Direct shear box tests on full-scale recycled aggregate used in temporary works

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Abstract (200 words)

The use of recycled aggregate is widely seen as an option in civil engineering projects to meet carbon offset targets. This material is used for a range of applications (e.g. load distribution platforms, sub-bases, general backfill) and can consist of natural aggregates or recycled components. Therefore, its engineering characteristics can vary widely. It is important to characterise accurately the material properties of the aggregate to guarantee safe, economical solutions. The angle of friction is often the main parameter required for geotechnical design and usually obtained by laboratory tests. However, when using standard laboratory equipment there is an upper limit to the size of particle that can be tested, rendering such apparatus inappropriate for obtaining the shear parameters of recycled aggregate (specified size fraction of 0-125mm). A new unique Giant Shear Box Facility, capable of testing samples with particle sizes up to 190mm diameter, has been established at City St George's, University of London. Series of tests were conducted to determine the strength parameters of the recycled aggregate currently being used for working platforms on HS2 – Euston Site. Three different material specifications were tested, the results indicating that the strength parameters were a function of both aggregate constituents and grading.

Keywords chosen from ICE Publishing list

Aggregates; Piles & piling; Shear strength; Temporary Works; Testing, Apparatus & Methods

List of notations

C_c is the Coefficient of Curvature

C_u is the Uniformity Coefficient

D_{10} is the particle size at which 10% of the particles are finer

D_{30} is the particle size at which 30% of the particles are finer

D_{60} is the particle size at which 60% of the particles are finer

M1 is the recycled aggregate with least level of control measures

M2 is the recycled aggregate with a medium level of control measures

M3 is the recycled aggregate with the highest level of control measures

z is the sample height

γ_s is the shear strain

Δh is the horizontal potentiometer measured displacement

ε_v is the volumetric strain

σ' is the normal effective stress

τ is the shear stress

Φ' is the angle of friction

1. Introduction

1.1 Background

A working platform is a ground-supporting structure which consists of coarse-grained material (mostly aggregates) and is often used as a safe and sufficiently durable surface for construction plant (such as piling rigs and cranes) to move and operate. It has become common practice to use recycled aggregate (mostly construction demolition waste such as brick and concrete) to reduce costs related to the temporary works on large scale infrastructure projects (TWf, 2019). These costs often relate to the extraction and transportation (lorry movements) of granular material and the risk of incidents during quarrying operations. Further benefits associated with the use of recycled aggregates are from the reduction in embedded carbon due to minimising extraction, transportation and landfilling of primary aggregates. However, these advancements towards more sustainable practices must also still satisfy current design approaches in order to prevent catastrophic failures; such as a piling rig overturning.

Granular working platform guidance (e.g. TWf, 2019; BRE 470, 2004) currently assume a failure mechanism in the granular layer which determines the thickness (and therefore stability) of the working platform. The main design parameter which influences the platform thickness is the angle of friction, Φ', of the material used in the construction. An overestimation of this angle would lead to a platform that is too shallow and therefore an unsafe structure. Conversely, underestimating this angle would lead to an uneconomic design in the form of an excessively thick platform. Depending on the sources from which the granular platform material is derived, its characteristics can vary significantly (e.g. particle size distribution, constituents and hardness of particles) and with them the representative angle of friction.

In the UK, recycled aggregate containing crushed hardcore materials (including concrete products and quarried natural aggregates) ranging in size from 0.063 mm to 125 mm (Department for Transport, 2017) is known as "Class 6F5" or, simply, "6F5". The inherent issues of both variability and particle size associated with 6F5 aggregate present significant challenges in assessing a representative shear strength determined as an angle of friction. It is not possible to obtain this parameter using standard apparatus because the particle size is too great. Even

commercially available “large” direct shear boxes, which have plan dimensions of 300 mm x 300 mm, are too small to meet recommended ratios of box size to particle size in both ASTM Standards (D3080, 2011) and BSI (1990). The heterogeneity of 6F5 aggregate results in it not being possible to use the technique of testing samples of the material in which the grading curve has been scaled down to allow testing in standard apparatus (Tanghetti, 2021). Therefore, to obtain reliable values of the shear strength parameters of 6F5 aggregate it is necessary to test the material in suitably large – non-standard – shear apparatus.

This has led to a collaboration between SCS Railways (Skanska, Costain, STRABAG Joint Venture Main Works lot S1 and S2) – one of the joint venture organisations constructing the UK’s High Speed 2 Railway (HS2) - and City St George’s, University of London to develop a suitable method for measuring the representative shear strength parameters of 6F5 aggregate. This study was based on testing 6F5 aggregate obtained from a number of HS2 sites in a series of direct shear tests using the Giant Shear Box facility developed at City St George’s, University of London, Tanghetti *et al.* (2019, 2021). The aim was to assist SCS Railways to reduce the cost and time associated with the construction of working platforms and contribute to HS2 achieving its 50% carbon reduction target through design efficiency.

1.2 Previous studies

A commonly used laboratory method for determining the angle of friction of soils is the direct shear test that, compared with other test methods (such as the triaxial test), is a relatively quick and inexpensive tool for determining the shear properties of the material under drained conditions. Standard shear box apparatus typically have a width (or diameter) of 64-73 mm (Bareither *et al.*, 2008) so the maximum particle size which could normally be accommodated in these apparatus whilst respecting the guidance in ASTM and BSI standards is approximately 5 mm and, depending on the testing device, rarely exceeds 10 mm with standard apparatus (Simoni & Houlsby, 2006).

Testing material in an apparatus that is not large enough (based on the ratio of particle to apparatus size) leads to a scale effect. This effect results in an increase in the measured angle

of friction when testing the sample in a box whose height/width to maximum particle size ratios fall below certain limits (e.g. Deiminiat *et al.*, 2022). Minimum ratios of height/width to maximum particle size are recommended in both ASTM D3080 (ASTM, 2011) and BS EN ISO 17892 10 (BSI, 2018). In the former it is specified that the ratio of width (or diameter) of the sample tested to maximum particle size should always exceed 10 and the height of sample to maximum particle size ratio should exceed 6.In the latterthe corresponding value of these ratios are 15 and 6. However, notwithstanding this guidance, studies are reported in the literature in which the results of shear tests showed a different response when testing samples of the same material in different box sizes, despite all of them adhering to the limits prescribed in the ASTM standard (Sobol *et al.*, 2015; Cerato & Lutenegger, 2006; Fu *et al.*, 2015). Of particular relevance, is that higher values of the angle of friction were measured when testing the same material in smaller shear boxes. Among these studies, is the research conducted by Fu *et al.* (2015) who tested samples of two different materials using an apparatus in which the height and diameter could be varied. These results demonstrated limiting values of height/width to maximum particle size ratios which appear more restrictive than the ones provided by the ASTM D3080 (in the sense that they would require a larger apparatus) in order to avoid scale effects. By observing the variation of the obtained friction angle when changing height and width of the model it was deduced that reliable results were obtained when the width (or diameter) of the sample to maximum particle size ratio exceeds 15 and the height to maximum particle size ratio is larger than 10.

An alternative approach that has been adopted for testing aggregates with large particle sizes consists of preparing a sample corresponding to a smaller scale representation of the original material and testing it using a standard apparatus (Moulay Smaîne *et al.*, 2014; Kim & Ha, 2014). The particle size distribution of the original soil is scaled to fit the size of a standard shear box so that proper values of height/width to maximum particle ratio can be maintained. Despite this being common practice when testing material with large particles which cannot properly fit the size of standard apparatus, the presence of a scale effect associated with the reduction of large particle sizescontent in a soil sample due to the scaling of the grading curve has been identified in the literature (Simoni & Houlsby, 2006; Moulay Smaîne *et al.*, 2014; Bareither *et al.*,

2008; Nakao & Fytus, 2008). However, in the case of 6F5, since the material is highly heterogenous, it is not possible to create a scaled sample that reflects both the constituents and the grading of the original material. Considering the previously explained scale effects influencing the measurement of the angle of friction of a sample, it has been proposed (e.g. by Bradfield *et al.*, 2015; Estaire & Santana, 2018) that the only way to measure reliably the shear strength properties of geomaterials that have a large particle size is to use an apparatus that maintains the sample size to apparatus limits identified by Fu *et al.* (2015).

