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Reuse of construction waste: performance under repeated loading

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The use of recycled aggregates has increased greatly over the last decade owing to enhanced environmental sensitivities. The level of performance required by such materials is dependent upon the applications for which they are used. Many recycled construction wastes have adequate shear strength in relation to various geotechnical applications. However, a possible drawback of these materials is the risk of crushing during repeated loading. The work reported in this paper examined two waste materials: crushed concrete and building debris, both regarded as construction wastes. Tests were also performed on traditionally used crushed rock, in this case basalt. The materials were subjected to repeated loading in a large direct shear apparatus. The amount of crushing was quantified by performing particle size analysis of the tested material. The results have shown that both recycled construction wastes were susceptible to particle crushing. The amount of crushing was influenced by both the vertical pressure and the number of loading cycles. This leads to a marked decrease in peak friction angle.

NOTATION

C_U	uniformity coefficient
D_{10}	maximum size of smallest 10% of sample
D_{60}	maximum size of the smallest 60% of sample
σ_n	normal stress
τ	shear stress
ν	specific volume
ϕ'	angle of internal friction

1. INTRODUCTION

The UK construction industry faces significant concerns about material supply in the future. Natural material resources are not unlimited, and their extraction causes increasingly unacceptable environmental impacts. The industry also produces a large amount of waste material, at about four times the rate of household waste production,¹ from activities such as demolition, excavation and site preparation. Waste from construction sites in the United Kingdom totals some 70 million tonnes per annum. A report by Sir John Egan on improvement of the construction industry highlighted the need to eliminate or recycle waste materials.² An earlier survey by Latham highlighted the scope for increasing the efficiency of

UK construction practices, and offered the prospect of reducing project cost by 30% by 2000 by recycling materials.³

The UK government has set a broad objective to reduce the supply of aggregates from primary land-won sources in England to 68% by 2006.⁴ It has also set a target for the use of secondary (reclaimed) aggregates in England from 40 million tonnes per annum by 2001 to 55 million tonnes per annum by 2006. In order for these targets to be achieved, designers need to play their part in encouraging the adoption of reclaimed materials.

Aggregates have many different applications in the construction industry, such as in concrete production, foundation and pavement applications such as sub-bases, railway tracks, drainage and general earthworks filling. They are also used for ground improvement purposes such as vibrated columns, gabion walls and slope stabilisation. Large quantities of freshly quarried stones are used in these applications. Recycling of construction waste materials would clearly provide substantial benefits to the industry in terms of reduced material supply and waste disposal cost, increased sustainability, and reduced environmental impact.

Construction waste, particularly waste produced by demolition, consists typically of heterogeneous materials with particle sizes ranging from gravel to boulders. Individual particles vary considerably in mechanical strength. Touahamia *et al.*⁵ examined ways of enhancing the shear strength of recycled material using geogrids, and found that the inclusion of geogrids increased the shear resistance by at least 20%. One of the problems encountered in this research was that the recycled material exhibited a significant amount of particle crushing during the shearing process, particularly in the case of crushed concrete. A similar observation was also made by Miura and O'Hara.⁶ They suggested that particle crushing was a significant problem in low-strength materials such as decomposed aggregates. The particle-crushing phenomenon is not unique to decomposed aggregates. Indraratna and co-workers^{7,8} performed a series of isotropically consolidated triaxial compression tests on basalt and found that the aggregates exhibited a strong tendency for crushing at large confining pressure at large strain deformation. Larger particles usually exhibit a stronger tendency for particle breakage.

However, Hyodo *et al.*⁹ reported a series of triaxial tests on silica sand and found that the particle crushing was very significant at high confining pressures. Such particle crushing and degradation can be a significant issue in certain geotechnical applications. Therefore any attempt to utilise construction waste for geotechnical applications should examine this factor carefully. This paper reports further work on the effects of repeated shear loading on the resistance to particle crushing of recycled construction wastes.

2. LABORATORY EXPERIMENTS

The laboratory work consisted of testing three coarse granular materials

- (a) crushed basalt
- (b) crushed concrete
- (c) crushed brickwork.

All three materials were categorised as uniformly graded gravel, with particle sizes ranging from 20 mm to 40 mm. Crushed concrete and building debris were prepared in the laboratory. The tests were performed in a 305 mm × 305 mm large direct shear box under four different vertical stresses.

