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Effect of geosynthetics on shear properties of recycled construction waste[#]

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ABSTRACT

Recycled concrete aggregates and recycled bricks, collectively known as construction and demolition wastes, are renewable resources. Considering the poor performance of recycled aggregate, geosynthetics are generally used to improve its roadability, and the geosynthetics with different strengths have an impact on the interface of the reinforced soil. The monotonic direct shear test on the interface of geosynthetics and reclaimed aggregate are studied based on large-scale direct shear instrument, and consider the influence of normal stress on the interface shear stiffness and damping ratio. Tests showed that: The peak shear stress at the recycled material / geosynthetic interface increases with the increase of the normal stress. The dilatancy of the unreinforced test is stable in the late shearing period, while the dilatancy of the reinforced test is increasing. The peak strength and residual strength of the interface are obviously improved with the increase of the strength of the glass fiber reinforced material, but the integrity of the soil is reduced to a certain extent, which affects the cohesion.

Keywords: Direct shear test, Recycled construction waste, Geosynthetics

NONMENCLATURE

Abbreviations	
RCA	Recycled Concrete Aggregates
RCM	Recycled Clay Masonry
Symbols	
τ_p	Peak shear stress
τ_r	Residual stress
T	Shear strengh
C	Cohesion of particle interface
φ	Internal friction angle
σ	Normal stress
K	Friction coefficient

1. INTRODUCTION

Compared with natural granular materials, construction waste recycled aggregates demonstrate unique sustainable advantages as renewable building materials. The porous structure and rough surface characteristics of recycled concrete aggregate (RCA) and recycled clay masonry (RCM) endow them with distinct physical properties that differ from natural materials in terms of mechanical strength and water absorption. Recent studies (Ge Pei et al., 2021) reveal that using these recycled materials in road engineering can reduce energy consumption by 15-20% during material production while maintaining equivalent bearing capacity. Particularly in pavement construction requiring massive natural resources, recycled aggregates can effectively alleviate the demand for natural stone mining, demonstrating dual benefits in resource regeneration and ecological protection.

Already, more than half of new roads in the United States use recycled concrete, with direct cost down 20%. In Japan, recycled gravel is used as subgrade material and concrete aggregate (Mei et al., 2024). The construction of the road surface itself is very expensive and requires a lot of natural resources, with the concept of resource conservation and ecological protection. China has guided the recycling of concrete pavement, and formulated the technical rules for Technical Guidelines for Recycling of Highway Cement Concrete Pavement and other technical standards. The use of recycled aggregate for highway pavement construction can bring many benefits for environmental, economic and social sustainability (Wang et al., 2021). Zhang et al. (2021) have verified that construction waste can meet the requirements of road performance through tests. Herrador et al. (2012) explored the pavement performance of construction and demolition waste as pavement base material, realized traffic load on real roads, and found that its bearing capacity met the requirements of pavement base.

At present, most of the construction waste recycling treatment is realized through the mixed form of recycled aggregate and soil (Rahman and Ahmad, 2020). The

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construction waste generated by the construction, maintenance and demolition of buildings or structures is very complex in composition, which is mainly divided into concrete blocks, masonry muck, rubble blocks, waste mortar and other wastes (Jan Pešta et al. 2020;Manuel et al., 2021). Vieira et al. (2015) and Santos et al. (2008) believe that recycled concrete and recycled bricks are the best alternative to natural particles in road construction. In order to make the best use of construction waste, some studies have involved the dynamic properties of a mixture of recycled concrete aggregate and recycled bricks under traffic loads. Arulrajah et al. (2012) and Arisha et al. (2016) conducted static triaxial shear and cyclic shear tests on different proportions of recycled concrete and recycled bricks mixtures. The study found that the higher the content of recycled bricks, the lower the elastic modulus. They indicated that some recyclable construction wastes, such as broken bricks, must be mixed with other durable aggregates to improve their performance in pavement base applications. The appropriate proportion of the recycled aggregate and enhance the bond between the aggregate is an effective means to strengthen the soil.