A survey of large shear boxes has been conducted by Menéndez & Estaire (2021). Examples of large shear box apparatus that were developed and used to investigate either the shear strength parameters of geomaterials or the soil/reinforcement element interaction properties are described in the literature (Davies & Le Masurier, 1997; Barr *et al.*, 1991; Jain & Gupta, 1971; Pedley, 1990; Krahan *et al.*, 2007, Bradfield *et al.*, 2015; Estaire & Olalla, 2005). Except for the specific example described by Davies & Le Masurier, 1997 and Barr *et al.* (1991), which was designed with a vertical shear plane to facilitate the investigation of mechanisms associated with the shear strength enhancement resulting from 2.8 m long steel soil nails located in sand or clay, all the examples found in the literature propose the use of a horizontal shear plane. Joist sections firmly attached to a strong floor (as described by Davies & Le Masurier, 1997) support the shear box and, at the same time, provide runways on which machine skates can slide allowing movement of one of the two halves (while the other one is maintained fixed). Considering the high stress levels required to shear large samples, a reaction frame (as suggested by Jain & Gupta, 1971) is required to support and resist the forces applied by hydraulic jacks which apply the normal and shear loads.

Examples of shear box apparatus developed to measure the shear strength parameters of geomaterials having particle sizes of up to 125 mm that are most relevant to the study reported herein are presented by Bradfield *et al.* (2015), Estaire & Olalla (2005) and Tanghetti *et al.* (2019 and 2021). Bradfield *et al.* (2015) fabricated a direct shear apparatus, with a specimen size of 720 mm x 720 mm x 600 mm (high) and a normal stress capacity of 4.5 MPa to test siltstone with particles up to 100 mm. The apparatus reported by Estaire & Olalla (2005) has a

shear plane of 1000 mm x 1000 mm and sample height of 1000 mm and has been used for testing crushed rock aggregates with particle sizes up to 200 mm, Menéndez & Estaire (2021), which the authors acknowledge is greater than the maximum particle size recommended by BS EN ISO 17892 10 (BSI, 2018).

The shear box developed at City St George's, University of London – and used for this study – contains a split container of internal dimensions 1,500 mm x 1,500 mm x 1,000 mm with a resulting internal volume of 2.25 m^3 (Tanghetti *et al.*, 2019 and 2021). These dimensions allow the apparatus to be used to determine the representative shear strength parameters of 6F5 aggregate which has particles up to 125 mm, since the ratios of both box width and height to maximum particle size are largely consistent with values recommended by both ASTM D3080 (ASTM, 2011), BS EN ISO 17892 10 (BSI, 2018) and Fu *et al.* (2015). More specific details of this apparatus are given later in this paper.

1.3 Materials tested

The material tested in this study was a recycled aggregate that consisted of crushed hardcore materials including crushed concrete and brick. The material met the UK Department of Transport Specification for Highway Works Series 600 (Earthworks) for a 6F5 aggregate. This is defined as an aggregate ranging in size from 125 mm to 0.063 mm (Department for Transport, 2017). This specification provides limits for the grading of 6F5, nevertheless, the material can still be highly variable in relation to the relative portions of its constituents and grading. In addition, its constituents can be highly variable.

A mass of 66 tonnes of 6F5 aggregate was used in this test series (19 tests in total). Material was obtained from an active construction site operated by SCS Railways. Material was sourced by SCS Railways from three suppliers permitting a comparison between 6F5 aggregate from different locations. Although, all material reported in this paper was classified as 6F5, meeting the standards above, it was further categorised by supplier; identified as M1, M2 and M3. The visual difference between the 6F5 aggregate supplied by the three suppliers can be seen in Figure 1. Clear differences in both the grading and constituents can be seen with M1 aggregate

containing evidence of timber, batteries and floor ties, M2 aggregate displaying less extraneous material, although crushed bricks and concrete are very evident, and M3 aggregate displaying more uniform, mostly, quarried natural aggregates.

Characterisation of these visual differences was essential. This was obtained through sampling, by SCS Railways, directly from the construction site prior to the material being bagged for transportation to City St George's, University of London for shear testing. Figures 2(a)-(c) show the particle size distribution curves for the 6F5 aggregate obtained from each supplier, with a breakdown of the constituents. Table 1 presents the descriptions associated with the letters describing the constituents. The specified "upper" and "lower" limits for the grading of a 6F5 aggregates are also plotted in Figures 2(a)-(c) (Department for Transport, 2017).

Although, as can be seen in Figure 2 (a), the grading curves for aggregate M1 were close to or exceeding the upper limit of 6F5 aggregate, as can be seen from Table 2, the percentage of fines, where fines are defined as particles less than 0.063 mm in size, in aggregate M1 is similar that that of aggregates M2 and M3. It is often preferable to have material classified as 6F5 to be well-graded where it is to be used as a working platform. The grading and consistency of the material can be assessed by relation to the Uniformity Coefficient (D_{60}/D_{10}), C_u, or the Coefficient of Curvature ($D_{30}^2/(D_{60}*D_{10})$), C_c. Values of these parameters show C_u increasing from 152 for aggregate M1 to 267.3 for aggregate M3. In the case of C_c, aggregate M1 has a much lower value of 2.2 compared with the 10.7 and 9.0 of aggregates M2 and M3, respectively. Further evidence of the heterogeneity of the material samples is in the range of C_u values. The difference between the highest and lowest C_u values increased progressively across the aggregates, measuring 205 for M1, 241 for M2, and 378 for M3.

BRE 470 (2004) specifies that well-graded gravel has values of $C_u > 6$. All C_u values are well above 6 which would indicate all material was well-graded. This is believed to be a consequence of the larger variation in particle size in these aggregates as well as a reflection of the variable nature of the source material.

Los Angeles Abrasion Tests were also conducted by SCS Railways on samples of the tested materials. This test measures the degradation of an aggregate with a higher percentage indicating a less durable material (i.e. resistance to fragmentation). According to BSI (2020) typical values of Los Angeles Abrasion Test for coarse aggregates should be less than 50. In addition, BSI (2018) states that as a general requirement for 6F5 that Class X constituents (as defined in Table 1) should be less than 1% and Ra (Bituminous Material, Table 1) also less than 50%. The constituents of aggregate M1, presented in Figure 2(a), indicate that the material consisted of 48% “concrete or concrete products”, 11.6% “unbound aggregates” (e.g. quarried natural aggregates) and 27.5% “clay masonry units”. The Los Angeles Abrasion Test average value was 39%. Aggregate M2, Figure 2(b), consisted of 47% “concrete or concrete products”, 19% “unbound aggregates” and 25.7% “clay masonry units”. The Los Angeles Abrasion Test average value being 28.2%. The average constituents of Aggregate M3, presented in Figure 2(c), were 9% “concrete or concrete products”, 80% “unbound aggregates” and 7% “clay masonry units”. The Los Angeles Abrasion Test average value was 32%. Therefore, the Los Angeles Abrasion Test and constituents showed values for all three materials were within the ranges expected for 6F5 aggregates.

Following the moisture guidance given by the Department for Transport (2017) the 6F5 aggregates, imported from directly from site, were at a suitable water content to allow for effective compaction. The water contents measured in the aggregates tested are given in Table 3. The average water contents for the samples of M1 and M2 aggregates were found to be 8.7% and 8.2%, respectively. Samples of the M3 aggregate were found to have a consistently lower water content with the average being 4.3%.

In summary, the data indicate that all the materials were well-graded, relatively low in moisture content and varied significantly in the proportion of constituents. Samples of each aggregate were tested in the giant shear box facility, the result of which are presented in the next section.

2. Testing

2.1 Giant shear box facility

The City St George's, University of London Giant Shear Box facility (Figure 3) has been described by Tanghetti *et al.* (2019 and 2021). The facility comprises of a large split box (internal dimensions 1.5 m x 1.5 m shear plane and 1 m high) constructed from 254x254x132 UC steel sections. The upper half of the box is prevented from moving horizontally during shear by a reaction frame, while the bottom half is free to move horizontally to shear the sample. To minimise friction between the top and bottom of the box during shearing, Acetal sheets are fixed to the lower and upper flanges of the top- and bottom-halves of the box, respectively. Prior to testing standard machine grease is applied to these sheets to provide additional lubrication. Tanghetti *et al.* (2021) showed the friction developed between the two halves of the shear box was 2.75 kN and this is considered in any calculation of shear force. To facilitate the horizonal movement of the bottom half of the box, the reaction frame, has three I-beams which are firmly attached to a strong floor in the laboratory. The spaces between the beams provide runways in which machine skates can slide. This arrangement retains the bottom half of the shear box laterally to ensure horizontal movement occurs in the direction of shear only.

The shear force is applied to the sample using four 500 kN hydraulic jacks (maintained in position by a reaction frame), which push the bottom section of the box in a horizontal direction creating a horizontal shear plane. The normal force is applied by a single 5 MN hydraulic jack fixed to a beam that is bolted to the reaction frame. Vertical stress is applied to the sample via a platen comprising a stiffened 30 mm thick plate designed to minimise deflections even at the maximum applied stress. The force is applied to the platen via a spherical saddle to allow rotation during shearing. The vertical jack is located 150 mm from midpoint of the platen in the direction of shear (i.e. towards the load cells in Figure 3). This is to permit the vertical force on the platen to act at the midpoint of the shear plane at the maximum shear displacement of 300 mm.

