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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

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

38

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

48

49 **1.2 Previous studies**

50 A commonly used laboratory method for determining the angle of friction of soils is the direct
51 shear test that, compared with other test methods (such as the triaxial test), is a relatively quick
52 and inexpensive tool for determining the shear properties of the material under drained
53 conditions. Standard shear box apparatus typically have a width (or diameter) of 64-73 mm
54 (Bareither *et al.*, 2008) so the maximum particle size which could normally be accommodated in
55 these apparatus whilst respecting the guidance in ASTM and BSI standards is approximately
56 5 mm and, depending on the testing device, rarely exceeds 10 mm with standard apparatus
57 (Simoni & Houlsby, 2006).

58

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

61 of friction when testing the sample in a box whose height/width to maximum particle size ratios
62 fall below certain limits (e.g. Deiminiat *et al.*, 2022). Minimum ratios of height/width to maximum
63 particle size are recommended in both ASTM D3080 (ASTM, 2011) and BS EN ISO 17892 10
64 (BSI, 2018). In the former it is specified that the ratio of width (or diameter) of the sample tested
65 to maximum particle size should always exceed 10 and the height of sample to maximum
66 particle size ratio should exceed 6. In the latter the corresponding value of these ratios are 15
67 and 6. However, notwithstanding this guidance, studies are reported in the literature in which
68 the results of shear tests showed a different response when testing samples of the same
69 material in different box sizes, despite all of them adhering to the limits prescribed in the ASTM
70 standard (Sobol *et al.*, 2015; Cerato & Lutenecker, 2006; Fu *et al.*, 2015). Of particular
71 relevance, is that higher values of the angle of friction were measured when testing the same
72 material in smaller shear boxes. Among these studies, is the research conducted by Fu *et al.*
73 (2015) who tested samples of two different materials using an apparatus in which the height and
74 diameter could be varied. These results demonstrated limiting values of height/width to
75 maximum particle size ratios which appear more restrictive than the ones provided by the ASTM
76 D3080 (in the sense that they would require a larger apparatus) in order to avoid scale effects.
77 By observing the variation of the obtained friction angle when changing height and width of the
78 model it was deduced that reliable results were obtained when the width (or diameter) of the
79 sample to maximum particle size ratio exceeds 15 and the height to maximum particle size ratio
80 is larger than 10.

81

82 An alternative approach that has been adopted for testing aggregates with large particle sizes
83 consists of preparing a sample corresponding to a smaller scale representation of the original
84 material and testing it using a standard apparatus (Moulay Smaïne *et al.*, 2014; Kim & Ha,
85 2014). The particle size distribution of the original soil is scaled to fit the size of a standard shear
86 box so that proper values of height/width to maximum particle ratio can be maintained. Despite
87 this being common practice when testing material with large particles which cannot properly fit
88 the size of standard apparatus, the presence of a scale effect associated with the reduction of
89 large particle sizes content in a soil sample due to the scaling of the grading curve has been
90 identified in the literature (Simoni & Houlsby, 2006; Moulay Smaïne *et al.*, 2014; Bareither *et al.*,

91 2008; Nakao & Fytus, 2008). However, in the case of 6F5, since the material is highly
92 heterogenous, it is not possible to create a scaled sample that reflects both the constituents and
93 the grading of the original material. Considering the previously explained scale effects
94 influencing the measurement of the angle of friction of a sample, it has been proposed (e.g. by
95 Bradfield *et al.*, 2015; Estaire & Santana, 2018) that the only way to measure reliably the shear
96 strength properties of geomaterials that have a large particle size is to use an apparatus that
97 maintains the sample size to apparatus limits identified by Fu *et al.* (2015).

98
99 A survey of large shear boxes has been conducted by Menéndez & Estaire (2021). Examples of
100 large shear box apparatus that were developed and used to investigate either the shear
101 strength parameters of geomaterials or the soil/reinforcement element interaction properties are
102 described in the literature (Davies & Le Masurier, 1997; Barr *et al.*, 1991; Jain & Gupta, 1971;
103 Pedley, 1990; Krahan *et al.*, 2007, Bradfield *et al.*, 2015; Estaire & Olalla, 2005). Except for the
104 specific example described by Davies & Le Masurier, 1997 and Barr *et al.* (1991), which was
105 designed with a vertical shear plane to facilitate the investigation of mechanisms associated
106 with the shear strength enhancement resulting from 2.8 m long steel soil nails located in sand or
107 clay, all the examples found in the literature propose the use of a horizontal shear plane. Joist
108 sections firmly attached to a strong floor (as described by Davies & Le Masurier, 1997) support
109 the shear box and, at the same time, provide runways on which machine skates can slide
110 allowing movement of one of the two halves (while the other one is maintained fixed).
111 Considering the high stress levels required to shear large samples, a reaction frame (as
112 suggested by Jain & Gupta, 1971) is required to support and resist the forces applied by
113 hydraulic jacks which apply the normal and shear loads.

114
115 Examples of shear box apparatus developed to measure the shear strength parameters of
116 geomaterials having particle sizes of up to 125 mm that are most relevant to the study reported
117 herein are presented by Bradfield *et al.* (2015), Estaire & Olalla (2005) and Tanghetti *et al.*
118 (2019 and 2021). Bradfield *et al.* (2015) fabricated a direct shear apparatus, with a specimen
119 size of 720 mm x 720 mm x 600 mm (high) and a normal stress capacity of 4.5 MPa to test
120 siltstone with particles up to 100 mm. The apparatus reported by Estaire & Olalla (2005) has a

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

125

126 The shear box developed at City St George's, University of London – and used for this study –
127 contains a split container of internal dimensions 1,500 mm x 1,500 mm x 1,000 mm with a
128 resulting internal volume of 2.25 m³ (Tanghetti *et al.*, 2019 and 2021). These dimensions allow
129 the apparatus to be used to determine the representative shear strength parameters of 6F5
130 aggregate which has particles up to 125 mm, since the ratios of both box width and height to
131 maximum particle size are largely consistent with values recommended by both ASTM D3080
132 (ASTM, 2011), BS EN ISO 17892 10 (BSI, 2018) and Fu *et al.* (2015). More specific details of
133 this apparatus are given later in this paper.

134

135 **1.3 Materials tested**

136 The material tested in this study was a recycled aggregate that consisted of crushed hardcore
137 materials including crushed concrete and brick. The material met the UK Department of
138 Transport Specification for Highway Works Series 600 (Earthworks) for a 6F5 aggregate. This is
139 defined as an aggregate ranging in size from 125 mm to 0.063 mm (Department for Transport,
140 2017). This specification provides limits for the grading of 6F5, nevertheless, the material can
141 still be highly variable in relation to the relative portions of its constituents and grading. In
142 addition, its constituents can be highly variable.