The application of construction waste recycled aggregate to replace natural aggregate in road construction needs to strengthen the overall performance of construction waste, Santos et al. (2008) first proposed the construction waste regeneration materials as geosynthetic reinforcement materials, they combined the direct shear and pull test to study the characteristics of geosynsynthetic materials and construction waste materials interface. Vieira et al. (2015) found that the variability of construction waste was low and suggested that construction waste as reinforced fill to make its better road performance. Vieira et al. (2016) studied the interface properties of the fine grain portion in construction waste and three kinds of geosynthetics through direct shear and pult-out tests, and the research results showed that fine grain portion in construction waste had interface peak shear stress similar to that of natural fillers.

In the urban transition towards sustainable energy systems, geosynthetic-reinforced recycled construction waste demonstrates value. At present, the high-speed railway in mountainous areas and road construction has been widely used in geosynthetic reinforced soil embankment (Shil et al., 2024), the advantages of reinforce are worth promoting in the field of engineering. The correct cognition of the strength and deformation of recycled construction waste and reinforcement solves the problems for construction waste recycling, and plays a guiding role in innovative utilization in road construction.

2. MATERIAL AND METHODS

2.1 Experimental materials

The original materials for the test were taken from the demolition construction dump site of Wenzhou, China. After preliminary sorting, broken the RCA and RCM which selected from the original materials, so as to reduce the particle size and improve the uniformity of particle shape. The road performance index of construction waste recycled particles subgrade was determined based on the "Test Methods of Aggregate for Highway Engineering" (JTG E42-2005) and "the Technical Guidelines for Construction of Highway roadbases in China" (JTG F20-2015). Test results and specifications of road performance are summarized in Table 2-1.

Table 2-1 *Test results and specifications of road performance*

Material	Performance density (g/cm^3)	Crushing Value (%)	Water absorption (particle size < 5mm) (%)	Water absorption (particle size > 5mm) (%)	Los Angeles Abrasion (%)	Soundness (%)	Shape Index (%)
Specification	≥2.5	≤30	≤3.0	≤3.0	≤25	≤12	≤25
RCA	2.45	23	14.5	9.1	22.6	14	9
RCM	2.55	12	6.0	2.8	21.3	14	7

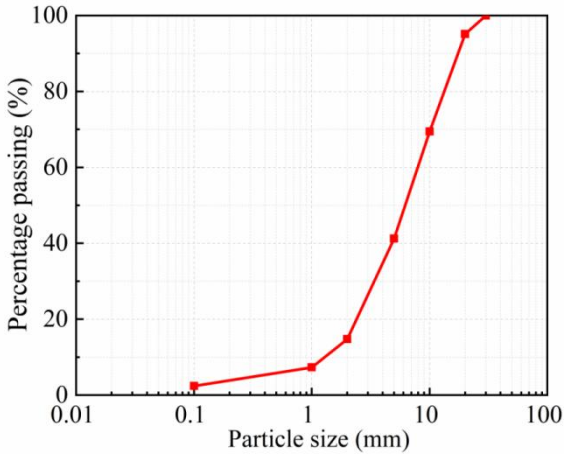

Fig. 2-1 Particle size distribution curves

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The prepared RCA and RCM will be configured with recycled gradation mixture according to the particle size distribution curves as shown in Fig. 2-1, and the content of RCA is 10% (the content of RCM is 90%). The reclaimed mixture configured according to the optimal moisture content should be left standing in a closed container for 24 hours to make the particles fully absorb water and prevent the particles from sliding due to excess water on the surface of the particles.

Table 2-2 lists the basic physical parameters of the mixture sample.