During testing potentiometers measure vertical displacement in four positions on the loading platen and the horizontal displacement in two positions on the bottom half of the box. Two load

cells mounted between the inside of the reaction frame and the top half of the box measure the horizontal force applied to the shear plane during shear which is resisted by the stationary top-half of the box. In addition, an in-line pressure transducer also records the hydraulic pressure required to move the bottom-half of the box in the hydraulic jacks. All measurements were recorded on a bespoke LABVIEW data logger using an NI cDAQ-9178 CompactDAQ at approximately one second intervals.

2.2 Sample preparation

The aggregate for each sample was delivered to City St George's, University of London in five 1 m^3 capacity full drop flap discharge bulk bags. Each bag was partially filled with approximately 800 kg of material but was weighed prior to being placed in the shear box to obtain the exact mass of the sample (Figure 4(a)).

Samples were prepared by compacting the 6F5 aggregate in the box in layers after having first removed any aggregate over 125 mm or metal rebar components. In each instance, the amount removed was estimated to be less than 0.5% of the total mass of a sample. To ensure each layer was uniform it was compacted using a small wacker-plate that was passed over the material layer for two minutes. It was not reasonably practicable to follow the Department for Transport (2017) given the relatively small plan area of the specimen, instead a consistent time was used. The wacker-plate can be seen within the bottom-half of the shear box in Figure 4(b). The sample was formed of five compacted layers with an average thickness of approximately 200 mm. Figure 4(c) shows the depth of the surface of a layer being measured relative to the top surface of the bottom-half of the shear box in order to determine its thickness (this was repeated in five locations). The size of the box necessitated the first two layers to be prepared in the bottom-half (Figures 4(d)) before the top-half was added (Figure (e)). Once the box was fully assembled three further layers could be prepared. In this way, one of the layers spanned the interface between the two halves of the box.

The sum of the thicknesses of each layer together with the sum of the mass of each layer were used to calculate the voids ratio and density of the specimen. The calculation of voids ratio used

a weighted average of densities based on the recorded percentages of the constituents from the SCS Railways site sampling. Values of aggregate densities ranged from 2654 kg/m^3 (M1) to 2686 kg/m^3 (M2). Values of voids ratio at the beginning of each test, where possible, are given in Table 3. These densities and void ratios can be combined to give unit weights for the materials tested. These unit weights are presented and compared to values specified in TWf (2019) in Section 3.2. Once the final material layer had been prepared the loading platen was lifted into place and the vertical loading system assembled, Figure 4(f).

2.3 Experimental procedure

A summary of the experimental programme is provided in Table 3, from which it can be seen that 19 specimens were tested. Seven tests were conducted using aggregate M1 together with six and four tests for aggregates M2 and M3, respectively. Test failures owing to hydraulic jack malfunctions are included in the table and have been marked with an asterisk because the site sampling provided additional data on the classification of the aggregates. All specimens were initially loaded to a vertical stress of 500 kPa (the force applied to the top cap was 1125 kN) so they were subjected to the same pre-consolidation stress and therefore had similar stress histories.

500 kPa was chosen to represent typical maximum equivalent uniform bearing pressures obtained when a piling rig (such as the Bauer BG33) is in “extracting” mode. The specimens were then sheared either under a nominal vertical stress of 500 kPa or after reducing the nominal vertical stress to the value required for the test, as given in Table 3. BRE 470 (2004) suggests that 200 kPa normal stress in a shear box should be used for determining a representative angle of friction. Since at least three stress levels are required for determining a representative angle of friction, and BS EN ISO 17892-10:2018 does not state preferred stress levels, 200 kPa, 300 kPa and 500kPa were often chosen.

Shearing commenced once all vertical displacements following compression or unloading, as appropriate, had reached a plateau (Figure 5). The shear force was applied by increasing the pressure to the horizontal jacks to maintain a displacement-controlled constant rate of

299 15 mm/min causing the bottom-half of the giant shear box to move. In most tests, the test was
300 stopped once both the horizontal potentiometers measured displacements greater than Δh =
301 300 mm (for a typical sample height z = 1,000 mm this corresponded to a shear strain, γ_s, of
302 $\Delta h/z$ = 30%).

3. Shear test results

3.1 Normalised shear-stress v. shear-strain

The shear stress, τ, was calculated by summing the readings from the two horizontal load cells and dividing this by the area of the shear plane, corrected to take account of the reduction in its length during shearing. The normal effective stresses, σ', was calculated using the vertical force applied by the 5 MN hydraulic fixed jack divided by the corrected area. Shear strain, γ, was calculated by dividing the average horizontal displacement measured by the horizontal potentiometers by the total height of the sample. Similarly, the volumetric strain, ε_v, was calculated using the average readings from the four vertical potentiometers.

The shear and normal effective stresses (τ and σ', respectively) and strains, γ and ε_v have been calculated for all the tests at the maximum recorded value of shear stress and are presented in Table 3. Figures 6 (a) – (f) show typical stress-strain curves and corresponding volumetric strains during shearing for the three aggregates, viz. M1 ((a) and (b)), M2 ((c) and (d)) and M3 ((e) and (f)). The tests shown in Figures 6(a), (c) and (e) were all conducted with an initial vertical effective stress of 200 kPa and those in Figure 6(b), (d) and (f) with and initial vertical effective stress of 500 kPa.

The tests conducted with an initial vertical effective stress of 200 kPa (Fig 6 (a), (c) and (e)) exhibit a relatively steep rise in shear stress to a shear strain of between 0.1 and 0.2 before approaching an ultimate state. These tests also demonstrated behaviour typical of soils that are dense (dry) of critical, i.e. initial compression followed by dilation during shear. During shearing aggregates M1 and M2 approach states where the there were no further volumetric strains. However, as can be seen in Fig 6 (e), even after 0.3 shear strain (i.e. 300 mm of horizontal displacement) aggregate M3 continued to dilate.

The tests conducted with an initial vertical effective stress of 500 kPa (Fig 6 (b), (d) and (f)) do not demonstrate a distinctive peak normalised shear stress. Rather, the results show that the aggregates achieved maximum values of normalised shear stress following the development of significant shear strain. Maximum values of normalised shear stress were approximately 1.0 for

aggregates M1 and M2 and the value for M3 was slightly higher at approximately 1.2. All tests demonstrated typical behaviour of soils that are loose (wet) of critical, i.e. compressing during shear. In all cases the samples were observed to reach a state where the shear stress was constant and there were no further volumetric strains. Aggregates M2 and M3 demonstrated this behaviour at -0.02 vertical strain whilst a higher value of -0.04 was observed in the results of aggregate M1.

Plots of shear stress v. shear strain for all tests for each of the aggregates are combined in Figure 7 (a), (b) and (c) for aggregates M1, M2 and M3, respectively. For all the aggregates the results showed that, as would be expected, increasing vertical stress results in an increase in both initial stiffness and maximum shear strength. The M3 aggregate samples results demonstrate a very consistent increase in maximum shear stress with increase in normal stress, whilst the aggregates M2 and M1 demonstrated less consistency. In terms of experimental scatter, the tests conducted on M2 aggregate samples showed behaviour that sits between that observed for the M1 and M3 aggregates.

From the plots of normalised shear stress against shear strain (Figures 7 (d) – (f)) the specimens with the largest spread of constituents also had the largest amount of variability in stress strain behaviour during shearing. Comparison of results for the M1 aggregate tests show a wide range in initial stiffness, stress-strain behaviour and maximum recorded normalised shear stress value, with the latter values ranging from 0.6 – 1.2. These specimens also, as shown in Figure 2, had a wide range of constituents with an average of 11.6% unbound aggregates (which was low compared with both M2 and M3 aggregates), and a relatively even distribution of both concrete products and clay masonry units. M2 aggregate samples, with on average a slightly higher portion of unbound aggregates, displays a slightly smaller range in final normalised shear stress values between 1.0 and 1.4. Lastly, the plots for the M3 aggregate samples indicate that the normalised shear stress against shear strain curves are very similar. The final values are all being approximately 1.2. The M3 aggregate samples had less variation in constituents (i.e. less recycled materials) and, on average, the proportion of quarried natural aggregates was in excess of 80%.

To investigate this observation further, values of maximum recorded normalised shear stress ratio obtained during shearing have been correlated with the percentage of unbound aggregates (i.e. quarried natural aggregates) for the M1, M2 and M3 aggregates in Figure 8(a). From this it can be seen that there is a marked difference between samples that contain a proportion of unbound aggregate less than a critical value of approximately 20% and those containing greater than this proportion of unbound aggregate. In the case of the former, there is considerable scatter in the value of maximum recorded normalised shear stress ratio. For the latter, the values are in a narrow range between 1.25-1.35. The scatter in the maximum recorded normalised shear stress for samples with a proportion of unbound averages less than the critical value can be explained by also considering the proportion of concrete products. From the plot of maximum recorded normalised shear stress ratio v. the total percentage of unbound aggregates and concrete products, Fig. 8(b), it can be seen that the maximum recorded normalised shear stress ratio increases systematically with the combined proportion of unbound aggregate and concrete up to a critical value of approximately 70%.