143

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

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

154

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

162

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

175

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

180

181 Los Angeles Abrasion Tests were also conducted by SCS Railways on samples of the tested
182 materials. This test measures the degradation of an aggregate with a higher percentage
183 indicating a less durable material (i.e. resistance to fragmentation). According to BSI (2020)
184 typical values of Los Angeles Abrasion Test for coarse aggregates should be less than 50. In
185 addition, BSI (2018) states that as a general requirement for 6F5 that Class X constituents (as
186 defined in Table 1) should be less than 1% and Ra (Bituminous Material, Table 1) also less than
187 50%. The constituents of aggregate M1, presented in Figure 2(a), indicate that the material
188 consisted of 48% "concrete or concrete products", 11.6% "unbound aggregates" (e.g. quarried
189 natural aggregates) and 27.5% "clay masonry units". The Los Angeles Abrasion Test average
190 value was 39%. Aggregate M2, Figure 2(b), consisted of 47% "concrete or concrete products",
191 19% "unbound aggregates" and 25.7% "clay masonry units". The Los Angeles Abrasion Test
192 average value being 28.2%. The average constituents of Aggregate M3, presented in Figure
193 2(c), were 9% "concrete or concrete products", 80% "unbound aggregates" and 7% "clay
194 masonry units". The Los Angeles Abrasion Test average value was 32%. Therefore, the Los
195 Angeles Abrasion Test and constituents showed values for all three materials were within the
196 ranges expected for 6F5 aggregates.

197

198 Following the moisture guidance given by the Department for Transport (2017) the 6F5
199 aggregates, imported from directly from site, were at a suitable water content to allow for
200 effective compaction. The water contents measured in the aggregates tested are given in Table
201 3. The average water contents for the samples of M1 and M2 aggregates were found to be
202 8.7% and 8.2%, respectively. Samples of the M3 aggregate were found to have a consistently
203 lower water content with the average being 4.3%.

204

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

208

209 **2. Testing**

210 **2.1 Giant shear box facility**

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

225

226 The shear force is applied to the sample using four 500 kN hydraulic jacks (maintained in
227 position by a reaction frame), which push the bottom section of the box in a horizontal direction
228 creating a horizontal shear plane. The normal force is applied by a single 5 MN hydraulic jack
229 fixed to a beam that is bolted to the reaction frame. Vertical stress is applied to the sample via a
230 platen comprising a stiffened 30 mm thick plate designed to minimise deflections even at the
231 maximum applied stress. The force is applied to the platen via a spherical saddle to allow
232 rotation during shearing. The vertical jack is located 150 mm from midpoint of the platen in the
233 direction of shear (i.e. towards the load cells in Figure 3). This is to permit the vertical force on
234 the platen to act at the midpoint of the shear plane at the maximum shear displacement of
235 300 mm.

236

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

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

245

246 **2.2 Sample preparation**

247 The aggregate for each sample was delivered to City St George's, University of London in five
248 1 m³ capacity full drop flap discharge bulk bags. Each bag was partially filled with approximately
249 800 kg of material but was weighed prior to being placed in the shear box to obtain the exact
250 mass of the sample (Figure 4(a)).

251

252 Samples were prepared by compacting the 6F5 aggregate in the box in layers after having first
253 removed any aggregate over 125 mm or metal rebar components. In each instance, the amount
254 removed was estimated to be less than 0.5% of the total mass of a sample. To ensure each
255 layer was uniform it was compacted using a small wacker-plate that was passed over the
256 material layer for two minutes. It was not reasonably practicable to follow the Department for
257 Transport (2017) given the relatively small plan area of the specimen, instead a consistent time
258 was used. The wacker-plate can be seen within the bottom-half of the shear box in Figure 4(b).

259 The sample was formed of five compacted layers with an average thickness of approximately
260 200 mm. Figure 4(c) shows the depth of the surface of a layer being measured relative to the
261 top surface of the bottom-half of the shear box in order to determine its thickness (this was
262 repeated in five locations). The size of the box necessitated the first two layers to be prepared in
263 the bottom-half (Figures 4(d)) before the top-half was added (Figure (e)). Once the box was fully
264 assembled three further layers could be prepared. In this way, one of the layers spanned the
265 interface between the two halves of the box.

266

267 The sum of the thicknesses of each layer together with the sum of the mass of each layer were
268 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/m³ (M1) to 2686 kg/m³ (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 $\Delta h =$
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 an 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) or critical, i.e. initial compression followed by dilation during shear. During shearing aggregates M1 and M2 approach states where 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

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

339
340 Plots of shear stress v. shear strain for all tests for each of the aggregates are combined in
341 Figure 7 (a), (b) and (c) for aggregates M1, M2 and M3, respectively. For all the aggregates the
342 results showed that, as would be expected, increasing vertical stress results in an increase in
343 both initial stiffness and maximum shear strength. The M3 aggregate samples results
344 demonstrate a very consistent increase in maximum shear stress with increase in normal stress,
345 whilst the aggregates M2 and M1 demonstrated less consistency. In terms of experimental
346 scatter, the tests conducted on M2 aggregate samples showed behaviour that sits between that
347 observed for the M1 and M3 aggregates.

348
349 From the plots of normalised shear stress against shear strain (Figures 7 (d) – (f)) the
350 specimens with the largest spread of constituents also had the largest amount of variability in
351 stress strain behaviour during shearing. Comparison of results for the M1 aggregate tests show
352 a wide range in initial stiffness, stress-strain behaviour and maximum recorded normalised
353 shear stress value, with the latter values ranging from 0.6 – 1.2. These specimens also, as
354 shown in Figure 2, had a wide range of constituents with an average of 11.6% unbound
355 aggregates (which was low compared with both M2 and M3 aggregates), and a relatively even
356 distribution of both concrete products and clay masonry units. M2 aggregate samples, with on
357 average a slightly higher portion of unbound aggregates, displays a slightly smaller range in
358 final normalised shear stress values between 1.0 and 1.4. Lastly, the plots for the M3 aggregate
359 samples indicate that the normalised shear stress against shear strain curves are very similar.
360 The final values are all being approximately 1.2. The M3 aggregate samples had less variation
361 in constituents (i.e. less recycled materials) and, on average, the proportion of quarried natural
362 aggregates was in excess of 80%.

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

377

378 **3.2 Angle of friction**

379 Values of maximum shear stress and the corresponding effective normal stress measured in
380 each test are plotted in Figure 9(a), (b) and (c) for aggregates M1, M2 and M3, respectively. A
381 line of best fit has been plotted for each set of data. For the M1 aggregate, Figure 9(a) shows
382 the test results identifying an angle of friction equal to 46.0° with coefficient of determination,
383 R^2 , equal to 0.980. For aggregate M2, Figure 9(b), the angle of friction is 47.6° with R^2 of
384 0.992. Finally, the M3 samples show an angle of 51.7° with R^2 of 0.9995. Given the size and
385 scale of the material tested this was deemed a very good agreement. To quantify the scatter of
386 the test results - given the inherent variability of M1 and M2 - the approach applied in this paper
387 is to calculate the standard deviation, and in turn the standard error, of all the secant angles
388 within a material group. These values may be used to ascertain a 95% confidence range from
389 the peak angle of friction. Essentially, this gives plus or minus values relative to the angle of
390 friction, Figure 8 (a), (b) and (c). The M1 aggregate has a 95% confidence range on of angle of
391 friction of $\pm 4.4^\circ$ whilst the M2 aggregate has a $\pm 2.5^\circ$ 95% confidence range and the M3
392 aggregate a 95% confidence of $\pm 0.6^\circ$.