Table 2-2 *Physical parameter of the mixture sample*

Physical parameter	value
Ratio of RCA and RCM	1:9
Specific gravity, ρ_a (g/cm^3)	2.54
Maximum dry density, $\rho_{d,max}$ (g/cm^3)	1.87
Optimum moisture content, ω_{opt} (%)	10.7
Water absorption，(%)	5.3
Compaction degree, D_c (%)	81.95
Coefficient of uniformity, C_u	6.12
Coefficient of curvature, C_c	1.23

Table 2-3 lists the technical specifications of geosynthetics.

sensors). The data acquisition system records horizontal/vertical displacements and shear stress.

In experiments, the lower soil sample was prepared first using layered filling (25mm per layer) and heavy hammer compaction. Geosynthetics were installed at the interface, clamped on both sides to the lower box with fixtures and iron plates. The upper box was filled using the same compaction method as the lower layer.

The shear rate of the monotone shear test was 1mm/min, conforming to the ASTM standard D5321 (2002), and the direct shear displacement was controlled at 60mm. The data acquisition system records horizontal and vertical movements, and all shear stress and displacement measurements were recorded at a frequency of 0.2s.

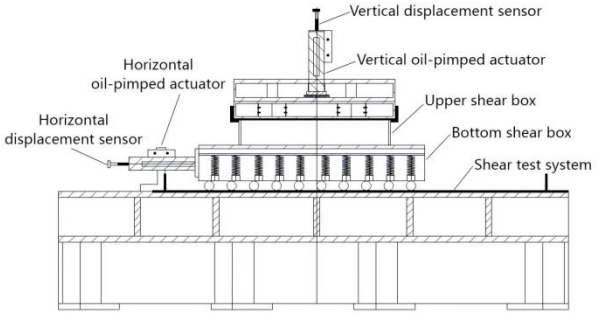

Fig. 2-2 Direct shear apparatus and direct shear box

Table 2-3 *The technical specifications of geosynthetics*

Specification	EGA30-30	EGA50-50	EGA80-80
Raw material	fiberglass	fiberglass	fiberglass
Basic weight	200 g/m^2	268 g/m^2	377 g/m^2
Transverse ultimate tensile strength	34 kN	51 kN	83 kN
Longitudinal ultimate tensile strength	33 kN	52 kN	82 kN
Elongation ultimate (%)	2.7 %	2.6 %	2.8 %
Hole size (mm)	25 × 25	25 × 25	25 × 25

2.2 Test apparatus and procedures

The direct shear instrument used in this paper is consisted with shear test, oil pump and data acquisition systems in Fig.2-2. This customized apparatus tests geosynthetic-soil interface shear properties. The upper/lower shear boxes have internal dimensions of 600 × 200 × 50 mm and 800 × 200 × 50 mm respectively, hydraulically actuated. The upper box connects to a hydraulic servo system allowing 150mm vertical movement, with computer-controlled cyclic vertical/horizontal loading. Maximum vertical/shear loads are 60 kN/35 kN (± 1% accuracy verified by pressure

3. RESULTS AND DISCUSSION

3.1 Stress-Displacement Relationship and Volumetric Behavior of Interfaces

Note that the maximum shear stress during shearing is termed as interface peak shear stress (τ_p), and the shear stress at the critical state (where the shear stress remains constant with increasing shear displacement) is named interfacial residual stress (τ_r) (Wang et al., 2019).

Fig.3-1 demonstrates that reinforced interfaces exhibit 33%-116% higher shear strength than unreinforced specimens under identical normal stresses. The reinforcement effect intensifies with increasing

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normal stress, as geosynthetics effectively restrict particle sliding and rotation. Notably, 50kN and 30kN fiberglass reinforcements showed comparable performance under high normal stresses.

