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Laboratory investigation of particle size effects on the shear behavior of aggregate-geogrid interface

Bingye Han [a,b], Jianming Ling [a], Xiang Shu [c,d], Hongren Gong [b], Baoshan Huang [a,b,e,*]

[a] Key Laboratory of Road and Traffic Engineering of the Ministry of Education, Tongji University, 4800 Cao'an Rd., Shanghai 201804, China
[b] Department of Civil and Environmental Engineering, The University of Tennessee, Knoxville, TN 37996, USA
[c] Hebei Research Institute of Construction and Geotechnical Investigation Co. Ltd., Shijiazhuang 050031, China
[d] The Technology Center of Geotechnical Engineering of Hebei Province, Shijiazhuang 050031, China
[e] School of Transportation Engineering, Tongji University, 4800 Cao'an Rd., Shanghai 201804, China

HIGHLIGHTS

- Direct-shear test was performed to understand aggregate-geogrid interface behavior.
- Impact of aggregate particle size on interfacial shear strength was analyzed.
- Three failure modes of aggregate-geogrid interface were identified.
- A method was proposed for determining optimal geogrid-aggregate combination.

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ABSTRACT

As an effective method to explore the interaction mechanism between aggregate particles and geogrids, a large-scale direct shear test was employed to study the shear behavior of aggregate-geogrid interface and the effects of particle size on the interfacial shear strength. Two types of geogrids with rectangular or triangular aperture and three single-sized coarse aggregates, 12.5–19 mm, 19–25 mm, 25–37.5 mm, were tested in this study. Multiple parameters were employed to investigate the reinforcement of geogrids in aggregate, including peak shear strength, residual shear strength, vertical displacement and interfacial shear strength efficiency coefficient, α. Results show that the values of α ranged from 0.78 to 1.01, and the aggregate-geogrid interface of AGG2 achieved the highest α among the three aggregates, indicating that the 19–25 mm aggregate had the best interlocking effect reinforced with geogrids used in this study. The combinations of geogrids and aggregate exhibited different interaction mechanisms and failure modes. Based on the test results, the method was improved for determining the appropriate geogrid aperture size for an aggregate gradation. Effective interlock could be achieved when the ratio of the equivalent aperture size to particle diameter was 1.30–1.71 for biaxial geogrids and 1.08–1.43 for triaxial geogrids.

1. Introduction

Use of geogrids in the base course is considered an effective way to improve the flexible pavement performance. In the past three decades, researchers have conducted a series of laboratory and field experiments to investigate the mechanical behavior of geogrid reinforcement [1–4]. The results showed that geogrids have a positive effect in enhancing pavement performance, including decreasing the thickness of base course [5–7], reducing the surface rutting [8–10] and extending the pavement service life [11,12].

Geogrids consist of longitudinal and transverse ribs with relatively large apertures, and the ribs of geogrids can confine aggregate and constrain the lateral movement of aggregate to improve pavement performance [7]. The movement of aggregate on geogrid surface or in the apertures of geogrid plays an important role in the interaction between the two mechanisms. However, the interaction is complicated and influenced by many factors including geogrid properties, aggregate properties and loading conditions [13]. Different methods have been used to understand their interaction mechanisms, including pull-out test [14–16], direct shear test [17,18], plane strain test [19,20], and torsional ring shear test [21,22]. Among these methods, the direct shear test, especially

* Corresponding author at: Visiting Professor, School of Transportation Engineering, Tongji University, Shanghai 201804, China; Edwin G Burdette Professor, Department of Civil and Environmental Engineering, The University of Tennessee, Knoxville, TN 37996, USA.
E-mail address: bhuang@utk.edu (B. Huang).

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the large-scale direct shear test, is one of the most commonly used methods to investigate the interface behavior between geogrids and aggregate. Many studies using direct shear test can be found in the literature [23–29].

The geogrid reinforcement effect largely depends on the interactions between the geogrids and aggregate. Gu et al. [30] investigated the effect of geogrid-aggregate shear coefficient on the mechanical reinforcement. Aggregate particles are likely to be trapped into apertures if the ratio of the aperture size to the aggregate particle size, A/D, is appropriate, resulting in an effective interlocking between aggregate and geogrids. Sarsby [31] revealed that the interaction between sand and geogrids can be maximized when the ratio of the minimum width of geogrid aperture to the average particle size, D_{50}, is larger than 3.5. Athanasopoulos [32] showed that the apparent interface friction angle can reach its peak value when the ratio of geotextile aperture size to the average sand particle size is approximately 1.60. Brown et al. [33] reported that the ratio of geogrid aperture size to the nominal size of ballast should be 1.4 based on the settlement behavior of geogrid-reinforced ballast. Indraratna et al. [34] concluded that the optimum ratio of geogrid aperture size to the average ballast size is 1.20 based on the interface shear properties. However, Tang et al. [25] and Liu et al. [24] reported that the shear behavior of the soil-geogrid interface and the aperture size are not closely related.