393 It is also noteworthy that although each sample was prepared in the same way and consolidated
394 to a maximum vertical effective stress of 500 kPa (Table 3) there was a variation in the bulk unit
395 weight between each group of aggregates. Also shown in Table 3 are the voids ratios for each
396 test where a weighted density was known from site reports. This shows the M3 material with a
397 much lower value which could be owing to the material having a slightly higher fines content,
398 lower moisture content, more evenly distributed particle size distribution and/or more uniform
399 shaped particles resulting in less overall voids. Moreover, TWf (2019) specifies that the bulk
400 unit weight or density for the aggregates used in platform material should be 20 kN/m³.
401 However, the average values of bulk unit weight for the aggregates containing the greater
402 proportion of recycled materials were 16.68 kN/m³ and 16.67 kN/m³ (for aggregates M1 and M2,
403 respectively), compared to a value of 20.31 kN/m³ for the M3 aggregate.
404
405 The higher proportion of quarried natural aggregates was observed, therefore, to have a
406 significant influence on the density of the aggregate samples together with both the shear
407 strength of the aggregate and the statistical reliability of this being obtained.
408
409

410 4. Conclusions

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

423
424 Essentially, the results presented in the paper indicate that the shear strength and the scatter
425 are a function of both the constituents and grading of the 6F5 material irrespective of the
426 effective vertical stress level applied. Aggregate M1 had an average percentage of unbound
427 aggregates equal to 11.6% which resulted in a strength parameter of 46.0° , aggregate M2 with
428 an average unbound aggregate of 19% gave 47.6° and, finally, aggregate M3 with 80% reached
429 51.7° . The tests where the percentages of unbound aggregates and concrete products were in
430 excess of approximately 70% showed the greatest shear strength values. It would therefore be
431 the recommendation of this work that larger proportions of combined unbound aggregates and
432 concrete (e.g. greater than 70%) can achieve higher friction angles with the highest values (up
433 to 50°) when the proportion of unbound aggregates is at least at the critical value of 20%.

434
435 Designers using guidance such as TWf (2019) would have used a value of 35° for the angle of
436 friction for recycled aggregate, this series of tests demonstrate that with a 95% confidence
437 range the lowest values were still greater than 40° . The impact of using the higher angles of
438 friction in design can be quantified using the design approaches specified by BRE 470 (2004)
439 and TWf (2019) for calculating working platform thickness. A variety of angles of friction (40° -

440 50°) were used to compute corresponding working platform thicknesses for a medium size piling
441 rig considering a fine subgrade with an undrained shear strength of 50 kN/m² and a coarse
442 subgrade with an angle of internal friction of 34°. In both case the density considered was
443 18.5 kN/m³. A working platform with an angle of friction of 40° gave thicknesses of 1300 mm
444 and 950 mm for BRE 470 (2004) and TWf (2019), respectively. At 50° the working platform
445 thicknesses reduce to 650 mm and 750 mm for BRE 470 (2004) and TWf (2019), respectively.
446 This is an average reduction in material of 36%.

447

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

454

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469 **References**

- 470 ASTM D3080/D3080M (2011). Standard Test Method for Direct Shear Test of Soils Under
471 Consolidated Drained Conditions. ASTM International. West Conshohocken, PA, USA.
- 472 ASTM D2487 (1985). Classification of Soils for Engineering Purposes: Annual Book of ASTM
473 Standards, D 2487-83, vol. 04, American Society for Testing and Materials, pp. 395–408
- 474 Bareither, C. A., Benson, C. H. and Edil, T. B. (2008). Comparison of shear strength of sand
475 backfills measured in small-scale and large-scale direct shear tests. Canadian Geotechnical
476 Journal 45: 1224-1236.
- 477 Barr, B. I. G., Davies, M. C. R. and Jacobs, C. D (1991). A large direct shear box - some initial
478 results of tests on soil nails. Ground Engineering.
- 479 Bradfield, L. R. Fityus, S. G. and Simmons, J. V. (2015). Large scale testing of mine spoil.
480 Australia New Zealand Conference on Geomechanics and was edited by Graham Ramsey.
481 Wellington, New Zealand, 22-25 February 2015.
- 482 BRE 470 (2004). Working Platforms for tracked plant. Building Research Establishment, UK
- 483 BSI (2020). EN 1097-2:2020 - Tests for mechanical and physical properties of aggregates - Part
484 2: Methods for the determination of resistance to fragmentation, British Standards Institution.
- 485 BSI (1990). BS EN 1377-7:1990 - Methods of test for soils for civil engineering purposes - Shear
486 strength tests (total stress), British Standards Institution.
- 487 BSI (2018). BS EN 13285:2018 - Unbound mixtures. Specifications, British Standards
488 Institution.
- 489 Cerato, A. B. and Lutenecker, A. J. (2006). Specimen Size and Scale Effects of Direct Shear
490 Box Tests of Sands. Geotechnical Testing Journal, Vol. 29, No. 6.
- 491 Davies, M. C. R. and Le Masurier, J. W (1997). Soil/Nail Interaction Mechanisms from Large
492 Direct Shear Tests. Ground improvement geosystems Densification and reinforcement, pp
493 492-499. January 1997.
- 494 Deiminiat, A., Li L. and Zeng, F. (2022). Experimental Study on the Minimum Required
495 Specimen Width to Maximum Particle Size Ratio in Direct Shear Tests. Civil Eng. 2022, 3,
496 66–84. <https://doi.org/10.3390/civileng3010005>
- 497 Department for Transport (2017). Manual of contract documents for highway works volume 1
498 specification for highway works series 600 Earthworks.

499 Divall, S., Davies, M.C.R., Stallebrass, S.E., Mahony, J., Quintavalle, S., Bowen-Bravery, J.,
 500 Johnson-Watts, T. & Mulligan, R. (2024). Giant shear box tests on recycled 6F5 for tracked
 501 plant platforms. Proc. of the XVIII European Conference on Soil Mechanics and
 502 Geotechnical Engineering, pp. 2249 – 2253. doi:10.1201/9781003431749-427
 503 Estaire, J. and Santana, M. (2018). Large Direct Shear Tests Performed with Fresh Ballast.
 504 Railroad Ballast Testing and Properties. Ed. Stark, TD, Swan, RH, Jr., & Szecsy, R. 100 Barr
 505 Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959: ASTM International,
 506 2018.
 507 Estaire, J. and Olalla, C. Analysis of shear strength of armour stone based on 1 m³ direct shear
 508 tests. (2005). In: VII Coastal Engineering, Algarve, Portugal, April 2005, pp. 341-350. Large
 509 Direct Shear Tests Performed with Fresh Ballast. Available from:
 510 [https://www.researchgate.net/publication/323403527_Large_Direct_Shear_Tests_Performed](https://www.researchgate.net/publication/323403527_Large_Direct_Shear_Tests_Performed_with_Fresh_Ballast)
 511 [_with_Fresh_Ballast](https://www.researchgate.net/publication/323403527_Large_Direct_Shear_Tests_Performed_with_Fresh_Ballast) [accessed Apr 02 2024].
 512 Fu, X., Zheng, X., Lei, X. and Deng, J. (2015). Using a modified direct shear apparatus to
 513 explore gap and size effects on shear resistance of coarse grained soil. Particuology 23, 82–
 514 89.
 515 Jain, S.P. and Gupta, R.C. (1971). Large shear box for tests on river bed material, Indian
 516 Geotechnical Society, 98-113
 517 Kim, D. and Ha, S. (2014). Effects of Particle Size on the Shear Behaviour of Coarse Grained
 518 Soils Reinforced with Geogrid. Materials 2014, 7(2), 963-979.
 519 Krahn, T., Blatz, J., Alfaro, M. and Bathurst, R. J. (2007). Large-scale interface shear testing of
 520 sandbag dyke materials. Geosynthetics International, 14, No. 2, 119–126.
 521 Moulay Smaïne, G., Gueye, B. and Zoubir, B. (2014). Influence of Grain Size Coarse Soil on
 522 Shear Strength. International Congress on Materials and Structural Stability. MATEC Web of
 523 Conferences Volume 11
 524 Muñoz Menéndez, M. and Estaire, J. (2021). Experimental study on the shear strength of
 525 medium-coarse rockfill, Proceedings of the 20th International Conference on Soil Mechanics
 526 and Geotechnical Engineering, Sydney 2021.
 527 Nakao, T. and Fityus, S. (2008). Direct Shear Testing of a Marginal Material Using a Large
 528 Shear Box. Geotechnical Testing Journal, Vol. 31, No. 5.

