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Investigation on the dynamic shear modulus and damping ratio of steel slag sand mixtures

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HIGHLIGHTS

- We investigated the dynamic shear modulus and damping ratio of SSM and CSM.
- The effects of confining pressure, mix proportion and curing age on the dynamic shear modulus and damping ratio were studied.
- The dynamic shear modulus and damping ratio of SSM and CSM are significantly affected by mix proportion.
- It is feasible to use SSM instead of CSM as the foundation treatment materials.

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ABSTRACT

This paper aims to investigate the dynamic shear modulus (G) and damping ratio (D) of steel slag sand mixture (SSM), and compared with the cement sand mixture (CSM) under the same conditions. A series of resonant column tests were conducted to explore the effects of confining pressure, mix proportion and curing age on the dynamic shear modulus and damping ratio. The results show that the dynamic shear modulus increases with the increase of confining pressure, whereas the damping ratio is found to be less influenced by confining pressure. An increase in curing age leads to an increase in dynamic shear modulus and a slowly decrease in damping ratio. The mix proportion significantly affects the dynamic shear modulus and damping ratio of SSM and CSM. The dynamic shear modulus of SSM initially increases and then decreases with the increase of steel slag content, and reaches the maximum when steel slag content is 40%. The dynamic shear modulus of CSM gradually increases with the increase of cement content. As the increase of steel slag and cement in the mixture, the damping ratios of SSM and CSM tend to increase first and then decrease, and the maximum damping ratio (D_{max}) also shows similar trend. When the steel slag content is 15%, the maximum dynamic shear modulus (G_{max}) and maximum damping ratio (D_{max}) of SSM are close to those of CSM with the 15% cement content. With the test findings, it is feasible to use 40% steel slag instead of 15% or less cement to mix with sand as the foundation treatment materials, which can not only improve the dynamic characteristics of the foundation, but also save resources and protect the environment.

1. Introduction

The low-strain dynamic shear modulus (G) and damping ratio (D) are important characteristics that are often used to determine the dynamic response of soils [1]. The dynamic shear modulus reflects the bearing capacity of soils, and the damping ratio expresses the amplitude attenuation of dynamic load in soils. The traditional cement sand mixture (CSM) has its own advantages and disadvantages in foundation treatment. In recent years, utilization of industrial by-products in engineering construction has received lots of attentions from researchers [2]. Steel slag is a by-product that is produced during the steel slag manufacturing process and often features high hardness [3], which makes the steel slag sand mixture (SSM) a promising foundation treatment material. However, past studies on the dynamic properties of SSM are still very limited and less information is available. So it is necessary to explore the feasibility of using steel slag instead of cement to mix with sand as foundation treatment materials.

The experimental investigations of the dynamic shear modulus and damping ratio of soils have been used by various researchers. Yong et al. [4] investigated the dynamic properties (shear modulus

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and damping ratio) of two selected tropical residual soils (sandy silt and silty sand) in Malaysia under different overburden pressures. Zhao et al. [5] studied the dynamic properties of silica gel, including small-strain shear modulus and damping ratio through a series of resonant column tests. Golpazir et al. [6] performed a series of cyclic triaxial tests to investigate the dynamic properties of polyurethane (PU) foams and PU foam-sand mixtures from intermediate to large strains. Song et al. [7] studied the small-strain stress-strain properties during cyclic loading of Lanzhou loess deposits, characterized by a very high void ratio, and they found that shear modulus at low strain levels was very sensitive to water content while the effect of water content on small-strain damping was relatively smaller. Ehsani et al. [8] investigated the dynamic properties of sand-granulated rubber mixtures prior to practical applications, and the results showed that tire inclusion significantly reduced the shear modulus and increased the damping ratio of the mixtures. Kumar et al. [9–11] conducted a series of resonant column tests to examine the effects of vibration cycles and cyclic strain history on the dynamic properties of sand. It needs to be mentioned that previous studies on dynamic shear modulus and damping ratio were mainly based on traditional geotechnical materials, whereas no research effort has been devoted to investigate the dynamic properties of combining use of steel slag and sand.

