Compressive characteristics of geogrid-reinforced steel slag

Liyan Wang¹*, Jinsong Li², Yunxiang Tao³, Qi Wang⁴

¹Corresponding Author, Professor (Ph D), School of Civil and architectural engineering, Jiangsu University of science and technology, Zhenjiang, Jiangsu Province, China, No.2 Mengxi Road, Zhenjiang, Jiangsu Province, China, E-mail: wly_yzu@163.com, Phone: +86 18118406438, ORCID: 0000-0002-6564-1090;

²Master’s student (Ba.), School of Civil and architectural engineering, Jiangsu University of science and technology, Zhenjiang, Jiangsu Province, China, No.2 Mengxi Road, Zhenjiang, Jiangsu Province, China, E-mail: 597423703@qq.com;

³Master’s student (Ba.), School of Civil and architectural engineering, Jiangsu University of science and technology, Zhenjiang, Jiangsu Province, China, No.2 Mengxi Road, Zhenjiang, Jiangsu Province, China, E-mail: 2440716609@qq.com;

⁴Master’s student (Ba.), School of Civil and architectural engineering, Jiangsu University of science and technology, Zhenjiang, Jiangsu Province, China, No.2 Mengxi Road, Zhenjiang, Jiangsu Province, China, E-mail: 982302645@qq.com;

Abstract. Steel slag is a solid waste from industrial recycling that is granular and has similar characteristics as those of soils. Geogrids could improve the stability of the granular steel slag, and the technology of geogrid-reinforced steel slag (GRSS) is proposed here. To understand the engineering behaviours of geogrid-reinforced steel slag (GRSS) as a foundation treatment method, it is first important to consider its compressive deformation behaviour. The compression deformation behaviours of GRSS were investigated by carrying out uniaxial compression tests. Furthermore, the compressive moduli of the GRSS were compared with those of traditional soils. The comparisons indicated that the reinforced effect of embedding a two-layer geogrid in the steel slag was the best, which was consistent with the conclusions of other studies. The comparisons also indicated that GRSS had a good compression resistance and had potential as a geotechnical backfill technology.

1. Introduction

Steel slag is a by-product of the steel-making process, and its annual output increases continuously with the increase in steel production. Slag is the second largest waste in the metallurgical industry. Ineffective use of waste steel slag will result in a large amount of dumping, the occupation of farmlands, and pollution of the environment. A waste steel slag yard is shown in Fig. 1. Steel slag has similar characteristics with sand and a high compressive strength. After ageing, the performance of steel slag is generally stable, and aged steel slag can be used as subgrade material and backfill material.

Geogrid is a common reinforcement materials in geotechnical engineering and has been widely applied to reinforce traditional backfill soils to improve their stability. In vertical loading, the geogrid could not only could restrict the lateral displacement of reinforced soils but could also reduce the settlement of reinforced soils. Therefore, many studies regarding the static and seismic behaviours of
geogrid-reinforced geo-structures were carried out in recent years [Nova-Roessig, 2006; Wang, 2011, 2014, 2015, 2017; Latha, 2008; Zhang, 2008].

To make geogrid reinforced steel slag (GRSS) as a good backfill technology and understand more engineering characteristics of GRSS, it is important to study its compressive deformation behaviour as a foundation treatment method. Hence, a series of uniaxial compression tests are carried out in this paper to investigate the compressive characteristics of GRSS.

2. Experimental Work

2.1 Test material

The waste steel slag used in the compression tests was produced by the Yonggang Company in Zhangjiagang, China. The grain size distribution of the waste steel slag is shown in Fig. 2, and Table 1 shows its characteristic parameters. The bulk density of the steel slag was approximately 2.1 g/cm³, and its gradation characteristics are as follows: d₆₀ = 1.2 mm, d₃₀ = 0.47 mm, d₁₀ = 0.13 mm, the coefficient of uniformity (Cu) was 9.2 and the coefficient of curvature is 1.42 (Cc). Therefore, the steel slag was classified as a well-graded material. The maximum and the minimum dry densities were 2.58 g/cm³ and 1.96 g/cm³, respectively. The free calcium oxide content of the waste steel slag was 3.2% (less than 5%), and the ignition loss was 7.8% (less than 8%), indicating that the waste steel slag could be applied in geotechnical backfill.