529 Pedley, M. J. (1990). The performance of soil reinforcement in bending and shear. PhD thesis,
530 Oxford University.

531 Simoni, A. and Houlsby, G. T. (2006). The direct shear strength and dilatancy of sand–gravel
532 mixtures. *Geotechnical and Geological Engineering*, 24, 523–549.

533 Sobol, E., Sas, W. and Szymanski, A. (2015). Scale effect in direct shear tests on recycled
534 concrete aggregate. *Studia Geotechnica et Mechanica*, Vol. 37, No. 2.

535 Tanghetti, G. (2021). Stability of Working Platforms for Tracked Plant. Doctoral Thesis, City,
536 University of London.

537 Tanghetti, G., Davies, M. C. R. and Goodey, R. J. (2021). Comparison of small- and full-scale
538 shear box tests on large particle size aggregate, In: *Proceedings of the 20th International*
539 *Conference on Soil Mechanics and Geotechnical Engineering*, Sydney 2021, Sydney,
540 Australia, pp. 75-80.

541 Tanghetti, G., Goodey, R. J., Divall, S., McNamara, A. M. and McKinley, B. (2019). Design and
542 development of a large shear box for testing working platform material, In: *Proceedings of*
543 *the XVII ECSMGE-2019*, Reykjavik, Iceland, pp. 1-7.

544 TWf (2019). TWf2019:2 Working Platforms - Design of granular working platforms for
545 construction plant: A guide to good practice. Temporary Works Forum, c/o Institution of Civil
546 Engineers, One Great George Street, London, SW1P 3AA, England.

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550

551 **Table captions**

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

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

556 Table 3. Summary of testing conducted on 6F5.

557

558 **Figure captions**

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

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

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

563 Figure 4. Photographs of the sample preparation stages.

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

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

567 Figure 7. Shear stress, τ v shear strain, γ_s for aggregates M1 (a), M2 (b) and M3 (c) above

568 Normalised shear stress, τ/σ' vs shear strain, γ_s for aggregates M1 (d), M2 (e) and M3 (f).

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571 and concrete products.

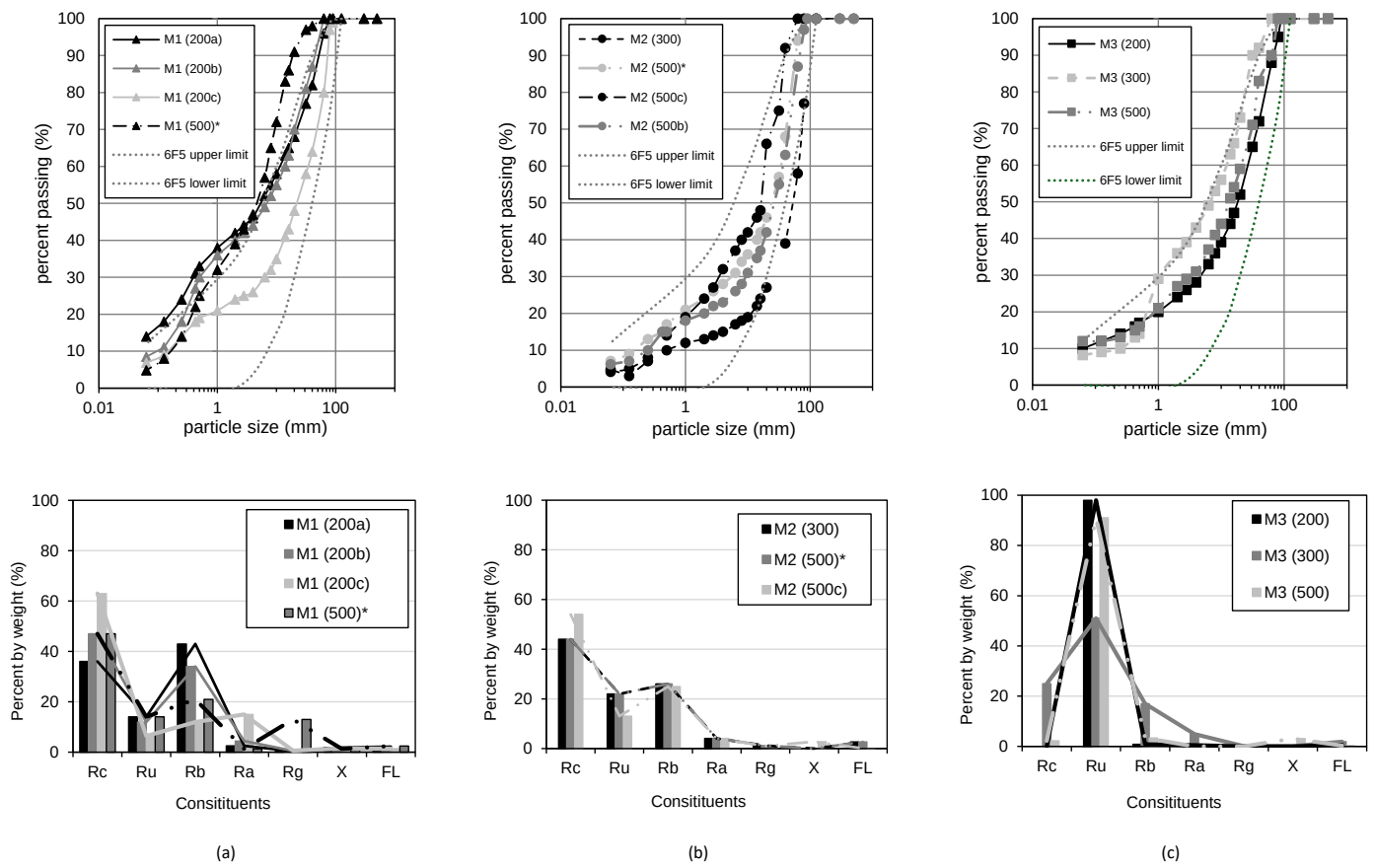
572 Figure 9(a). Shear stress, τ , v. vertical effective stress, σ'_v , aggregate M1.

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

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



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).