3.2 Angle of friction

Values of maximum shear stress and the corresponding effective normal stress measured in each test are plotted in Figure 9(a), (b) and (c) for aggregates M1, M2 and M3, respectively. A line of best fit has been plotted for each set of data. For the M1 aggregate, Figure 9(a) shows the test results identifying an angle of friction equal to 46.0° with coefficient of determination, R2, equal to 0.980. For aggregate M2, Figure 9(b), the angle of friction is 47.6° with R2 of 0.992. Finally, the M3 samples show an angle of 51.7° with R2 of 0.9995. Given the size and scale of the material tested this was deemed a very good agreement. To quantify the scatter of the test results - given the inherent variability of M1 and M2 - the approach applied in this paper is to calculate the standard deviation, and in turn the standard error, of all the secant angles within a material group. These values may be used to ascertain a 95% confidence range from the peak angle of friction. Essentially, this gives plus or minus values relative to the angle of friction, Figure 8 (a), (b) and (c). The M1 aggregate has a 95% confidence range on of angle of friction of ±4.4° whilst the M2 aggregate has a ±2.5° 95% confidence range and the M3 aggregate a 95% confidence of ±0.6°.

It is also noteworthy that although each sample was prepared in the same way and consolidated to a maximum vertical effective stress of 500 kPa (Table 3) there was a variation in the bulk unit weight between each group of aggregates. Also shown in Table 3 are the voids ratios for each test where a weighted density was known from site reports. This shows the M3 material with a much lower value which could be owing to the material having a slightly higher fines content, lower moisture content, more evenly distributed particle size distribution and/or more uniform shaped particles resulting in less overall voids. Moreover, TWf (2019) specifies that the bulk unit weight or density for the aggregates used in platform material should be 20 kN/m^3. However, the average values of bulk unit weight for the aggregates containing the greater proportion of recycled materials were 16.68 kN/m^3 and 16.67 kN/m^3 (for aggregates M1 and M2, respectively), compared to a value of 20.31 kN/m^3 for the M3 aggregate.

The higher proportion of quarried natural aggregates was observed, therefore, to have a significant influence on the density of the aggregate samples together with both the shear strength of the aggregate and the statistical reliability of this being obtained.

4. Conclusions

A series of giant shear box tests was conducted to measure the representative shear strength parameters of 6F5 aggregate, a material commonly used in the UK for temporary works working platforms. A total of 66 tonnes of material with a particle size of up to 125 mm in diameter were tested in the experimental programme. The material with the least level of control over the particle sizes and constituents, aggregate M1, was found to have the lowest angle of friction value at 46.0° and the largest 95% confidence range on of angle of friction ±4.4° of the materials tested in the experimental programme. Conversely, the material with the greatest level of control over the particle sizes and constituents, aggregate M3, was observed to have the highest angle of friction equal to 51.7° and had the smallest 95% confidence range on of angle of friction in the series of tests of ±0.6°. Following this trend the M2 aggregate, considered to have a level of control between the two previous extremes, showed an angle of friction and 95% confidence interval of 47.6° and ±2.5°, respectively.

Essentially, the results presented in the paper indicate that the shear strength and the scatter are a function of both the constituents and grading of the 6F5 material irrespective of the effective vertical stress level applied. Aggregate M1 had an average percentage of unbound aggregates equal to 11.6% which resulted in a strength parameter of 46.0°, aggregate M2 with an average unbound aggregate of 19% gave 47.6° and, finally, aggregate M3 with 80% reached 51.7%. The tests where the percentages of unbound aggregates and concrete products were in excess of approximately 70% showed the greatest shear strength values. It would therefore be the recommendation of this work that larger proportions of combined unbound aggregates and concrete (e.g. greater than 70%) can achieve higher friction angles with the highest values (up to 50°) when the proportion of unbound aggregates is at least at the critical value of 20%.

Designers using guidance such as TWf (2019) would have used a value of 35° for the angle of friction for recycled aggregate, this series of tests demonstrate that with a 95% confidence range the lowest values were still greater than 40°. The impact of using the higher angles of friction in design can be quantified using the design approaches specified by BRE 470 (2004) and TWf (2019) for calculating working platform thickness. A variety of angles of friction (40°-

50°) were used to compute corresponding working platform thicknesses for a medium size piling rig considering a fine subgrade with an undrained shear strength of 50 kN/m^2 and a coarse subgrade with an angle of internal friction of 34°. In both case the density considered was 18.5 kN/m^3. A working platform with an angle of friction of 40° gave thicknesses of 1300 mm and 950 mm for BRE 470 (2004) and TWf (2019), respectively. At 50° the working platform thicknesses reduce to 650 mm and 750 mm for BRE 470 (2004) and TWf (2019), respectively. This is an average reduction in material of 36%.

In conclusion, the primary aim of this study was to be able to obtain a greater understanding of the stress strain behaviour of recycled aggregate in order to improve characterisation of the strength parameters of these materials and inform the safe, economic and minimum carbon design of construction working platforms. It is clear that using a higher angle of friction during the design of a granular working platform would result in shallower depths and, hence, less material (with associated economic and carbon costs of transport).

Acknowledgements

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546 Engineers, One Great George Street, London, SW1P 3AA, England.
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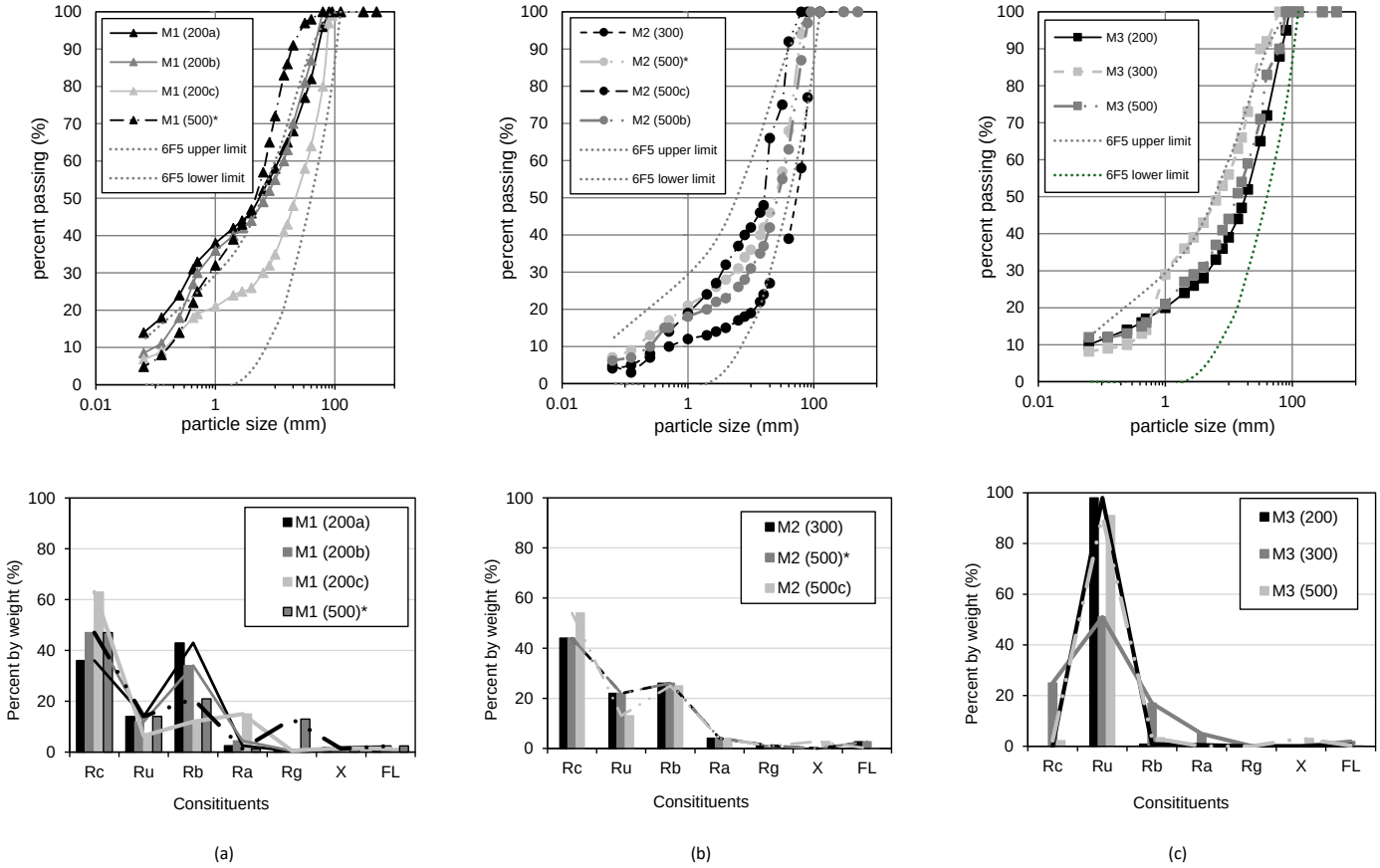
Table captions

Figure captions

Figure 1. Photographs taken of aggregates M1, M2 and M3.