The basalt fibre is a kind of new inorganic, environmental protection and high-performance fibre material. The geogrid in the test was made of basalt fibre. The width of the transverse rib of the geogrid was equal to the width of the longitudinal rib. Since the test diameter of the sample was small at 61.8 mm, the rectangular mesh spacing of the test geogrid was designed to be 5 mm x 5 mm. The tensile strength of the test geogrid was designed to be 2.2 kN/m² according to a similar criterion. The natural water content of the steel slag was defined to be 9%.

2.2 Test schemes

A uniaxial compressive equipment was applied to investigate the compressive characteristics of the GRSS. The size of the test sample was 61.8 mm (Φ) x 20 mm (H), and the qualities of the test samples were confirmed according to the relative density of the steel slag.

The steel slag samples were divided into 4 layers for compaction, and the steel slag samples with relative densities of 30%, 50% and 70% were compacted 5, 10, and 15 times per layer, respectively, after which the contact surfaces were shaved. The specific test schemes are listed in Table 2. The number of geogrid reinforcement layers (n) was 0, 1, 2 and 3, respectively. The vertical pressure (p) was loaded step-by-step from 50 kPa to 400 kPa.
3. Results and Discussions

3.1 Effect of relative density
The compressive modulus (Es) is one of the important indices used to measure the compressive characteristics of geo-materials. Here, the effects of the relative density and number of geogrid reinforcement layers on the compressive modulus of the GRSS were studied. The compressive moduli of the GRSS are shown in Table 3 under different working conditions.

To unify the comparison standard, the compressive modulus in the stress range from 100-200 kPa is applied as an index to evaluate the level of soil compression. Fig. 3 shows the relationship between the relative density and the compressive moduli in the stress range from 100-200 kPa under different numbers of reinforcement layers. It can be seen from Fig. 3 that the relative density and the number of geogrid reinforcement layers had a significant effect on the compressive modulus of the geogrid-reinforced steel slag. In practical engineering, the compressive modulus could be improved by changing the relative density of the reinforced steel slag. When the relative density cannot be changed, the geogrid layers could be embedded in the steel slag to resist compressive deformation.

It can also be seen from the figure that the compressive moduli could be significantly improved by embedding a two-layer geogrid (n=2) for the steel slag with a low relative density (Dr=30%). When embedding a three-layer geogrid (n=3), the compressive modulus could not be further improved. The compressive moduli could be significantly improved by embedding a one-layer geogrid (n=1) for the steel slag with a high relative density (Dr=70%), but when embedding more geogrid layers, the compressive moduli were gradually reduced and could not be further improved.

3.2 Effect of the number of geogrid reinforcement layers
Fig. 4 shows the relationship between the number of geogrid reinforcement layers and the compressive moduli under different relative densities. As can be seen from Fig. 4(a), the compressive moduli increased with the increase in the number of geogrid reinforcement layers for a loose steel slag with a relative density of 30%, except for the low stress range from 50-100 kPa. The compressive modulus of the three-layer reinforced steel slag (n=3) in the low stress range from 50-100 kPa was smaller than that of the two-layer reinforced steel slag (n=2). The reason is that too many contact interfaces between the geogrid and steel slag brought an increased contact porosity, and steel slag particles in a loose state could fill the contact porosity. Then, the reinforced interface could be easily compressed under a low stress, resulting in a smaller compressive modulus.

As can be seen from Fig. 4(b), the compressive moduli increased with the increase in the number of geogrid reinforcement layers for the mid-dense steel slag with a relative density of 50%, except for three-layer reinforced steel slag (n=3). The compressive moduli of the three-layer reinforced steel slag (n=3) were smaller than that of the two-layer reinforced steel slag (n=2) in the stress range from 50-300 kPa. With the increase in the vertical pressure stress, the compressive moduli increased and

Fig. 3 Relationships between the relative density and compressive moduli of geogrid-reinforced steel slag (100-200 kPa)
became equal to that of two-layer reinforced steel slag (n=2) in the stress range form 300-400 kPa. These phenomena indicate that most of the compressive deformation for the loose state reinforced steel slag had been finished in the low stress section so that the compressive deformation was smaller in the high stress section and the compressive modulus became larger.