Although limited researches have been conducted to determine the optimum ratio of geogrid aperture size to aggregate particle size, their conclusions are different or even contradictory. Most of researchers use the average particle size, $D_{50,}$ as a particle indicator to determine the proper ratio of aperture size of geogrids to particle size. However, the use of D_{50} may not be reasonable because the D_{50} is merely a general index of gradation. In fact, particles in the size of D_{50} that can interlock with geogrids may not exist, or if particles in this size exist, the interlocking may come from other particles instead of D_{50}. Also, the percentage of too coarse or too fine aggregate particles could significantly affect the D_{50}, but they contribute little to interlocking between aggregate and geogrids. Therefore, to determine the optimum ratio of A/D, single-sized aggregate is more appropriate. In addition, triaxial geogrids have been successfully used to reinforce different unbounded granular materials. The mechanical reinforcement of biaxial and triaxial geogrids was investigated and compared in other studies [35,36]. However, limited research has been conducted on the optimum ratio of A/D. Therefore, more research efforts are needed to gain a better understanding when triaxial geogrids are used.

The objective of this paper was to utilize the large-scale direct shear tester to explore the effect of particle size on the shear behavior of aggregate-geogrid interface, including both biaxial and triaxial geogrids. The findings from the study can serve as a basis for development of a practical guideline on the recommendation on the optimum A/D ratios. In this study, three single-sized aggregates and two types of geogrids with different aperture shapes were tested to determine the optimum ratio of aperture size to particle size to maximize the benefits of geogrid reinforcement in aggregate. Three possible modes of aggregate-geogrid interface failure were proposed based on the results.

2. Materials and test methods

2.1. Materials

The aggregate used in the study was crushed limestone with angular to sub-angular particles. To investigate the influence of particle size on the shear behavior of aggregate-geogrid interface, the aggregate was sieved and divided into three single-sized aggregate particles, AGG1 (12.5–19 mm), AGG2 (19–25 mm), AGG3 (25–37.5 mm). Its specific gravity was 2.754, 2.791 and 2.733 for AGG1, AGG2 and AGG3, respectively. The geogrids were extruded biaxial polypropylene geogrids and punched polypropylene triaxial geogrids. Their mechanical and physical properties are listed in Table 1.

Table 1
Mechanical and physical properties of geogrids.

Geogrid	Biaxial	Triaxial
Tensile strength at 5% (kN/m)	30	–
Radial stiffness at 0.5% (kN/m)	–	270
Junction efficiency (%)	90	95
Aperture size (mm)	32 × 31	46 × 46 × 46

2.2. Direct shear device

A large-scale direct shear box consisted of a fixed upper box and a moveable lower box, and their dimensions were 50 cm × 50 cm × 18 cm and 65 cm × 50 cm × 18 cm, respectively, as shown in Fig. 1. During the testing, shear area decreased during the shearing, and a shearing force of up to 100 kN could be applied. A normal stress was also applied through a rigid square plate to the aggregate with a capacity of up to 100 kN. The two actuators could apply either displacement-controlled or load-controlled static or cyclic shear force. The horizontal and vertical displacements were measured automatically by two Linear Variable Differential Transformers (LVDT). The maximum measurements of horizontal and vertical actuators were 127 mm and 254 mm, respectively. To reduce the effect of temperature on the experiment, room temperature was kept constant at 20 ± 1 °C.

2.3. Test procedures

The aggregates were air dried and compacted by a concrete electric vibrator in four layers, and the number of vibration and compaction for each layer was 40 times to ensure that the relative dry density of aggregate was kept at 55–58%. The size of geogrids installed at the interface was 71 cm × 48.5 cm, and the geogrids were fixed with steel bars and screws at the front and rear sides of lower box to ensure that the geogrids could be mobilized during the testing. The direct shear test was conducted at different normal stresses of 50, 100 and 150 kPa with a constant shear rate of 1 mm/min in according with ASTM D 5321 [37]. These normal stresses were selected according to the base stress levels in pavement and previous studies [24,28,38]. The test was completed when the horizontal shear displacement reached 100 mm. Table 2 presents the variables considered in the study.

To ensure the accuracy and consistency of the direct shear test, four pre-tests were finished under the same experiment conditions to check the reproducibility. AGG1 particles were used in the pre-test at a normal stress of 50 kPa. The results of shear stress versus shear displacement curves are shown in Fig. 2 and descriptive statistic parameters of the results are presented in Table 3, including peak shear stress τ_p, horizontal displacement at peak shear stress Δ_h, and residual shear stress at the end of the test τ_R. The coefficients of variation of the peak shear stress reported in other researchers' results were 28% and 4.8%, respectively [38,39]. Compared to their coefficients of variation, the results of the current study were considered repeatable and accurate.

3. Results and discussion

The results of the large-size direct shear tests include shear stress versus shear displacement curves, vertical displacement versus shear displacement curves, peak shear strengths and residual shear strengths of aggregate and aggregate-geogrids, and interfacial shear strength efficiency coefficients for different aggregates.

3.1. Shear stress-shear displacement curves

Figs. 3 through 5 show the shear stress-shear displacement curves and vertical displacement-shear displacement curves for different interfaces of reinforced and unreinforced aggregate, including the aggregate-aggregate interface (N), the aggregate-biaxial geogrid interface (R), and the aggregate-triaxial geogrid interface (T). To ensure the repeatability of the tests, two replicates were tested for the unreinforced and reinforced aggregates at each stress state. Fig. 3 shows the case of AGG1 (12.5–19 mm). It was found that the shear stress increased with the increase of the normal stress. The shear stress gradually increased to a peak shear stress during the testing, and then decreased to a residual stress at the end of the test. Both the peak interfacial shear stress of aggregate-biaxial geogrids and aggregate-triaxial geogrids were lower than that of unreinforced aggregate. In Fig. 3, a positive vertical displacement represents a dilation while a negative vertical