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Application of secondary steel slag in subgrade: Performance evaluation and enhancement

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ABSTRACT

Steel slag accumulates heavily in China and has caused significant environmental burdens. In this study, secondary steel slag (SSS) was used a potential material in subgrade treatment. This study first blended SSS of different contents with lime soil and inspected the performances of the mixes in terms of compactability, strength and expansion ratio. The optimum treatment effect was obtained at a proportion of 50% SSS, 45% soil and 5% lime. Scanning electron microscopy test was conducted to reveal the strength development of SSS lime soil. The components of SSS were then supplemented by lime and metakaolin referring to the oxide compositions and proportions of the Portland cement. The unconfined compressive strength (UCS) of the reconstituted SSS increased from 0.73 MPa (plain SSS) to 4.09 MPa at 28d. Three agents, NaOH, NaCl and Na_2SO_4, were selected to further improve the activity of the reconstituted SSS. At the content of 5%, the UCSs of the specimens activated by NaCl and Na_2SO_4 increased to 8.02 MPa and 10.88 MPa at 28d, respectively. The reconstitution and activation of SSS is an effective way to improve the performance in subgrade treatment.

1. Introduction

Steel slag is the by-product of metallurgical industry. An estimation of 100 million metric ton of steel slag are produced in China each year and the resulting environmental burdens are growing. According to the production technology, steel slag can be classified as Basic Oxygen Furnace (BOF), Electric Arc Furnace (EAF) and Ladle Refining (LF) slags (Meng and Liu, 2009). Steel slag has been used in pavement construction in miscellaneous ways. Regular applications include as replacement of aggregate in asphalt mixture, granular base and sub-base, as mineral additive in cement stabilization, and as filler to treat subgrade soil. (Aiey et al., 2004; Masoudi et al., 2017; Pasetto and Baldo, 2010).

With proper pre-processing and sufficient in-place quality control procedures, steel slag can perform credibly well as asphaltic aggregate (Ahmedzade and Sengoz, 2009). Chen and Wei (2016) designed asphalt mixtures incorporating BOF steel slag as coarse aggregate in laboratory and built a test road using three different types of asphalt mixtures. Field data indicated that the ride quality and friction characteristics of the BOF section performed as well as or better than the sections constructed using natural aggregate.

Steel slag has advantages of sound internal friction, free draining ability, good compactability as well as low water absorption. These qualities quantify it as good construction material for base and sub-base courses (Oluwasola et al., 2014). Behiry (2013) evaluate the effect of quantity of steel slag on the mechanical properties of the blended mixes with crushed limestone aggregates. The optimum density and strength for the sub-base mixes with the least construction cost were obtained at a blend of 70% steel slag and 30% limestone.

The major chemical compositions of cement (C2S, C3S and C4AF) that present in steel slag feature it as cementitious material. Steel slag, together with other by-products (blast furnace slag, fly ash etc.), can produce excellent cement stabilization products (Altum and Yimax, 2002; Iacobescu et al., 2013; Papayianni and Anastasiou, 2010). Rosales et al. (2017) analyzed the cementation and pozzolanic reaction characteristics of stainless steel slag waste to evaluate its strength activity and environmental impact. The authors recommended replacing up to 20% of cement with stainless steel slag waste.

Steel slag can also be used in subgrade soil to enhance its strength due to the existence of cementitious components (Poh et al., 2006; Ashango and Patra, 2016). However, in natural conditions, the cementitious activity is limited so that the potential of steel slag is not fully explored. Furthermore, a negative effect of steel slag application in subgrade treatment is the volume

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expansion. The volume instability of steel slag comes from the hydration of free lime and free periclase in a humid environment.

In this study, secondary steel slag (SSS) was used to in subgrade treatment. The SSS was produced by 2 times of circulating magnetic separation of the original steel slag. The purpose is to clear free lime, free periclase and free metallic elements etc. that would cause volume instability and environmental pollution concerns. By using SSS, it is intended to: 1) determine the optimum design and evaluate the performance of SSS treated subgrade soil; 2) perform component supplement and activation designs of cementitious components in SSS to further enhance the strength.

2. Materials

2.1. Steel slag

In this study, raw steel slag was first processed by circulating magnetic separation and then grinded to finer size. The obtained SSS has a natural water content of 24.6% and a maximum dry density of 2.06 g/cm^3, as shown in Fig. 1a. The gradation curve of SSS is shown in Fig. 1b. C_c and C_u are the coefficients of curvature and uniformity, which are the two common parameters used for characterizing the gradation curve. By calculation, C_c is 5 and C_u is 0.8 so that particle distribution of SSS is uniform but not well graded. The dominant grain sizes are 0.075–0.25 mm, accounting for 62.3% of the total mass.