As can be seen from Fig. 4(c), the compressive moduli increased first and then decreased with the increase in the number of geogrid reinforcement layers for the dense steel slag with a relative density of 70%. In the stress range from 50-200 kPa, the compressive modulus increased when the geogrid reinforcement layer varied from zero layers (n=0) to one layer (n=1) but decreased when the geogrid reinforcement varied from one layer (n=1) to three layers (n=3).

In general, the reinforced effect of embedding a two-layer geogrid (n=2) in the steel slag was the best. The test conclusion was consistent with the conclusions in other references [Yang, 2006; Yang, 2009].

![Fig. 4](image)

**Fig. 4** Effect of the number of reinforced layers on the compressive moduli of the geogrid-reinforced steel slag

![Fig. 5](image)

**Fig. 5** Comparisons of the compressive moduli between the geogrid-reinforced steel slag and traditional soils (MPa)
4. Comparison with traditional soils
To better understand the compressive resistance of the GRSS technology, it is necessary to compare the compressive moduli of the GRSS with those of the traditional soils. The compressive moduli of traditional soils and GRSS in the stress range from 100-200 kPa under different relative densities are shown in Fig. 5. It can be seen that the effect of the relative density on the compressive modulus was greater than that of the number of geogrid reinforcement layers on the compressive moduli.

The compressive moduli of the GRSS were greater than those of mucky soil and plastic clay and reached the same values of the compressive moduli of the half-dry and hard clay and sand. The compressive moduli of the geogrid-reinforced steel slag in a loose state reached the same level of the compressive moduli of fine sand. The compressive moduli of the GRSS in a mid-dense state reached the same level of the compressive moduli of medium sand. The compressive moduli of the GRSS in a dense state reached the same level of the compressive moduli of coarse sand.

5. Conclusions
(1) The compressive moduli of the GRSS increased with the vertical pressure. The change rules of the compressive moduli of the geogrid-reinforced steel slag with the increase in the relative density were not exactly the same under different numbers of reinforcement layers. The compressive moduli increased with the increase in the relative density for small numbers of reinforcement layers. The compressive moduli in a mid-dense state were smaller than those in a loose state when using more reinforcement layers.

(2) The compressive moduli increased with the increase in the number of geogrid reinforcement layers for the reinforced steel slag in the loose state, except for the low stress section. The compressive moduli first increased and then decreased with the increase in the number of geogrid reinforcement layers for the reinforced steel slag in the mid-dense and dense states. Overall, the reinforced effect of the two-layer geogrid was the best.

(3) Multiple contact interfaces brought by several geogrid reinforcement layers had a significant effect on the compressive moduli, especially for the reinforced steel slag in a dense state. The more contact interfaces there were, the smaller the compressive moduli of the GRSS were. The effect of the contact interfaces between the geogrid and the steel slag on the compressive moduli in the low-stress region was more obvious than in the high-stress region.

(4) The compressive moduli of the GRSS were greater than those of the mucky soil and plastic clay and reached the same values of the compressive moduli of the half-dry and hard clay and sand. The compressive moduli of the reinforced steel slag in a loose state, in a mid-dense state and in a dense state respectively reached the levels of the compressive moduli of fine sand, medium sand and coarse sand. The comparisons indicated that the GRSS had both a good compression resistance and has potential in backfill technology.