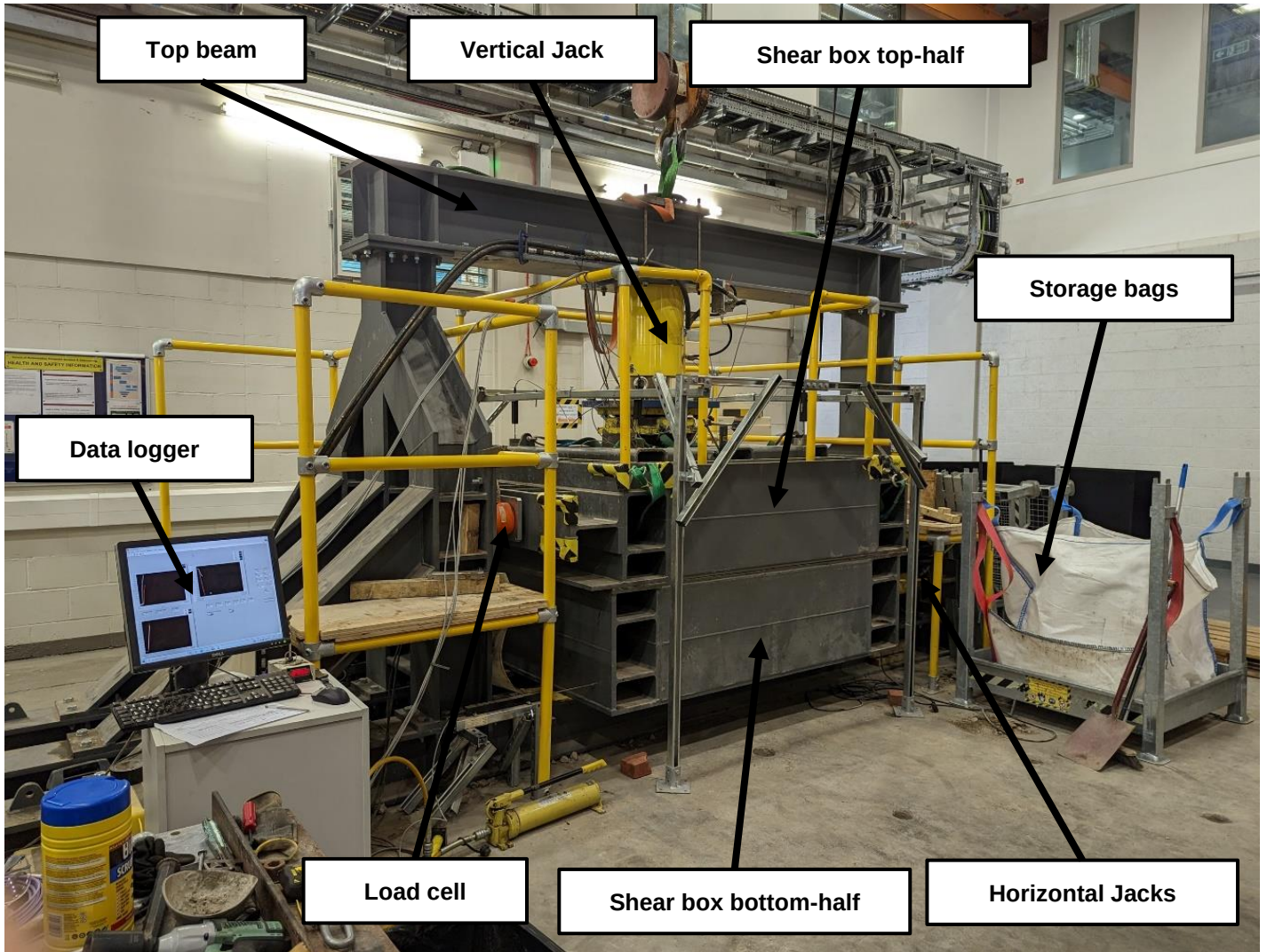
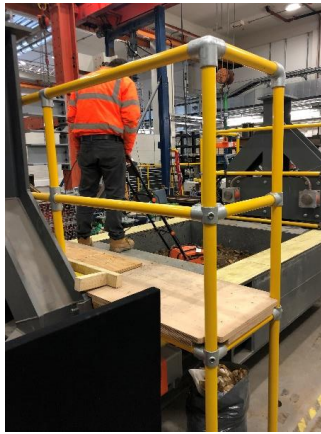


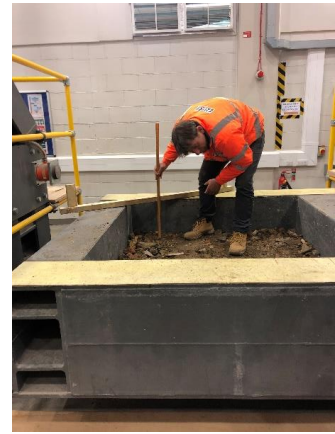
Figure 3. Photograph of the Giant Shear box facility at City St George's, University of London (Divall et al., 2024).



(a)



(b)



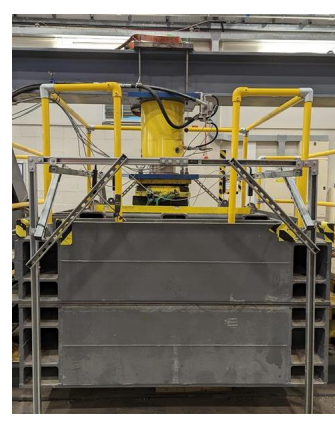
(c)



(d)



(e)



(f)

Figure 4. Photographs of the sample preparation stages.

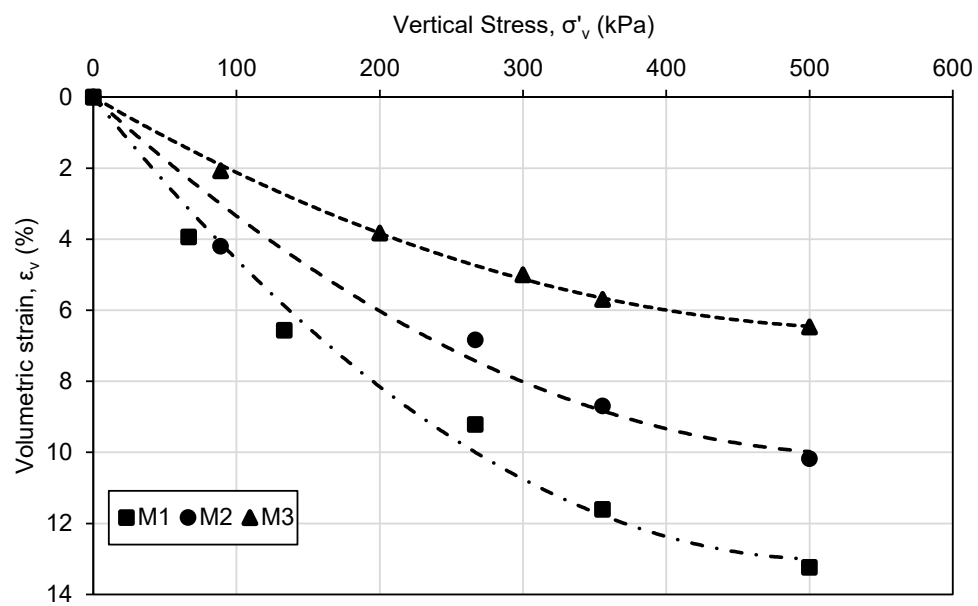
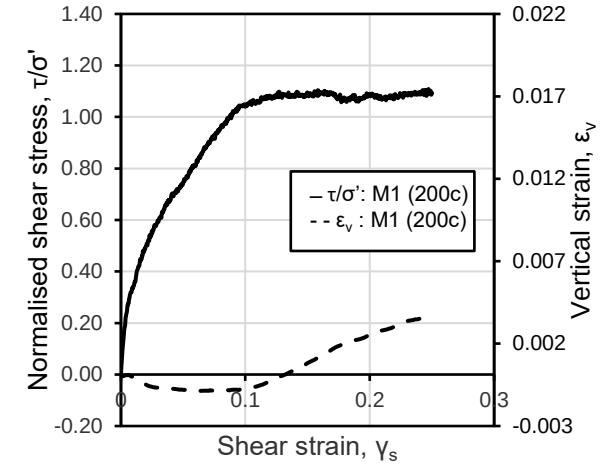
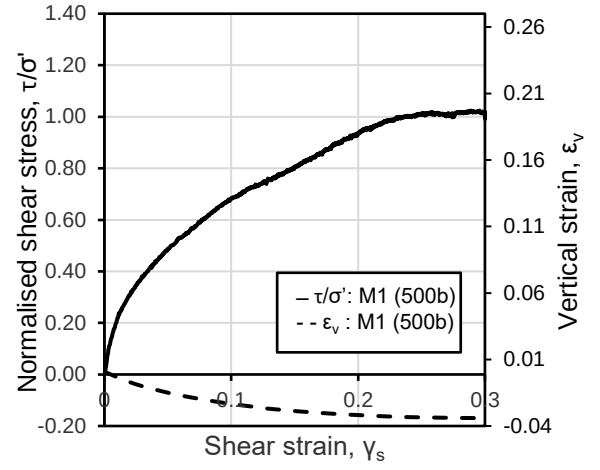