X-ray dispersive spectrum test was conducted on SSS sample to identify the major components, with the results shown in Fig. 2. CaO and SiO_2 are the main oxides of SSS with the content up to 80% and the content of Al_2O_3 is less than 5%. The main mineral components of SSS are γ-$CaSi_2O_4$, β-$CaSi_2O_4$ and Ca_3SiO_5, which include cement clinker minerals and therefore have the potential gelling property. In SSS, there are no free Fe, Mn, S and SO_3 elements so that it will not cause environmental pollution problem in subgrade treatment.

2.2. Soil and lime

The soil was taken from a highway project in Zhejiang Province in China. The properties of soil were investigated in laboratory, as shown in Table 1. Hydrated lime was used in this study.

3. Performance evaluation of SSS stabilized soil

Before the applications of SSS in subgrade treatment, the soil was first modified by lime to meet the requirements of liquid limit (LL) and plasticity index (PI). Then SSS was applied to treat lime soil. The mixes were evaluated in terms of compactability, bearing capacity and expansion ratio.

3.1. Lime soil test

As shown in Table 1, the original soil cannot meet the requirement of LL and plastic limit (PL) so that lime was used to modify. Three lime contents, 1%, 3% and 5%, were selected. After compaction test, LL and PI are plotted in Fig. 3.

With the increase of lime content, LL decreases continuously, from 54.1% (control), to 53.8%, 49.6% and 44.4%; and PI decreases from 28.1 (control), to 23.2, 19.9, and 17.1. At the lime content of 3%, LL is very close to the threshold value so that 5% of lime was used to modify the soil. Hereafter all the soil samples were first modified by 5% of lime before applying further measures. The California Bearing Ratio (CBR) value of the original soil enhance slightly from 5.5% to 7.1% with the addition of lime.

3.2. SSS lime soil test

Three contents of SSS, 30%, 50% and 80%, were added to the lime soil. Compaction test, unconfined compressive test and expansion test were conducted to observe the changes of performance of the SSS stabilized soil. The three tests followed the specifications of T0804-1994, T0805-1994 (Department of Transportation (2009)) and T0124-1993 (Department of Transportation (2007)), respectively.

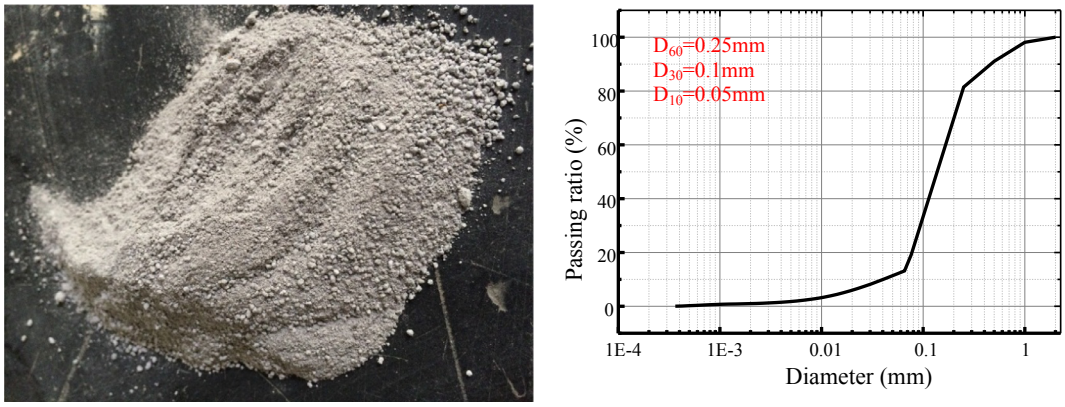
3.2.1. Compaction test

Fig. 4 depicts the relationship of water content and dry density for SSS lime soil. The maximum dry density of lime soil is about 1.78 g/cm^3, and the maximum dry density of pure steel slag is about 2.06 g/cm^3. The maximum dry densities of SSS lime soil is in the range of 1.81–1.85 g/cm^3 in different dosage of steel slag, and the optimum water content changes in the range of 13.17%–13.98%. The maximum dry density increased with the increase of slag content, and the change of the optimum water content is less than 1%.

3.2.2. Unconfined compressive test

Unconfined compressive test was conducted on the specimens of SSS lime soil, with the results listed in Table 2.

The UCSs of SSS lime soil increase significantly compared to those of lime soil. At 7d, the strength is small; at 28d, the strength grows slightly; and at 60d, the strength grows dramatically. The UCSs of the designs at 60d and 90d are close, which means the



a. Appearance of SSS b. Gradation of SSS

Fig. 1. Appearance and gradation of SSS.