Note: Table 1 gives the definitions and * indicates the tests with hydraulic jack issues.

Figure 2. Particle Size Distribution plots for aggregates M1 (a), M2 (b) and M3 (c).

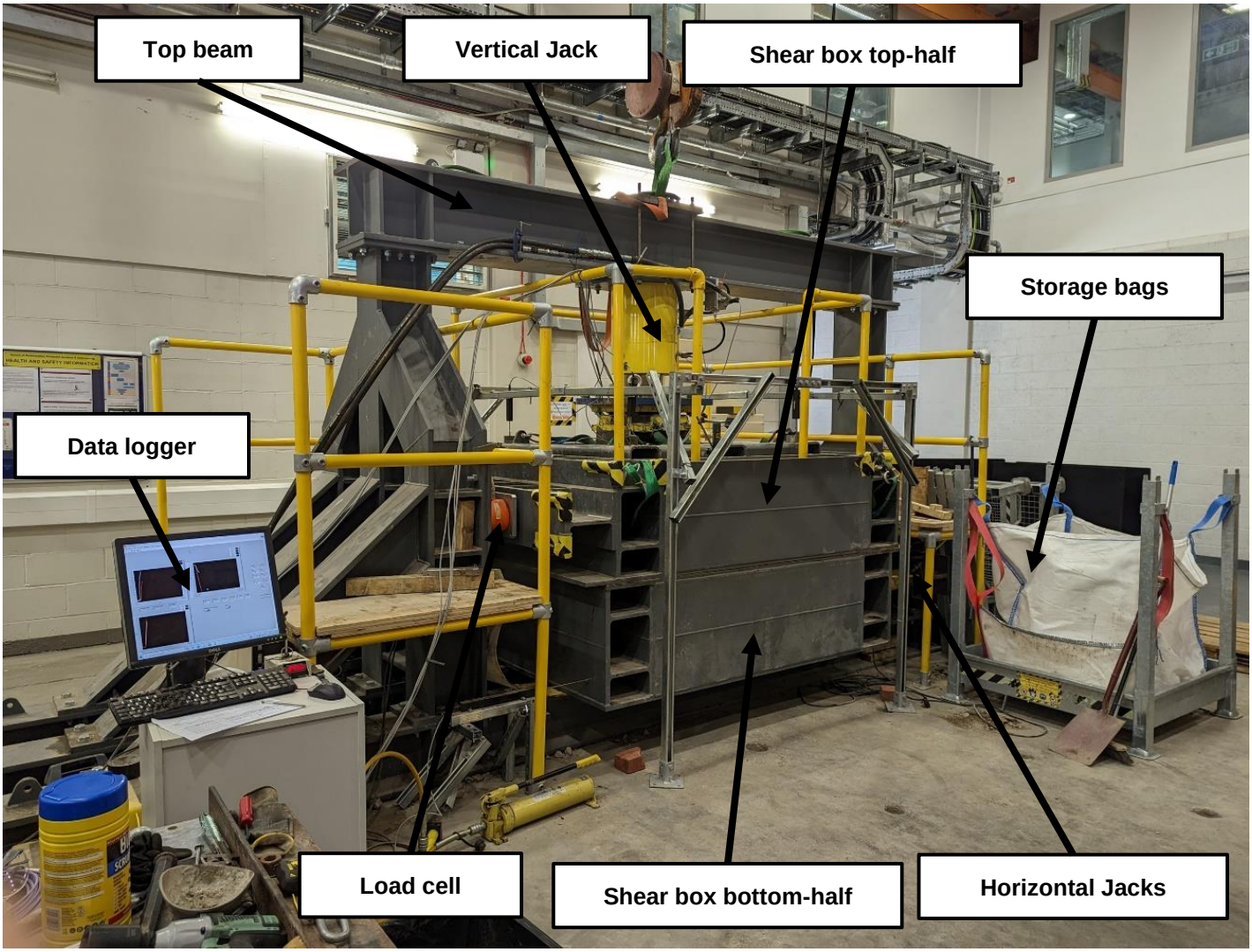
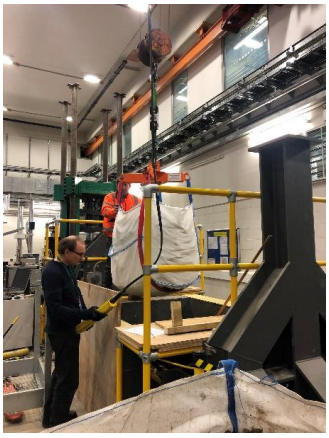
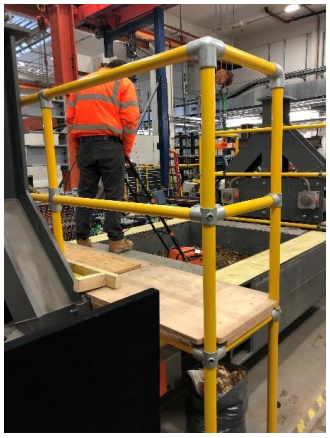


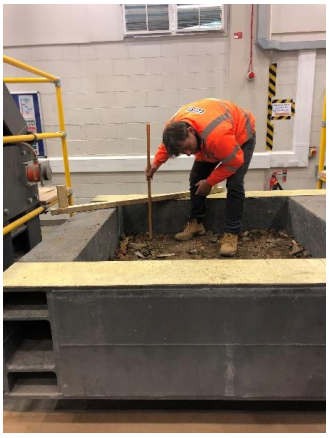
Figure 3. Photograph of the Giant Shear box facility at City St George's, University of London (Divall et al., 2024).



(a)



(b)



(c)

(d)

(e)

(f)

Figure 4. Photographs of the sample preparation stages.

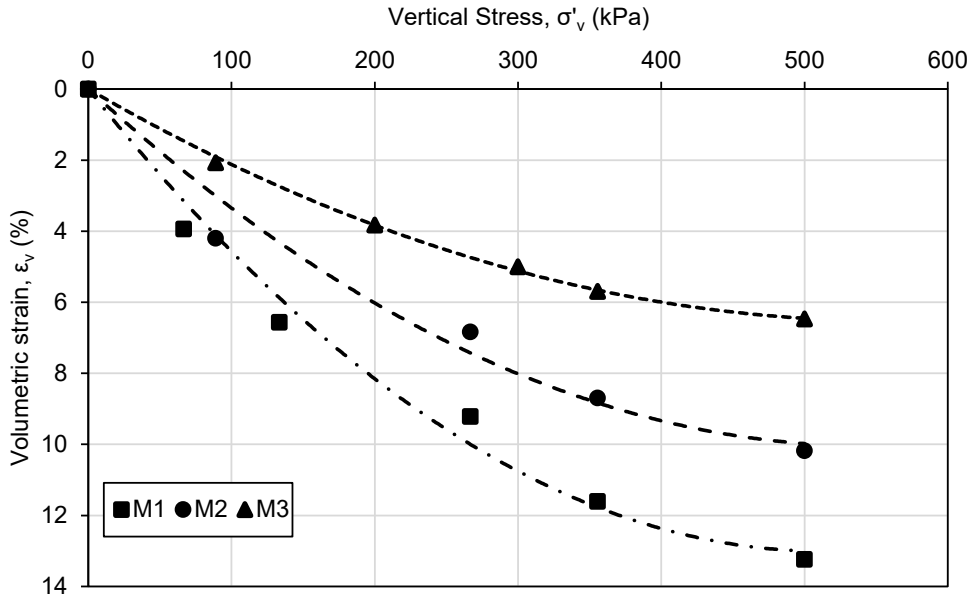
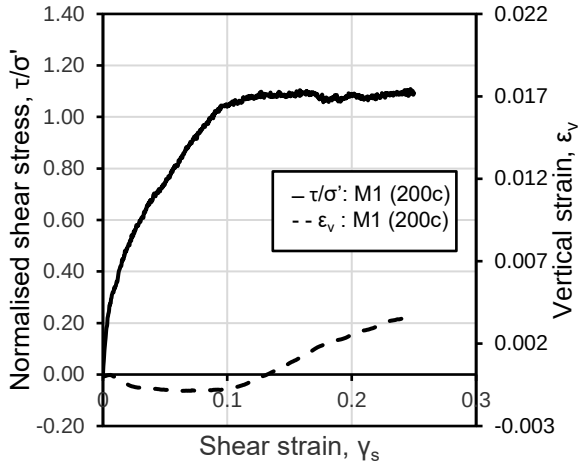
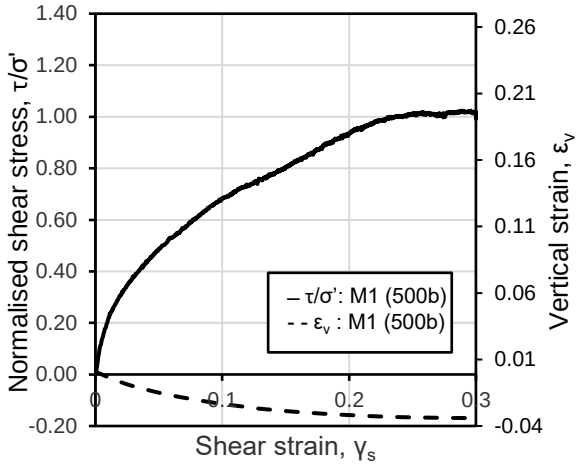