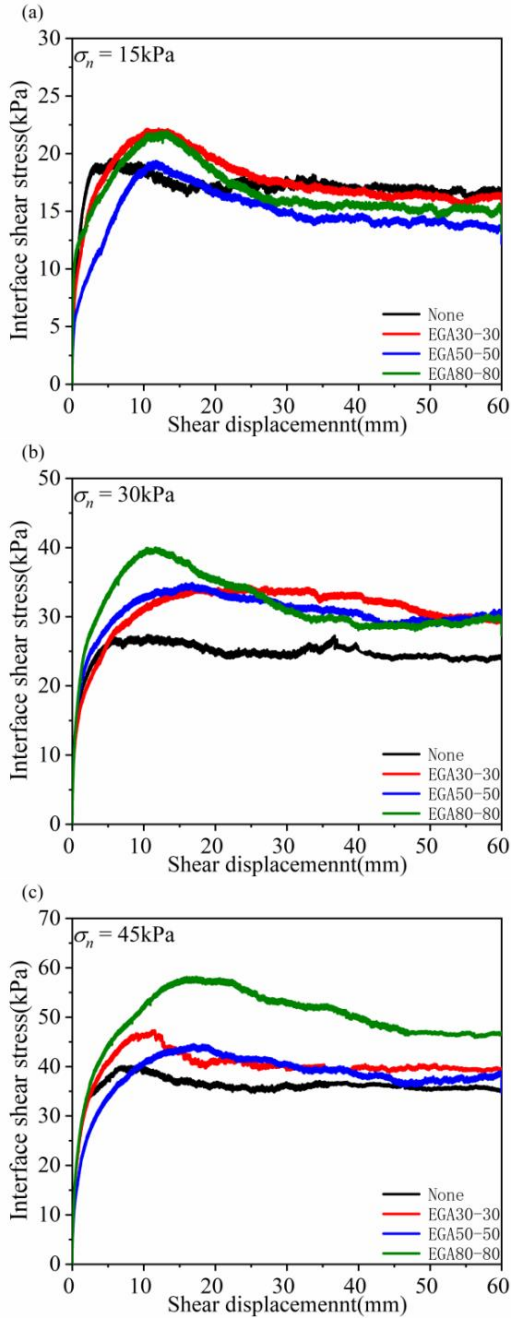

Fig. 3-1 Shear stress-shear displacement relationship

As shown in Fig.3-2, all specimens initially exhibited shear contraction (negative values) followed by dilation (positive values). Reinforced interfaces demonstrated continuous dilatancy growth during shearing, contrasting with the stabilized dilation in unreinforced specimens. At 15kPa normal stress, 30kN/50kN geosynthetics reached maximum shear displacements of 0.27mm. Under 50kN/80kN reinforcements, displacements increased by 33% and 116% respectively compared to unreinforced cases, indicating geosynthetic strength and normal stress jointly govern interface volumetric behavior.