The uniformly graded basalt was obtained from a local supplier (Whitemountain Quarries, Belfast). The crushed concrete came from concrete cubes tested in the Northern Ireland Technology Centre Construction Division Laboratory at Queen's University Belfast. Preparation of cubes used 12 mm aggregates, and the cubes had an average compressive strength of 35 MN/m². The cubes were crushed and the resulting material sieved. Particles having sizes between 20 mm and 40 mm were considered to be suitable for testing. The building debris was obtained from a

convenient demolition site. The crushed brickwork contained predominantly bricks (at least 95% by mass) and mortar. Wood content was removed, and the brickwork was crushed and then sieved. Particle sizes between 20 mm and 40 mm were again considered suitable for testing.

The tests were performed under four different initial vertical pressures: 60 kPa, 120 kPa, 240 kPa and 300 kPa. The vertical force remained constant during shearing. In each test the amount of material used for preparing the sample was carefully measured. The materials were compacted in the box in three layers using a vibrating plate intended to simulate the likely site procedure used in laying such materials. The sample preparation process can lead to some particle crushing,¹⁰ but the effect is considered small compared with the crushing caused by the shearing process, as indicated by the segregated particle degradation along the shear plane noted in the shear box tests. Samples were sheared at 1.5 mm/min. During shearing the shear displacement, the vertical displacement and the shear load applied to the sample were carefully recorded. Using this information the stress–strain responses of the materials were established. Particle densities (that is, aggregate densities) were measured and found to be 2700 kg/m³, 2450 kg/m³ and 2000 kg/m³ for crushed rock, concrete and crushed brickwork respectively. The average specific volumes before shearing of the basalt, crushed concrete and building debris were 1.74 ± 0.03 , 2.08 ± 0.05 and 1.90 ± 0.07 respectively. The variation is small given the nature of the test and compaction method adopted.

The primary objective of the work was to examine the performance of the recycled materials when subjected to repeated shearing under constant vertical loading. Tests were

Fig. 1. Stress–strain response of basalt during repeated shearing; (a) initial vertical pressure 60 kPa; (b) initial vertical pressure 300 kPa

conducted using 1, 2, 4 or 8 loading cycles. These were carried out by shearing the sample to the maximum shear displacement possible and then reversing the shear displacement in order to bring the box back to its original position. At this stage, prior to starting the subsequent loading cycle, the top plate on the sample was readjusted, if necessary, as the plate had a tendency to rotate during the loading cycle.

At the end of the test each sample was sieved in order to establish the amount of crushing associated with the shearing process.

3. TEST RESULTS AND EVALUATION

Figures 1, 2 and 3 illustrate the relationship between the shear stress and horizontal displacement for basalt, crushed concrete

and building debris respectively for samples subjected 60 kPa and 300 kPa of vertical stresses. Also shown in Figs 1, 2 and 3 are the changes in the volume of the sample during shearing. The samples were taken to the maximum horizontal displacement that could be applied in one direction in the large direct shear apparatus.

The first loading cycle generally produced a stress–strain curve typical of hard coarse granular material, whereby the shear stress gradually increased with shear displacement to a well-defined maximum. The maximum shear stress was mobilised at a horizontal displacement of about 25 mm. However, for subsequent loading the stress–strain curves were less typical of hard granular material, particularly at high vertical pressures. In these cases the failure shear stress for analysis purposes was taken as the pressure at the end of the test, after the last cycle.

When shearing was performed with a vertical stress of 60 kPa, the increase in shear resistance was accompanied by a reduction in volume at the earlier stage of shearing; this was followed by dilation for all three materials tested. This pattern continued in subsequent loading cycles. At a vertical stress of 300 kPa the altered basalt exhibited an increase in shear resistance accompanied by a contraction at the earlier stage of shearing followed by dilation. However, crushed concrete and crushed brickwork exhibited reduction in volume throughout the entire shearing process. This pattern persisted in every loading cycle. The specific volume during the shearing was calculated from the vertical displacement of the loading plate. In the second and subsequent loading cycles the initial sample height was measured prior to each stage.