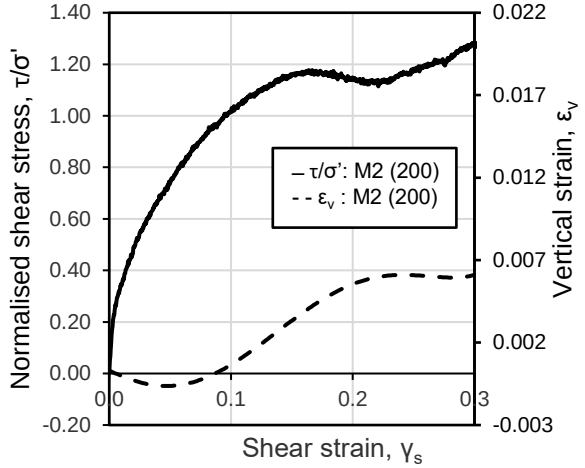
Figure 5. Vertical displacements of aggregates M1, M2 and M3 following compression



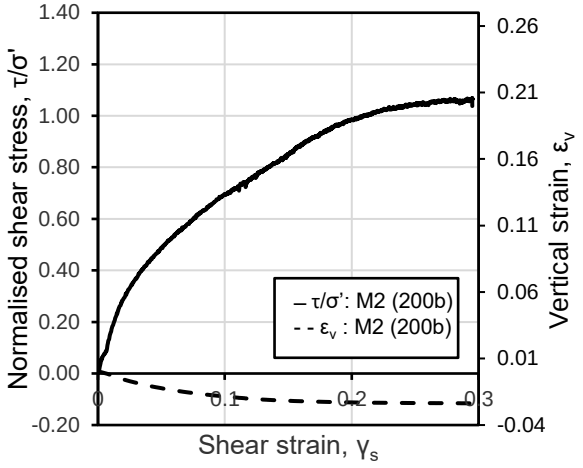
(a)



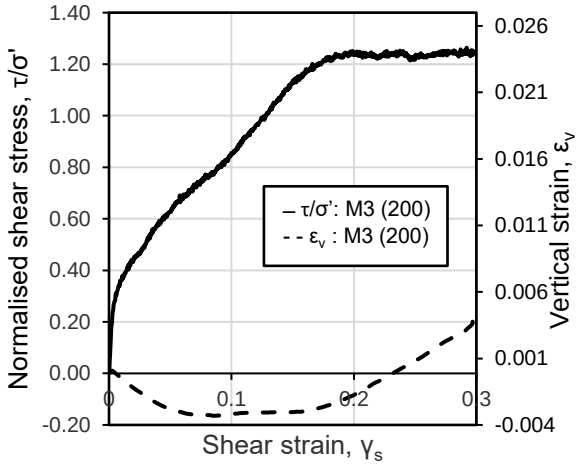
(b)



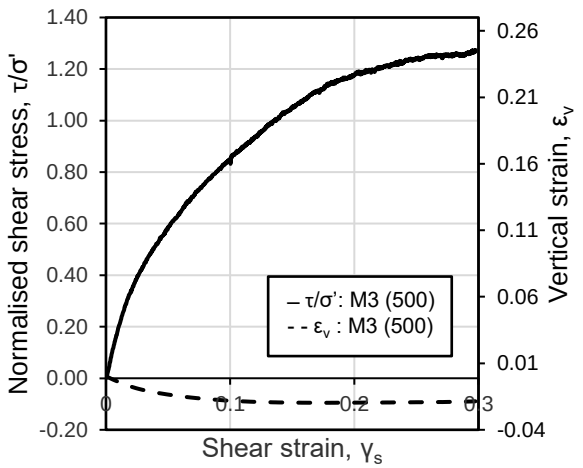
(c)



(d) – M2 (500b)



(e) - M3 (200)



(f) – M3 (500)

Figure 6. Normalised shear stress, τ/σ' (solid line) and vertical strain, ε_v (dashed line) v shear strain, γ_s