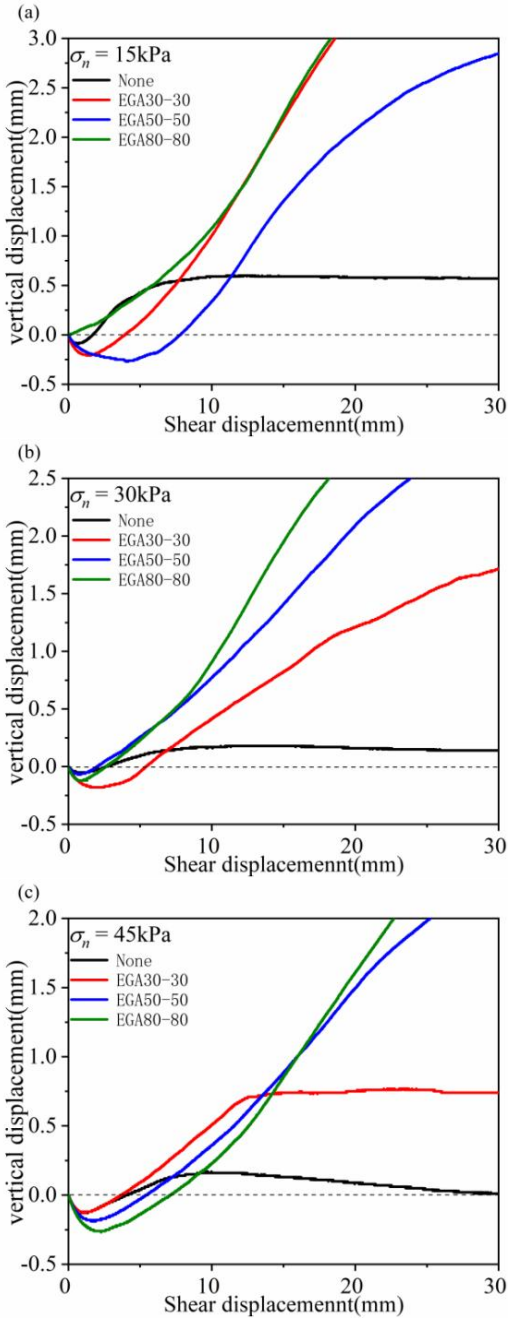

Fig. 3-2 Comparison of shear displacement-vertical displacement under different geosynthetics strengths

3.2 Peak and residual shear strength and deformation

Assuming that the shear stress on the shear surface is evenly distributed, the shear strength of recycled graded mixture conforms to the Moore-Coulen strength theory. The calculation formula of the shear strength on

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the shear surface of the regenerated graded mixture is expressed as:

$$T = C + \sigma \tan\varphi \qquad (3\text{-}1)$$

Mohr-Coulomb strength theory can also be used to calculate the shear strength of the interface between geosynthetic materials and recycled graded mixtures:

$$T_{sg} = C_{sg} + \sigma \tan\varphi_{sg} \qquad (3\text{-}2)$$

The friction coefficient ratio is:

$$K = \tan\varphi_{sg} / \tan\varphi \qquad (3\text{-}3)$$

Where T is the shear strength of the shear plane of recycled graded mixture; C is the cohesion of particle interface; σ is the normal stress of the interface of geosynthetics and aggregates; φ is the internal friction angle of aggregates.

Fig. 3-3 presents the interface peak and residual shear stress envelopes (R^2 denotes regression coefficient). The interfacial adhesion and friction angle are critical parameters for shear strength analysis: with increasing normal stress, the peak apparent cohesion (C_p) values are 8.14, 9.38, 7.65 and 3.72 kPa, while residual apparent cohesion (C_r) measures 7.09, 3.71, 3.59 and 2.22 kPa. The peak friction angles (φ_p) range from 34.86° to 50.42° , and residual friction angles (φ_r) from 31.69° to 47.32° . The corresponding peak (K_p) and residual (Kr) interface friction coefficients are 1/1.21/1.20/1.73 and 1/1.32/1.23/1.74 respectively. All geogrid types exhibit friction coefficients exceeding unity, demonstrating geosynthetics effectiveness in enhancing shear strength of recycled graded mixtures. The R^2 values approaching 1 for shear-normal stress fitting curves confirm excellent regression reliability.

Fig. 3-4 shows the parameter curve of the peak and residual strength regarding the cohesion force and the internal friction angle. As the strength increases, the cohesion force decreases linearly, the possible reason may be the highstrength geosynthetics weaken the occlusal interaction between the particles during the shear process, thus reducing the shear strength on the shear plane. The variation of geosynthetics strength also has a great influence on the internal friction angle, and the internal friction angle with geosynthetics is always greater than that without geosynthetics.