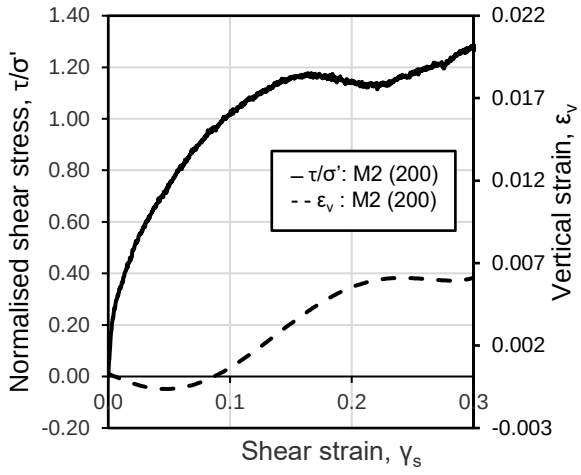
Figure 5. Vertical displacements of aggregates M1, M2 and M3 following compression



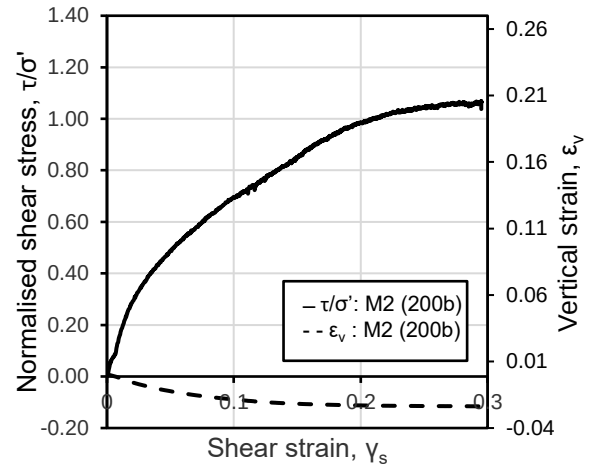
(a)



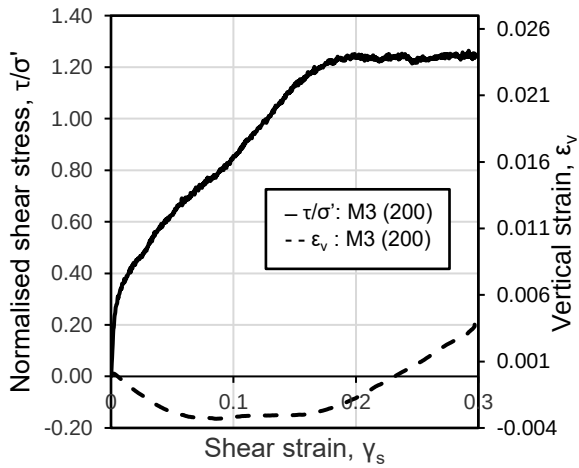
(b)



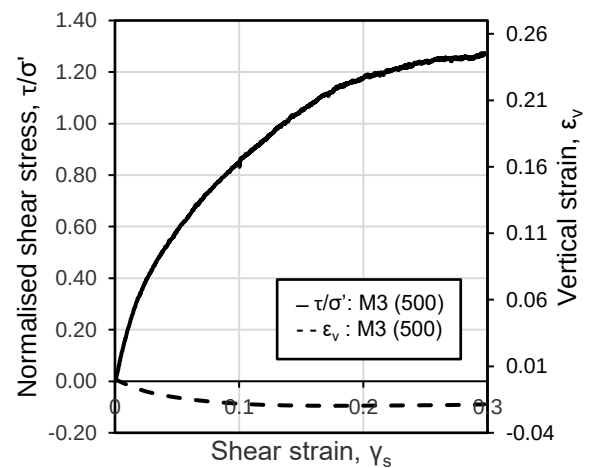
(c)



(d) – M2 (500b)

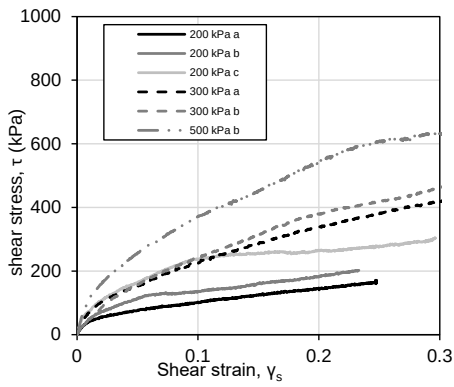


(e) - M3 (200)

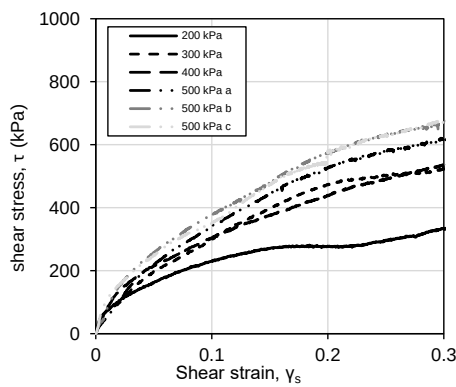


(f) – M3 (500)

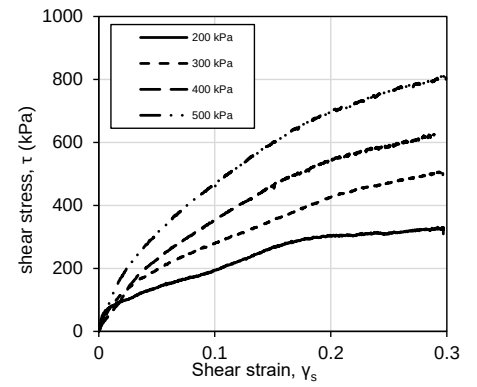
Figure 6. Normalised shear stress, τ/σ' (solid line) and vertical strain, ϵ_v (dashed line) v shear strain, γ_s



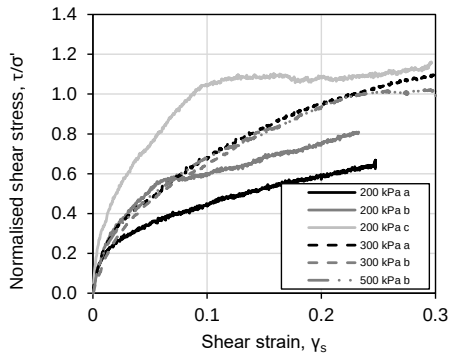
(a)



