwhile enhances the strength of clay. The effect of ladle furnace slag (LD) compared to the lime was also investigated by Manso et al. (2013). Their study on three kinds of soil showed that 2% of lime is corresponding to 4% of LD in consequence of reduction in swelling and increasing of strength.

A study on the effect of slag on unconfined compressive strength (UCS) of soft soil was presented by Yadu and Tripathi (2013). The specimens were prepared by different amount of slag (i.e. 3, 6, 9 and 12%). The results indicated that by adding 9% of slag, the UCS increases by 28% compared to the neat (unreinforced) soil.

On the other hand, using fibers to reinforce soil is considered as an alternative method regards to chemical stabilization techniques and other methods in order to increase the strength and reduce the swell potential of expansive soil (Cai et al., 2006; Viswanadham et al., 2009). Fibers also change the brittle behavior of lime treated soil to the ductile one (Cai et al., 2006). Introducing various reinforcement materials in gravel sub-bases laid on expansive soil subgrade, results in increasing load carrying capacity of the flexible pavements (Prasad et al., 2010). There are especially some available researches focused on strength enhancement of sandy soils by carpet waste reinforcing fibers (Ghiassian et al., 2004). Moreover, some studies are done on swelling and strength

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Table 1
Geotechnical properties of the soils.

Property	CB	C	B
% fines passing through 75 μm (No. 200) sieve	100	89	100
USCS classification	CH	CH	CH
Specific gravity	2.76	2.78	2.55
Liquid limit (%)	59	53	229
Plastic limit (%)	21	18	45
Plasticity index (%)	38	35	184
Optimum moisture content, OMC (%)	22	19	32
Maximum dry unit weight, $\gamma_{d,max}$ (kN/m^3)	16.3	16.8	12.1
Free swell, FS (%)	8.5	1.5	47
Swelling pressure, SP (kPa)	81	28	357
Unconfined Compression Strength, UCS (kPa)	426	–	–

Table 3
Some physical and mechanical properties of carpet waste fibers.

Property	Value
Yarn Type	Acrylic (polyacrylonitrile: PAN)
Chemical Formulation	$(C_3H_3N)_n$
Density	1.18
Average diameter (mm)	0.665
Tex[a] No.	163.68
Fusion Temperature (°C)	322
Tensile strength (MPa)	70
Modulus of elasticity (GPa)	3.2
Breaking elongation (%)	17.4

[a] Tex is defined as a weight of 1000 m long fiber.

behavior of two types of expansive soils at different compaction states and fiber contents of 1, 3, and 5% which is shown that the fiber content results in reduction of the swelling pressure and significant enhancement in the UCS of soil samples (Mirzababaei et al., 2013a, 2013b);

It is estimated that annual world iron slag output in 2013 was in the order of 260 to 320 million tons, and steel slag about 170 to 250 million tons which approximately BOF and EAF (steel slags) account for the 55% of total slag production (Oss, 2014). To have an idea about the considerable area needed for disposal, it is enough to know that the 20 million tons of BOF slags are estimated to occupy 2.5 million square meters (El Haggar, 2005). Data on the amount of world carpet waste fibers is unavailable but as a specific example, about 400,000 tons of carpets are sent to landfill in the UK in 2015 (Sotayo et al., 2015) and 2.3 million tons of carpets and rugs were generated in the municipal solid waste in the United States (Wang et al., 2003). Therefore, waste materials are required to pay money for disposing. In addition, the huge space needed to dump wastes has become a real challenge. So, from environmental and economical points of view applying these waste and by-product materials would be necessary in construction engineering.

In order to find out the effective percentage and contribution ratio of each additives (i.e. slag and carpet waste fibers), the experiments were designed and analyzed by the Design Expert 7 software. The response variables were included swelling and UCS test results.

2. Materials and methods

2.1. Materials

The laboratory man-made expansive soil (hereinafter called CB) was obtained from combination of 90% of natural soil prepared from North region of Isfahan, Iran (soil C) and 10% sodium activated bentonite

Table 2
Physical properties and chemical composition of BOF slag.

Property	Value
Type of slag	Basic Oxygen Furnace Slag (BOF)
% fines passing through 0.15 mm (No. 100)	100
Specific gravity	2.69
Chemical composition (%)	
SiO_2	19
Al_2O_3	4.5
CaO	49
FeO & Fe_2O_3	14.5
MgO	2.5
MnO	4
P_2O_5	3
TiO_2	0.95
K_2O	0.05
V_2O_5	2.5

(soil B) to fabricate a high swelling capacity soil. In this regard, various amount of bentonite was added to the natural clay. The Atterberg limits and swelling properties were measured. Consequently, adding 10% of bentonite to soil C for making soil CB expansive was suitable. The general properties of the soils (soil C, B and CB) are presented in Table 1. The basic oxygen furnace (BOF) slag was supplied by Isfahan Steel Company, Isfahan, Iran (Table 2). The grains of original provided slag was almost powder and passed 100% through sieve No.4 which the fraction >0.15 mm in size was removed by sieving. The polyacrylonitrile (PAN) reinforcing fibers known in the market as acrylic was prepared from Sheikh Safi Carpet Factory, Isfahan, Iran. All PAN fibers collected for this work were considered as waste fibers which were derived during the shearing process of carpets (Table 3). Since, these fibers were waste of carpet manufacturing, there were a high variance in fiber diameter (d) and length (L) (length varied from 1 to 10 cm and diameter ranged from 0.4 mm to 0.9 mm approximately). Therefore, for evaluating the effect of fiber length and diameter, the aspect ratio of fibers (i.e. L/d) was considered as the independent variable in experimental program (Viswanadham et al., 2009). The used slag, fiber and one of the tested samples for swelling and UCS tests are shown in Fig. 1.

2.2. Experimental design and optimization method

Central composite design (CCD), which is a widely used form of response surface methodology (RSM) was employed to design the

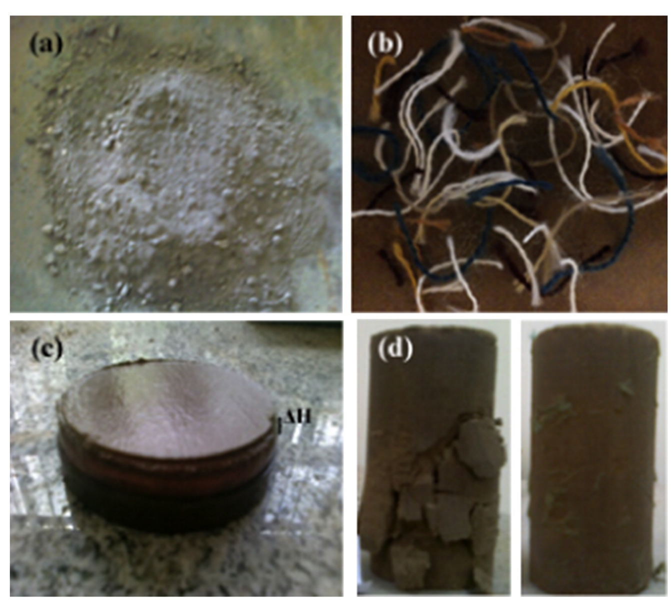

Fig. 1. Photograph of (a) slag; (b) carpet waste fibers; (c) the swelled sample after swelling test in consolidation ring; (d) two samples before and after UCS test.