Figure 4 shows the relationship between the maximum shear stress and the maximum vertical pressure at the maximum v for all three materials tested under repeated loading. Based on a linear interpretation of the shear strength envelope, an estimated angle of internal friction, ϕ' , of basalt in the first loading cycle is approximately 47° , which reduced to 45° after eight cycles. This reduction is negligible for practical applications. The friction angle, ϕ' , of crushed concrete reduced from 43° in the first cycle to 38° in the eight cycles. This reduction in the angle of internal friction due to repeated loading is significant. A similar reduction was observed when building debris was taken through the sequence of loading cycles, with ϕ' reducing from 43° in the first cycle to 39° in the eighth cycle. The reduction in the angle of internal friction of these materials was largely due to particle crushing caused by the repeated loading. At the end of the test the sample in the box was carefully examined in order to assess the amount of particle crushing. Three distinct layers were identified when crushed concrete and building debris were taken through the sequence of repeated loading.

- The top layer generally contained intact material, with no significant evidence of particle crushing, suggesting little influence from the compaction process.
- The middle layer contained distinctively different material from the original material used, particularly in the case of crushed concrete, where the intense shearing process stripped off the mortar surrounding the aggregate used in manufacturing the concrete, leaving a thin blanket of aggregate along the line of the shearing plane.

Fig. 4. Strength envelope for: (a) basalt; (b) crushed concrete; (c) crushed brickwork

- The bottom layer contained smaller particles and the stripped hardened mortar from the concrete, which had migrated downwards into the voids of the original material used for making the sample.

The above observations have prompted further assessment of the quantity of particle crushing in relation to the vertical pressure at which the shearing was performed and the number of loading cycles.

After each test, at the completion of the particular loading cycle the tested material was sieved in order to establish the

Fig. 5. Particle size distribution original and after testing (after loading cycle 1): (a) basalt; (b) crushed concrete; (c) crushed brickwork

Fig. 6. Particle size distribution original and after testing (after loading cycle 8): (a) basalt; (b) crushed concrete; (c) crushed brickwork

particle size distribution. Figs 5 and 6 show the particle size distributions for basalt, crushed concrete and crushed brickwork subjected to a single loading cycle and eight loading cycles respectively under various vertical pressures. Particle size distributions of the above materials were also assessed after four loading cycles, but for simplicity they are not shown here. As can be seen, basalt was more resistant to particle crushing. The coefficient of uniformity C_U ($C_U = D_{60}/D_{10}$) of the original material was approximately 1.15. This increased slightly to 2.3 after eight loading cycles when sheared under 300 kPa of vertical stress. It appears that crushed concrete and building debris are very susceptible to particle crushing. This observation agrees with the previous findings reported by Miura and O'Hara,⁶ who suggested that severe particle crushing was a particular problem in low-strength aggregates. Indraratna and Salim⁸ reported that the particle crushing of

basalt was strongly influenced by consolidation pressure and axial strain under triaxial loading. This agrees with the present findings that the amount of crushing appears to have increased with the magnitude of vertical pressure and the number of loading cycles. The coefficient of uniformity, C_U , of the original crushed concrete and building debris was 1.15 and 1.6 respectively. After the intense shearing process, through eight loading cycles under 300 kPa of vertical pressure, uniformity coefficients increased to 4.5 and 7 for crushed concrete and brickwork respectively. These increases are significant, and agree with the visual observations made during the test.

4. CONCLUSION

The performances of recycled concrete and brickwork were compared with traditionally used crushed rock, in this case basalt. The samples of these materials were tested in a 305 mm

shear box under initial vertical stresses of 60–300 kPa. The samples were subjected to repeated shear loading for up to eight cycles.

The work has shown that recycled construction wastes have significant shear strength, and these materials could be utilised in various geotechnical applications. The angle of internal friction of the basalt reduced from 47° to 45° after eight loading cycles. When the recycled concrete was subjected to repeated loading the angle of internal friction reduced from 43° to approximately 38°, whereas for crushed brickwork the reduction was from 43° to 39°. The reductions in the frictional resistance, particularly in the case of recycled materials, are due largely to particle crushing caused by the repeated loading. The amount of crushing appeared to have increased with the intensity of the vertical pressure normal to the shearing plane, leading to a significant amount of vertical compression of the material. This study therefore suggests that a careful consideration must be given to the suitability of these materials in civil engineering applications where the loading conditions are intensive and cyclic in nature.

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