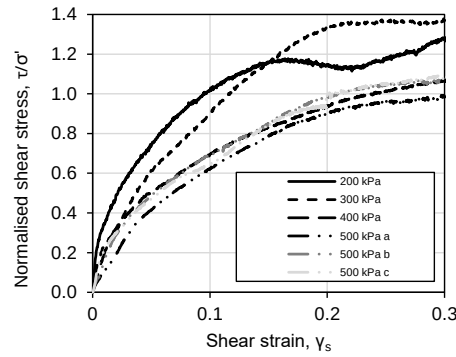
(b)



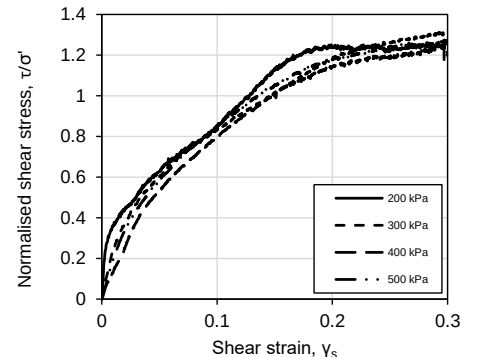
(c)



(d)



(e)



(f)

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).

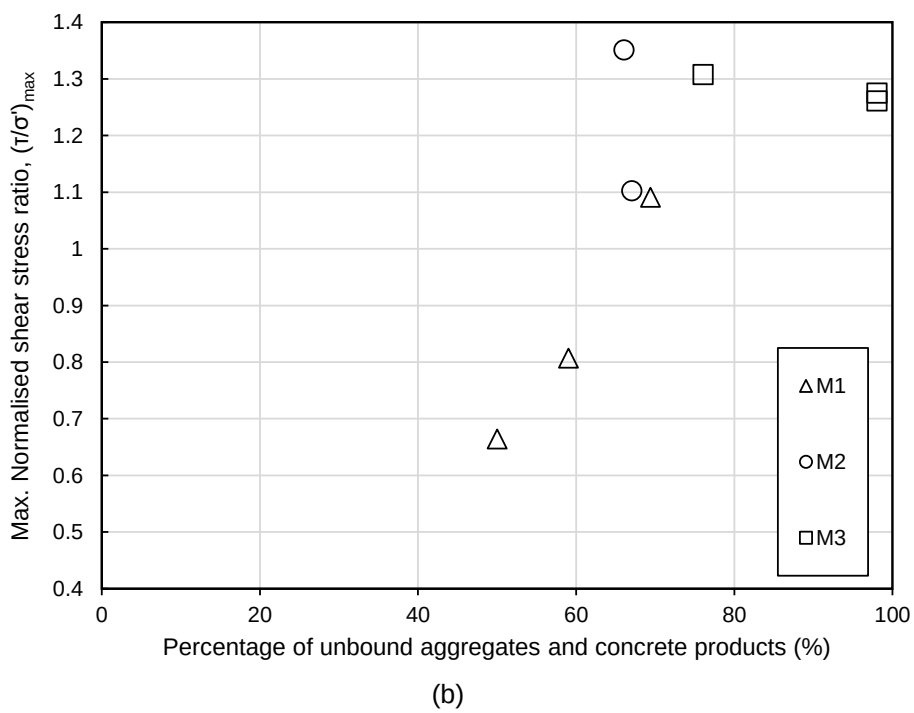
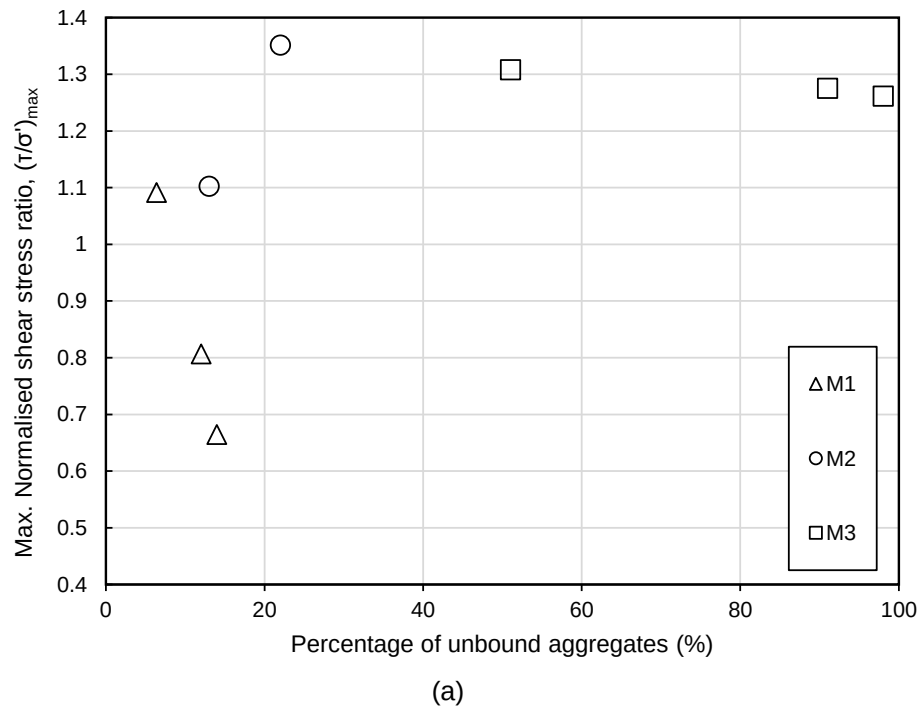
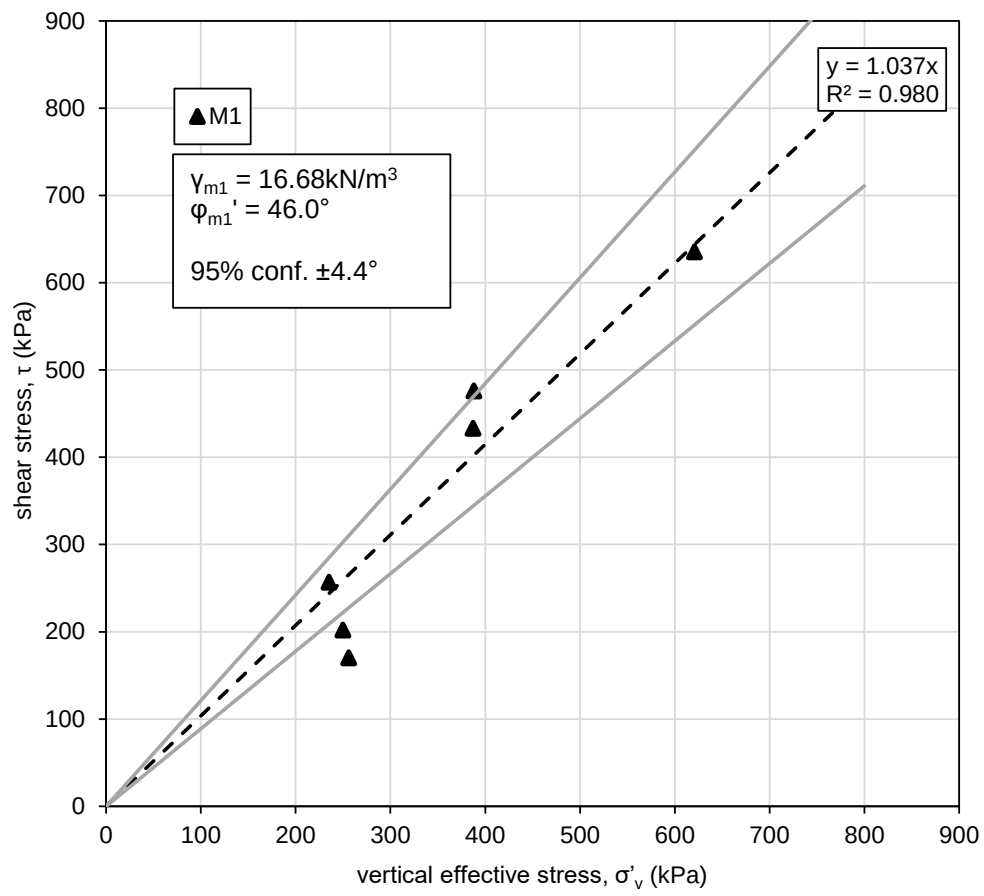


