Dynamic and Static Measurements of Small-Strain Moduli of Basic Oxygen Furnace Slag

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Abstract: Steel slag is an industrial by-product generated during the steel and ironmaking processes. In recent years, it has been increasingly used as a sustainable resource due to its excellent mechanical properties. Steel slag serves as a viable substitute for conventional construction materials, contributing to both environmental impact reduction and improved seismic performance. BOF slag (basic oxygen furnace slag), one type of steel slag, resembles crushed stone or sand in appearance and physical characteristics, and is used in various civil engineering applications such as road base courses, general fill materials, and concrete aggregates. This research aims to evaluate the dynamic and static small-strain moduli of BOF slag through laboratory triaxial tests combined with elastic wave measurements. Dry triaxial tests were conducted under isotropic consolidation and drained shear conditions, during which both P- and S-wave velocities were measured to determine the elastic moduli. The results revealed that the dynamic modulus obtained from wave measurements was higher than the static modulus, indicating that BOF slag exhibits clear pressure-dependent stiffness and strong potential as a sustainable geomaterial.

Keywords: ***BOF slag, Steel slag, Small-strain triaxial test, Elastic wave measurement.***

Introduction

In recent years, under the framework of the United Nations Sustainable Development Goals (SDGs), geotechnical engineering has increasingly emphasized sustainability and resource recycling. Japan, which is frequently affected by natural disasters such as earthquakes and tsunamis, has a strong demand for resilient and environmentally friendly construction materials. In this context, the use of industrial by-products as substitutes for natural geomaterials has gained considerable attention (Yildirim et al., 2011).

Among these by-products, basic oxygen furnace (BOF) slag, produced during the steelmaking process, has shown great potential as a sustainable geomaterial. BOF slag resembles natural sand or crushed stone in both appearance and physical characteristics, which has been widely used in civil engineering applications such as road base layers, backfill materials, and concrete aggregates (Shen et al., 2009). However, fine BOF slag often contains free lime (f-CaO) and free magnesia (f-MgO), which can cause volume instability through hydration. Therefore, coarse and aged BOF slag is generally preferred to ensure long-term stability.

Although BOF slag has been widely used in construction, studies on its triaxial mechanical properties remain limited, especially concerning its dynamic behavior under small-strain conditions. To address this gap, this study investigates the small-strain dynamic and static moduli of dry BOF slag through a series of laboratory triaxial tests combined with elastic wave measurements.

Materials and Test methods

In this study, samples were prepared using BOF slag ($\rho_s = 3.49\ g/cm^3$, $D_{50} = 2.14\ mm$, under $4.75\ mm$), which was provided by a Japanese foundry from the same batch. Figure 1 shows the particle size distribution of the BOF slag for this study.

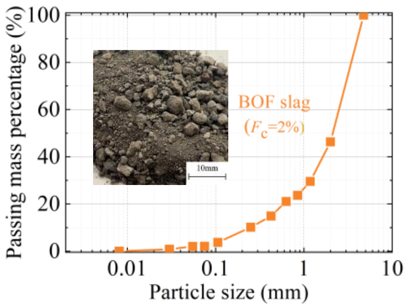

Figure 1, Particle size distribution and image of BOF slag.

In the small-strain triaxial test with elastic measurements, the cap and pedestal of the apparatus were equipped with disk transducers to measure elastic waves during the test. The specimen had a diameter of 75 mm and a height of 150 mm. A local deformation transducer (LDT) was used to measure small axial displacements when the axial strain change was less than 0.1%. The testing procedure consisted of specimen preparation, isotropic consolidation with small-strain cyclic loading, and shearing. Elastic waves were measured during both the consolidation and shearing stages. All testing conditions are summarized in Table 1. Figure 2 illustrates the method used to determine the elastic wave velocities, where the travel time was defined as the interval between the start point of the transmitted wave and that of the received wave.