| Table 1 Characteristic parameters of the steel slag |
|---------------------------------------------------|
| Bulk density (g/cm$^3$) | $d_{10}$ (mm) | $d_{30}$ (mm) | $d_{60}$ (mm) | Coefficient of uniformity | Coefficient of curvature | Maximum dry density (g/cm$^3$) | Minimum dry density (g/cm$^3$) | Free calcium oxide content | Ignition loss |
|------------------------|------------|-------------|-------------|------------------|-----------------|-----------------|-----------------|-----------------|-------------|
| 2.1                    | 1.2        | 0.47        | 0.13        | 9.2              | 1.42            | 2.58            | 1.96            | 3.2%            | 7.8%        |

| Table 2 Test schemes |
|----------------------|
| Relative density $D_r$ | Control density $\rho_c$ (g/cm$^3$) | Water content $\omega$ (%) | Loading density $\rho$ (g/cm$^3$) | Vertical pressure $p$ (kPa) | Number of geogrid reinforcement layers (n) |
|-----------------------|------------------------|---------------------|-----------------|-------------------|-------------------------------|
| 30%                   | 2.11                   | 9                   | 2.28            | 50, 100, 200, 300, 400 | 0, 1, 2, 3                   |
| 50%                   | 2.23                   | 9                   | 2.41            | 50, 100, 200, 300, 400 | 0, 1, 2, 3                   |
| 70%                   | 2.37                   | 9                   | 2.56            | 50, 100, 200, 300, 400 | 0, 1, 2, 3                   |
Table 3 Compressive moduli under different working conditions (MPa)

| Number of reinforcement layers (n) | Vertical pressure p (kPa) | E_s (MPa) |
|-----------------------------------|---------------------------|-----------|
|                                   |                           | D=30%     | D=50%     | D=70%     |
| 0                                 | 50-100                    | 15        | 17        | 22        |
|                                   | 100-200                   | 25        | 30        | 37        |
|                                   | 200-300                   | 38        | 38        | 53        |
|                                   | 300-400                   | 43        | 48        | 60        |
|                                   | 50-100                    | 15        | 21        | 27        |
| 1                                 | 100-200                   | 27        | 33        | 41        |
|                                   | 200-300                   | 38        | 41        | 58        |
|                                   | 300-400                   | 46        | 52        | 65        |
|                                   | 50-100                    | 21        | 23        | 24        |
| 2                                 | 100-200                   | 31        | 33        | 39        |
|                                   | 200-300                   | 39        | 43        | 63        |
|                                   | 300-400                   | 48        | 54        | 71        |
|                                   | 50-100                    | 18        | 16        | 19        |
| 3                                 | 100-200                   | 31        | 29        | 36        |
|                                   | 200-300                   | 45        | 42        | 52        |
|                                   | 300-400                   | 55        | 55        | 63        |

Acknowledgements
This research was financially supported by the Natural Science Foundation of Jiangsu Province (Grant No. BK20161360), the Six Major Talents Peak in Jiangsu Province in China (Grant No. 2016-JZ-020) and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (Grant No. SJCX18_0773).

References
[1] Ahmed, E. A. E. B. (2013). “Evaluation of steel slag and crushed limestone mixtures as subbase material in flexible pavement.” Ain Shams Engineering Journal, Vol. 4, pp. 43-53.
[2] Bao, C. G., Wang. M. Y., and Ding, J. H. (2013). “Mechanism of Soil Reinforced with Geogrid.” Journal of Yangtze River Scientific Research Institute, No. 30, pp. 34-41. (In Chinese)
[3] Wang, B. H., Wang, Z. H., and Zuo, X. (2017). “Frequency Equation of Flexural Vibrating Cantilever Beam Considering the Rotary Inertial Moment of an Attached Mass.” Mathematical Problems in Engineering, Vol. 4, pp. 1-5.
[4] Feng, H. W. (2012). “The research of deformation rule of high embankment reinforced by geogrid reinforced in construction period”. Hebei University of Technology. (In Chinese)
[5] Gao, Y. F., Yang, S. C., Zhang, F., and Leshchinsky, B. (2016). “Three-dimensional reinforced slopes: Evaluation of required reinforcement strength and embedment length using limit analysis.” Geotextiles and Geomembranes, Vol. 44, No. 2, pp. 133-142.
[6] Nguyen, M. D., Yang, K. H., Lee, S. H., Wu, C. S., and Tsai, M. H. (2013). “Behavior of nonwoven-geotextile-reinforced sand and mobilization of reinforcement strain under triaxial compression.” Geosynthetics International, Vol. 20, No. 3, pp. 1-20.