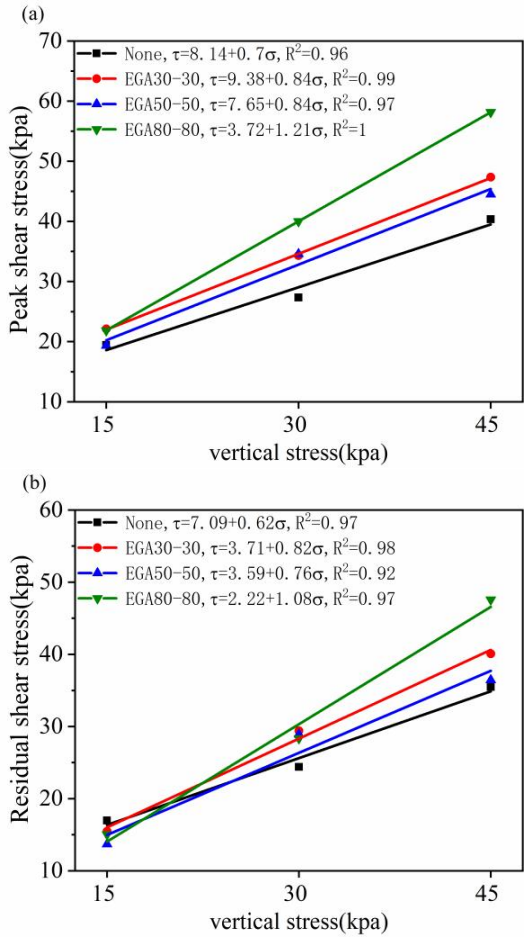

Fig. 3-3 (a) Interface peak shear stress envelope; (b) Interface residual shear stress envelope.

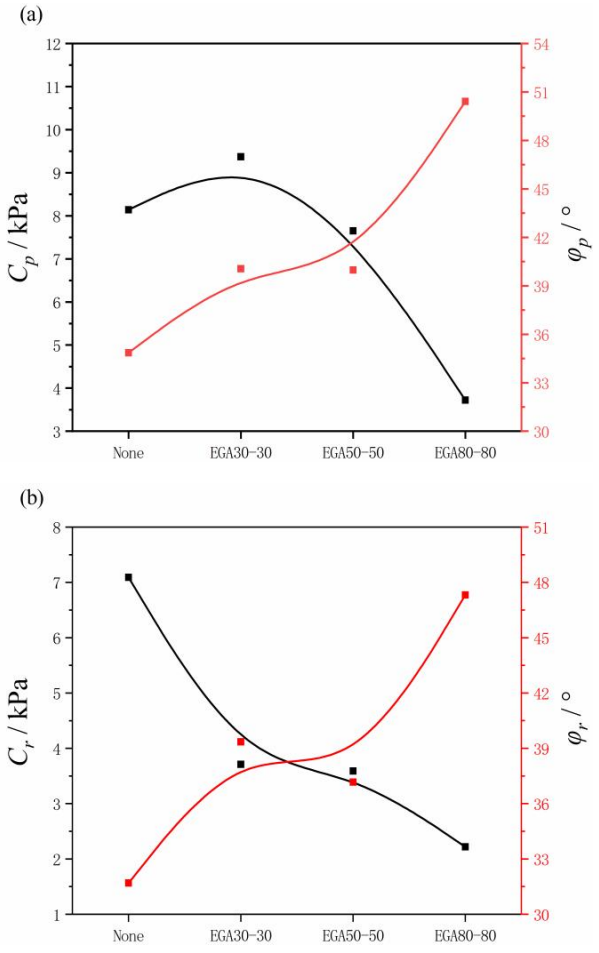

Fig. 3-4 (a) Peak strength parameter; (b) Residual strength parameter.

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4. CONCLUSIONS

This paper conducted a systematic investigation of the effect of the shear properties of the recycled material/geosynthetic interface under different conditions through a series of static shear tests. The sum up everything that has been stated so far:

(1) Under the action of different normal stresses, the recycled material/geosynthetic interface showed typical shear-softening and dilation behaviors under the different normal stresses. The peak shear stress and residual shear stress both increase with the increase of normal stress. The dilatancy of the sample is not directly related to the grid, but is related to the normal stress.

(2) The shear strength and friction coefficient of the recycled material/geosynthetic interface are higher than those of the unreinforced recycled construction waste particle interface under the same conditions, which is more obvious with large normal stress. The reinforced effect of high strength (80kN) geosynthetic is the best. Some obvious reasons for the recycled material/geosynthetic interface cohesion decreased to a certain extent are related to the fact that the geosynthetics weaken the occlusion effect between the particles.

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