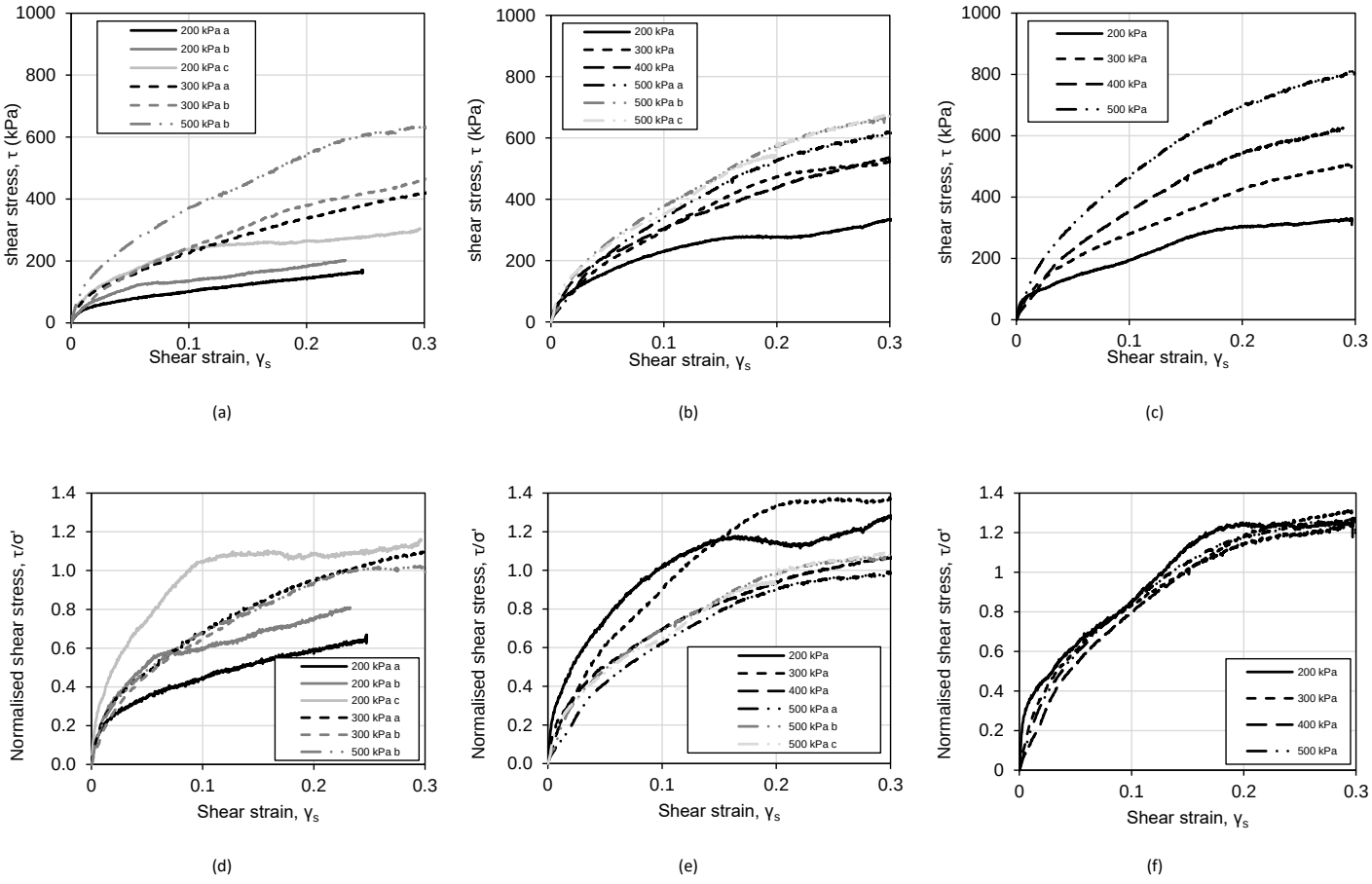
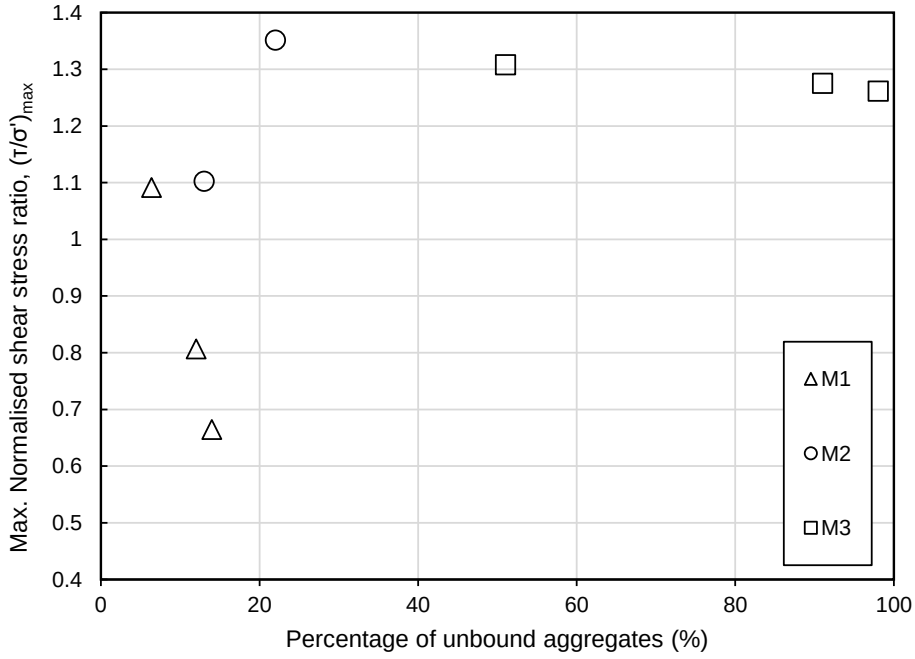
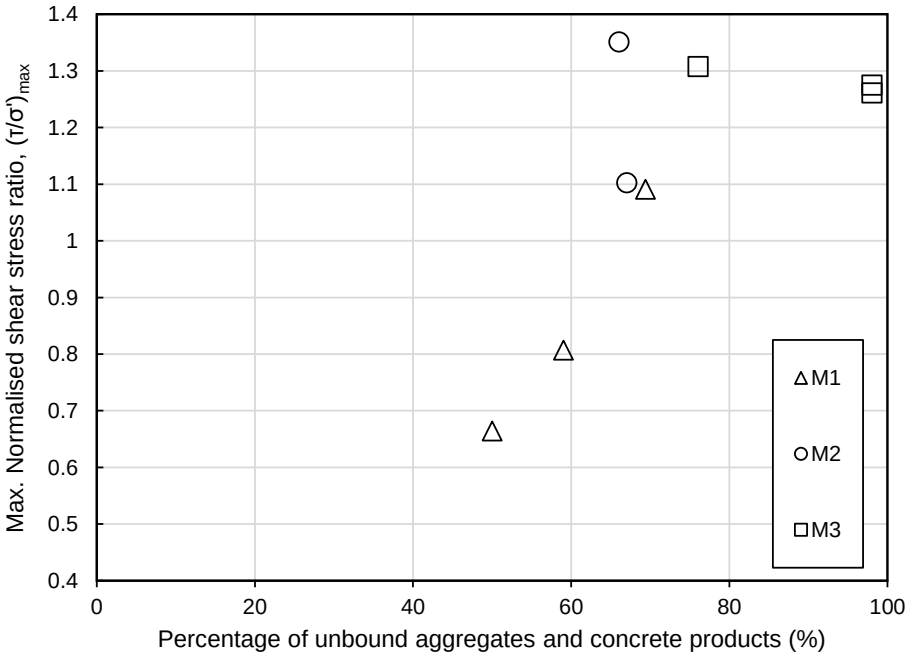


Figure 7. Shear stress, τ v shear strain, γ_s for aggregates M1 (a), M2 (b) and M3 (c) above Normalised shear stress, τ/σ' vs shear strain, γ_s for aggregates M1 (d), M2 (e) and M3 (f).

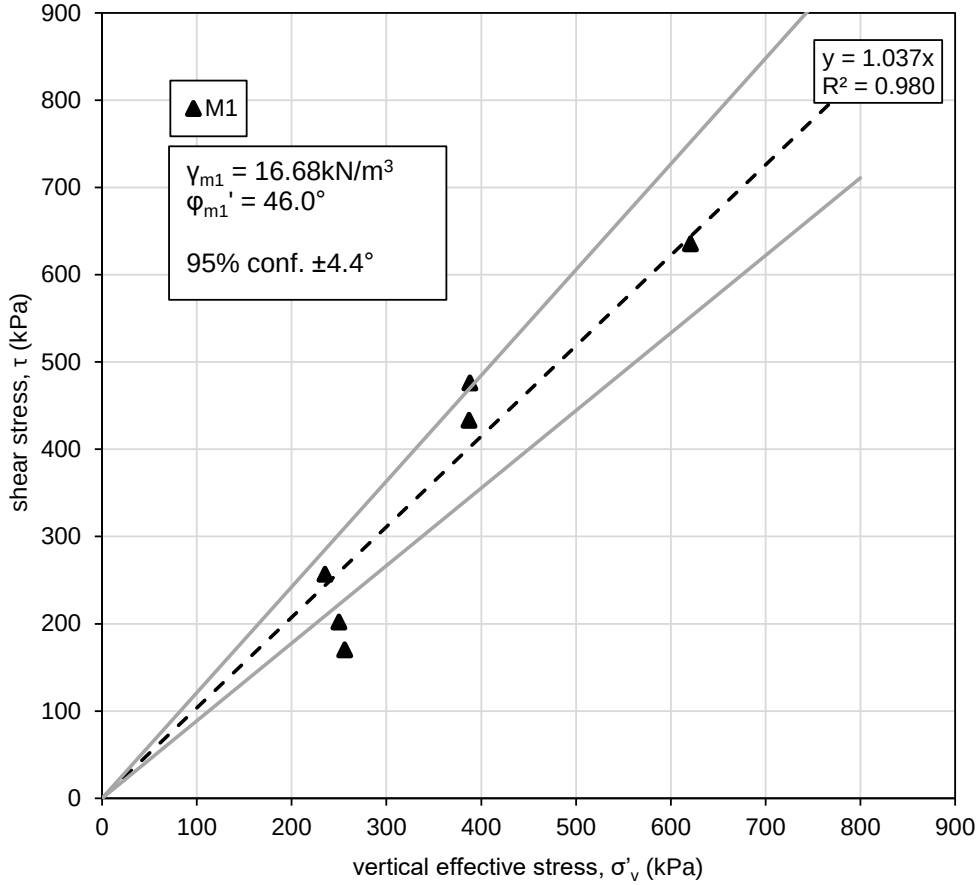


(a)



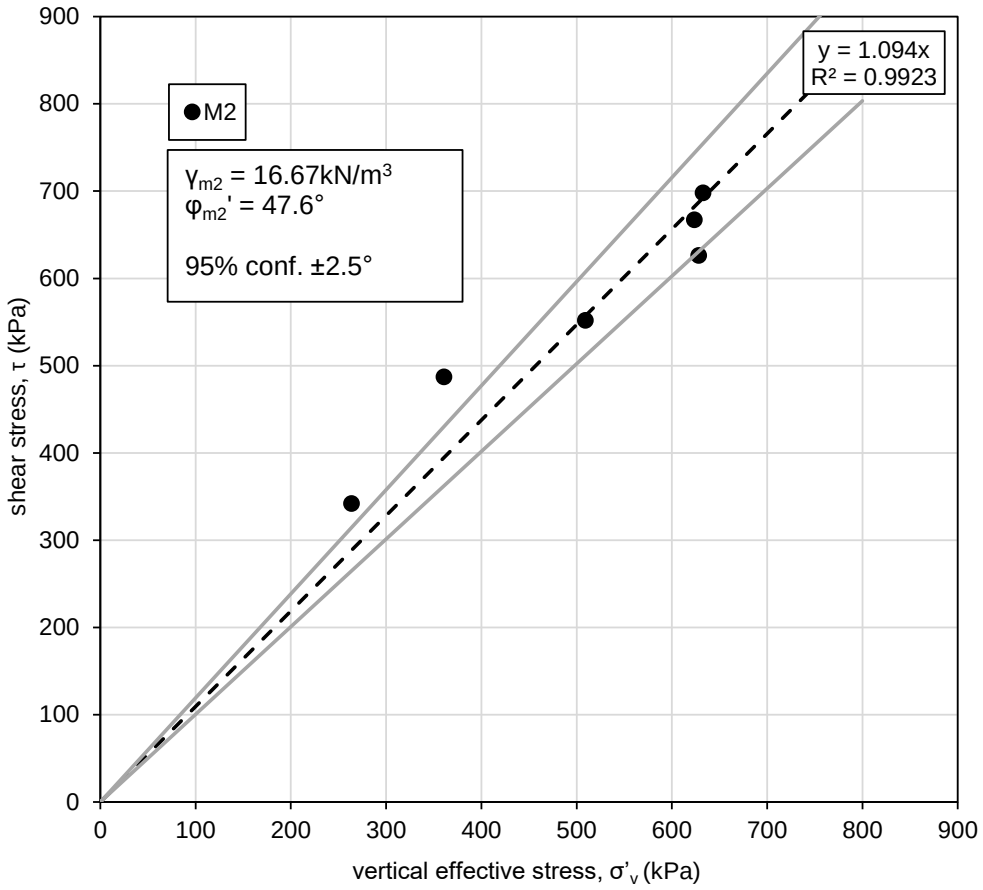
(b)