The static Young's modulus (E_{LDT}) was calculated from the local stress–strain relation measured by LDT during small cyclic loading:

$$E_{LDT} = \frac{\Delta q}{\Delta \varepsilon_{a,local}} \qquad (1)$$

The dynamic moduli were derived from P- and S-wave velocities (V_p, V_s) measured by disk transducers:

$$G = \rho V_s^2, \qquad K = \rho\left(V_p^2 - \frac{4}{3}V_s^2\right) \qquad (2), (3)$$

$$\nu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}, \quad E_{ew} = 2G(1+\nu) \qquad (4), (5)$$

Here, ρ is the specimen dry density. E_{LDT} represents the static modulus, while E_{ew} represents the dynamic small-strain modulus.

Table 1, Test conditions.

Material	Relative density Dr (%)	Confining pressure p'(kPa)	Elastic wave	Frequency (kHz)
BOF slag	60	50, 100, 200	S, P	4, 6, 15

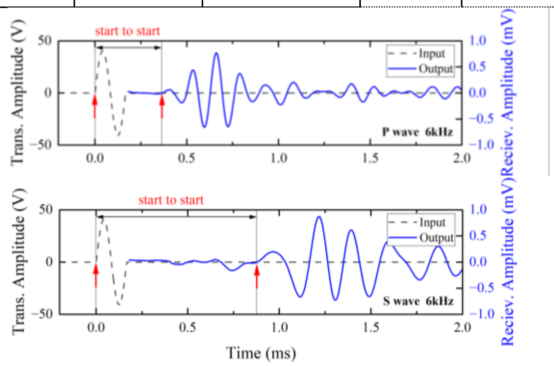

Figure 2, Determination of elastic wave velocities.

Results and Discussions

Figure 3 shows that dynamic small-strain elastic modulus (G, E_{ew}, K) of BOF slag increased with isotropic confining pressure, while the Poisson's ratio ν decreased with pressure, indicating reduced lateral deformation and stronger particle interlocking. It shows that the small-strain stiffness of dry BOF slag is strongly pressure-dependent due to the rearrangement and compression of irregular particles.

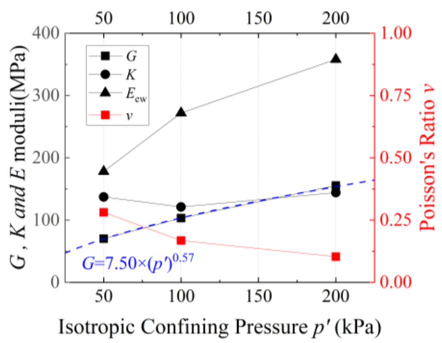

Figure 3, Elastic parameters versus confining pressure.

Figure 4 compares the Young's modulus obtained from LDT (E_{LDT}) and from elastic waves (E_{ew}) for BOF slag and Toyoura sand (Tsutsumi et al., 2006). E_{ew} was consistently higher than E_{LDT}, reflecting the difference between small-strain dynamic and static stiffness. Although BOF slag and Toyoura sand differ in material properties, their Young's moduli were found to be comparable. It shows that BOF slag has strong stress dependency and potential as a pressure-sensitive geomaterial.

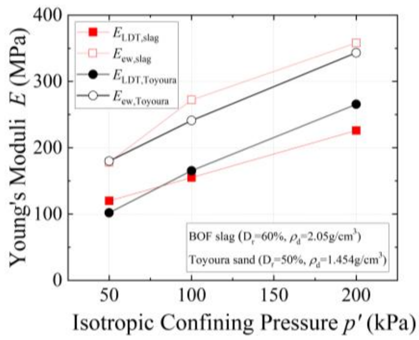

Figure 4, Comparison of Young's moduli.

Conclusion

In this study, the dynamic and static small-strain moduli of BOF slag were evaluated through a series of triaxial tests. The main findings and conclusions are as follows:

1. The elastic stiffness of dry BOF slag increased significantly with isotropic confining pressure.

2. The dynamic modulus E_{ew} obtained from elastic wave measurements was higher than the static modulus E_{LDT}, reflecting the difference between small-strain dynamic stiffness and static cyclic stiffness.

In the future, further studies will consider the effects of particle gradation and carbonation on the small-strain stiffness and long-term mechanical behavior of BOF slag.

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