Steel slag is obtained as industrial by-product and its recycling utilization considering environmental protection has been a concern for people. According to Das et al. [12], 2–4 tons of waste are produced during the manufacture of every single tonne of steel. Most of BOF (basic oxygen furnace) steel slag has been recycled in developed countries [13]. About 1.5 million metric tons of BOF steel slag produced in Germany are used as an aggregate material in construction applications annually [14], and approximate 97% of BOF steel slag is recycled in the same ways in the U.K. [15]. Although a large amount of waste steel slag are recycled, there is still about 35% unused steel slag dumped as waste [16]. In China, the annual production of steel slag is about 30Mt, with only about 22% utilization rate [17,18]. The chemical composition of steel slag varies due to its highly variable production method and raw materials [19]. On the whole, its chemical composition consists of CaO, SiO_2, Al_2O_3, Fe_2O_3 and MgO. It should be noted that steel slag contains about 10% of MgO and 40% of CaO in which there is more than 5% of free CaO [20]. This risk can be eliminated or greatly reduced by weathering the steel slag in outdoor condition for a sufficient period of time before [21]. In addition, traditional Portland cement is not an environmental friendly material due to its manufacture creates a large mount of greenhouse gas emissions, and it also consumes a great deal of natural resources and energy [19]. Based on previous studies, effective utilization of steel slag as a substitution of traditional Portland cement in foundation treatment would save resources and protect the environment.

The present research aims to replace traditional Portland cement with steel slag as the main material in foundation treatment, and to investigate the dynamic shear modulus and damping ratio of SSM using resonant column tests. The test results of SSM are also compared with those of CSM under similar conditions. The test results will provide a theoretical foundation for the practical application of SSM so that it can be widely applied in foundation treatment.

2. Experimental

2.1. Test equipment

The resonant column apparatus had been used for testing the SSM and CSM specimens. It is a fixed-free apparatus in which the cylindrical specimen is fixed at its bottom and only its top is vibrating. The resonant column test was performed by applying a sinusoidal torque via an electromagnetic drive system to the specimen. The drive system consists of a four-arm rotor that has a permanent magnet fitted to the end of each arm and a support cylinder to which four pairs of wire coils are fitted. The basic principle of the resonant column test is to vibrate a cylindrical soil specimen in a fundamental mode of vibration, in torsion or flexure. Once the fundamental mode is established, measurements of resonant frequency and amplitude of vibration are made, and then the dynamic shear modulus and shearing strain amplitude of specimen can be obtained.

2.2. Materials

The materials tested are steel slag, Portland cement and sand. The physical and mechanical properties of steel slag are shown in Table 1. The chemical compositions of steel slag may vary with the changes in composition of the raw ore and manufacturing process. Based on the statistical results, most steel slag consists primarily of CaO, MgO, SiO_2, Al_2O_3 and FeO. The minerals of the steel slag determined by X-ray diffraction are mainly C_3S ($3CaO{\cdot}SiO_2$), β-C_2S ($2CaO{\cdot}SiO_2$), $2CaO{\cdot}Al_2O_3$, $2CaO{\cdot}Fe_2O_3$, RO phase (a CaO-FeO-MnO-MgO solid solution), free CaO and free MgO, etc [18]. Besides, steel slag also has a large hydraulicity. Due to the impact of CaO, the PH value of steel slag can reach 10–12 when reacts with water [22]. Therefore, the use of steel slag for foundation treatment will also play an important role in corrosion resistance.

The major chemical compositions of Portland cement (P.O32.5) are $3CaO{\cdot}SiO_2$, $2CaO{\cdot}SiO_2$, $3CaO{\cdot}Al_2O_3$ and $4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$. It can be better hardened when meet with water, then maintains and develops its strength. The major technical indexes of Portland cement are shown in Table 2 [22].

The steel slag and sand used in this test were obtained by manual screening. The particle size of steel slag and sand is controlled below 4 and 2 mm, respectively. The particle size distribution curves of the steel slag and sand are shown in Fig. 1. Based on the particle size distribution curves, the uniformity coefficients of steel slag and sand are 5.72 and 2.31, respectively, and the curvature coefficients of steel slag and sand are 0.85 and 1.22, respectively.

2.3. Mix proportions

The tests were carried out on specimens with the same water content. The mass ratio of water to solid material was 15%. For SSM, the content of solid materials represented by steel slag is 20, 30, 40 and 50%, and represented by symbols Gs20, Gs30, Gs40 and Gs50, respectively. Similarly, for CSM, the content of solid materials represented by cement is 8, 12 and 15%, and represented

Table 1
Physical and mechanical properties of steel slag.

Number	Indexes	Norm	Test results
1	Crushing value (%)	≤26	17.5
2	Apparent relative density	≥2.60	3.30
3	Water absorption (%)	≤2	2.3
4	Soft stone content (%)	≤3	2.6
5	Asphalt adhesion (level)	≥4	4.2
6	Wear loss in Los Angeles	≤28	18.5
7	Polished stone value	≥42	45
8	Free-calcium oxide (f-CaO) (%)	≤3	0.14
9	Immersion expansion rate (%)	≤2	0.43
10	Impact value (%)	≤25	14