Figure 8(a). Max. Normalised shear stress ratio, (τ/σ')max, v percentage of unbound aggregates.
Figure 8(b). Max. Normalised shear stress ratio, (τ/σ')max, v percentage of unbound aggregates and concrete products.



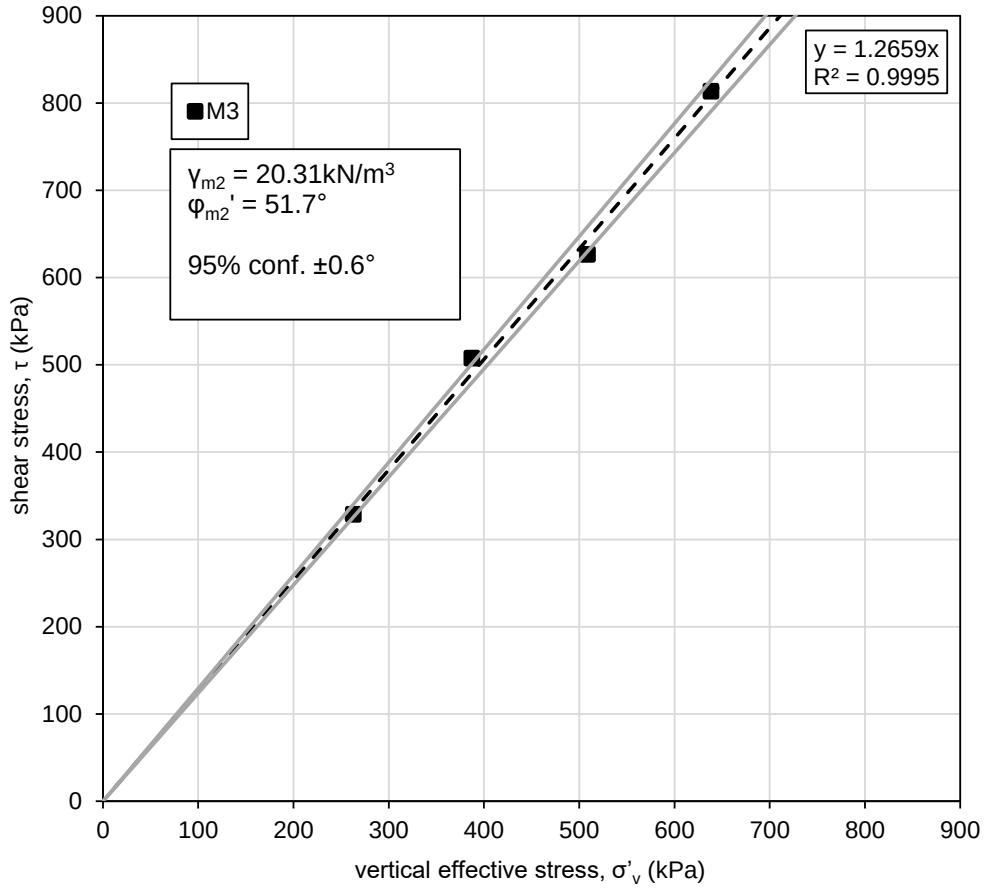
(a)

Figure 9(a). Shear stress, τ, v vertical effective stress, σ'_v, aggregate M1.



(b)

Figure 9(b). Shear stress, τ, v vertical effective stress, σ'_v, aggregate M2.



(c)

Figure 9(c). Shear stress, τ, v vertical effective stress, σ'_v, aggregate M3.

Tables

Symbol	Description
R_c	Concrete, concrete products & concrete masonry units.
R_u	Unbound aggregate, natural stone & hydraulically bound aggregate.
R_b	Clay masonry units (i.e. bricks & tiles), calcium silicate masonry units & aerated non-floating concrete
R_a	Bituminous Material
R_g	Glass
X	Other: Cohesive (i.e. clay & soil), gypsum plaster, miscellaneous - metals (ferrous & nonferrous), non-floating wood
FL	Floating Particles - given as the percentage remaining

Table 1: Labels for the classification test for the constituents of coarse recycled aggregate (after BSI, 2018).

Test ID	Los Angeles, LA (%)	C_u (D_{60}/D_{10})	C_c ($D_{30}^2/(D_{50}*D_{10})$)	D_{10}	D_{30}	D_{50}	D_{60}	% of fines
M1 (200a)	37	187	0.23	0.064	0.43	5.1	12.0	14
M1 (200b)	42	136	0.17	0.103	0.50	7.15	14.0	9
M1 (200c)	-	245	7.61	0.146	6.30	22.5	35.8	7
M1 (500)*	38	40	0.78	0.179	1.00	4.4	7.2	5
Ave.	*39.0*	*152.0*	*2.2*	*0.1*	*2.1*	*9.8*	*17.2*	*8.8*
M2 (300)	26.2	152	35.63	0.414	30.50	51.5	63.0	4
M2 (500)*	-	204	4.23	0.175	5.15	25.8	35.8	7.1
M2 (500c)	23.4	53	1.89	0.340	3.40	16	18.0	5
M2 (500a)	35	294	1.00	0.088	1.50	25.7	25.8	9
Ave.	*28.2*	*175.8*	*10.7*	*0.25*	*10.1*	*29.8*	*35.6*	*6.3*
M3 (200)	31	424	16.96	0.061	5.15	18	25.8	10
M3 (300)	35	46	0.32	0.261	1.00	6.3	12.0	8
M3 (500)	32	332	9.59	0.060	3.40	14	20.0	12
Ave.	*32.7*	*267.3*	*9.0*	*0.13*	*3.2*	*12.8*	*19.3*	*10.0*

Table 2: Summary data for the determination of Particle Size Distribution and Los Angeles Abrasion Tests.

Test ID	Nominal vertical stress (kPa)	Bulk unit weight (kN/m^3)	Voids ratio, e, at start of test	Moisture content (%)	Vertical stress at peak (kPa)	Peak shear stress (kPa)	Secant angle of friction (degrees)
M1 (200a)	200	16.1			256.0	170.0	33.59
M1 (200b)	200	16.5			250.0	202.0	38.94
M1 (200c)	200	17.6	0.600	7.3	235.2	256.7	47.49
M1 (300a)	300	16.9			387.0	433.0	48.21
M1 (300b)	300	16.3	0.783	10.6	388.0	476.0	50.82
M1 (500)*	500	17.6	0.657	10.8	-	-	-
M1 (500a)*	500	17.97			-	-	-
M1 (500b)	500	16.8	0.655	6.1	620.7	635.6	45.68
M2 (200)	200	15.5	0.829	7.2	264.0	342.0	52.33
M2 (300)	300	15.4	0.789	4.5	361.0	487.0	53.45
M2 (400)	400	17.3	0.644	7.4	509.3	551.9	47.30
M2 (500)*	500	16.75	0.772	11.2	-	-	-
M2 (500a)	500	18.1	0.659	12.1	628.5	626.2	44.90
M2 (500b)	500	16.8	0.715	8.7	623.9	667.2	46.90
M2 (500c)	500	16.8	0.726	9.4	633.0	698.0	47.80
M3 (200)	200	19.4	0.423	5.1	262.9	328.7	51.60
M3 (300)	300	20.9	0.309	4.3	387.4	507.6	52.65
M3 (400)	400	20.6	0.333	4.7	508.8	626.5	50.90
M3 (500)	500	20.4	0.322	3.2	638.4	813.4	51.87
Note: * is for tests that had hydraulic jack issues.							

Table 3: Summary of testing conducted on 6F5 aggregates.