Figure 8(a). Max. Normalised shear stress ratio, $(\tau/\sigma')_{\max}$, v percentage of unbound aggregates.

Figure 8(b). Max. Normalised shear stress ratio, $(\tau/\sigma')_{\max}$, v percentage of unbound aggregates and concrete products.



(a)

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

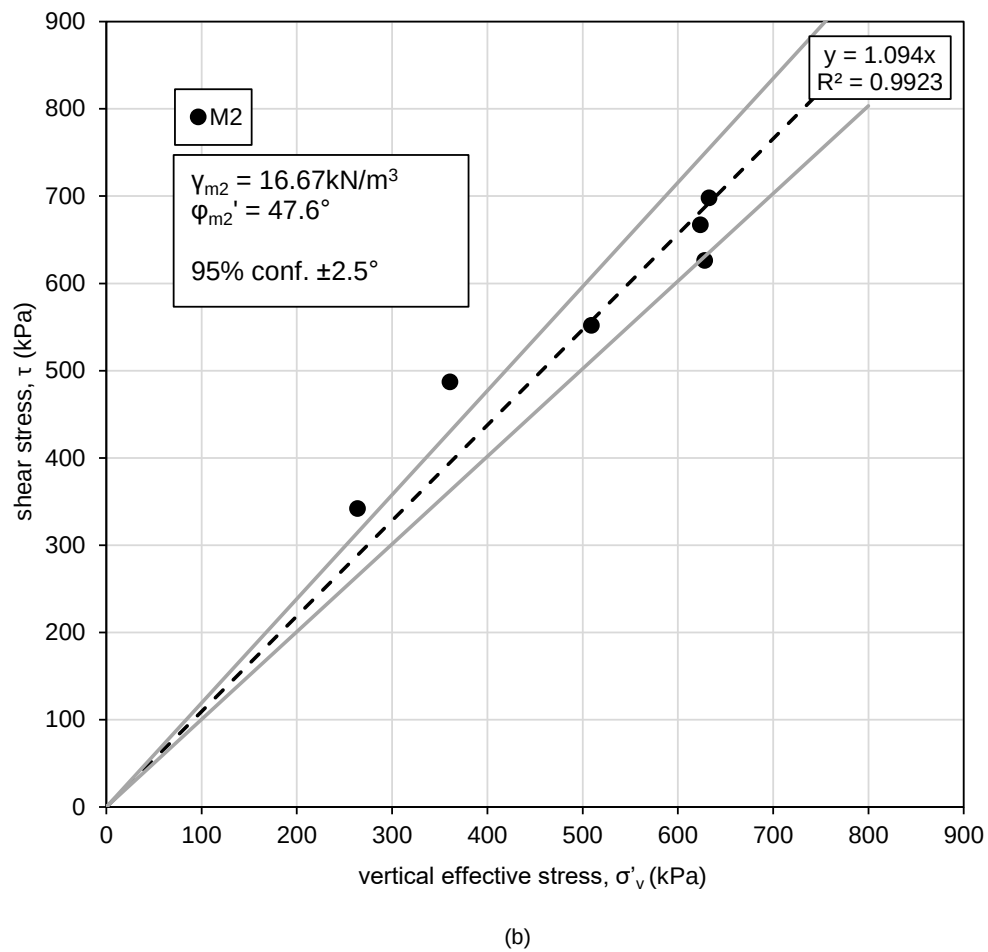
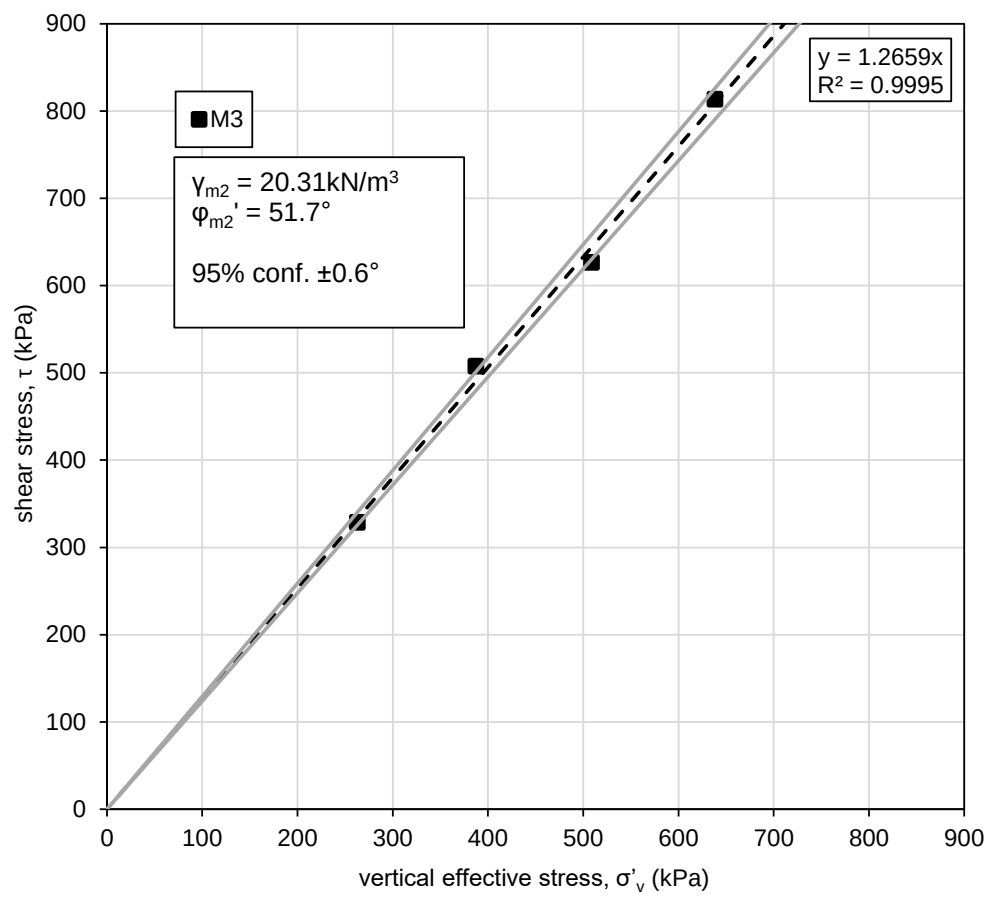


Figure 9(b). Shear stress, τ , v vertical effective stress, σ'_v , aggregate M2.



(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.