Shear behaviour of crushed concrete and bricks

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Abstract: Demolition waste materials mainly consist of concrete and bricks and arise from the demolition of existing structures and buildings. Environmental and economical reasons make their recycling necessary, but to date, their use is curtailed due to the lack of research in determining their properties. This paper reports on the efforts to understand the behavioural characteristics of three types of recycled material to determine their potential for engineering fill applications. For this purpose, their physical and mechanical characteristics have been extensively investigated. Two types of crushed concrete, one obtained straight after demolition and the other processed to industry specifications, and one type of crushed brick was tested. An extensive large scale shear box test regime was employed to determine the shear strength behaviour of the materials. The influence of the normal stress on the peak friction angle, the shear stress-horizontal displacement relationship and horizontal displacement-vertical displacement behaviour of the materials are discussed in this paper. The results show that the behaviour of the three recycled materials during shear testing is similar to the behaviour exhibited by natural granular materials from literature. Concluding, the shear box test results have shown that the specific demolition waste products exhibit considerable shear strength and can be utilised in construction as low level engineering fill.

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Shear behaviour of crushed concrete and bricks

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Abstract

Demolition waste materials mainly consist of concrete and bricks and arise from the demolition of existing structures and buildings. Environmental and economical reasons make their recycling necessary, but to date, their use is curtailed due to the lack of research in determining their properties. This paper reports on the efforts to understand the behavioural characteristics of three types of recycled material to determine their potential for engineering fill applications. For this purpose, their physical and mechanical characteristics have been extensively investigated. Two types of crushed concrete, one obtained straight after demolition and the other processed to industry specifications, and one type of crushed brick was tested. An extensive large scale shear box test regime was employed to determine the shear strength behaviour of the materials. The influence of the normal stress on the peak friction angle, the shear stress-horizontal displacement relationship and horizontal displacement-vertical displacement behaviour of the materials are discussed in this paper. The results show that the behaviour of the three recycled materials during shear testing is similar to the behaviour exhibited by natural granular materials from literature. Concluding, the shear box test results have shown that the specific demolition waste products exhibit considerable shear strength and can be utilised in construction as low level engineering fill.

1. INTRODUCTION

Primary aggregates are utilised in different construction applications, such as general engineering fill, pavement engineering, concrete production and railway ballast. The UK construction industry extracted about 235 million tonnes[1] of construction aggregates in 2005 and it is estimated that the amount of aggregates needed in the UK will rise further, especially with the construction requirements of events such as the Olympic Games in

London in 2012. There are environmental problems that arise from the consequential extensive quarrying activities that are not just restricted to the quarry sites, such as the transportation of the materials causing noise, air pollution and traffic congestion problems. The UK construction industry also produces large amounts of construction and demolition waste arising from the construction, repair, maintenance and demolition of buildings and structures. It includes brick, concrete, topsoil and subsoil and generally contains small quantities of timber, metal and plastics. The UK Government faces stringent European Union targets to reduce the amount of landfilled waste and the recycling of some of the demolition waste materials will assist significantly in meeting these targets and reduce the environmental impact of the construction industry.

A future increase in the re-use of demolition waste will benefit the industry as well as the environment. The cost of landfilling demolition waste has increased significantly through the introduction of the landfill tax in 1999[2]. In addition, the aggregates levy in 2002[1] has increased the cost of using primary aggregates. These costs have been compounded by the increase in costs of both the haulage of primary aggregates to site and the removal of waste materials to the disposal sites, and given the cost of over-ordering construction materials (to cover possible material wastage), it would appear that the reuse of waste materials makes both environmental and economic sense.

Despite the apparent attractions offered through recycling construction waste, the re-use of these materials has some restraints and disadvantages that have to be taken into consideration in order for their application to construction projects to be effective. It has generally been assumed in practice that the behaviour of such fills would be similar to that of natural aggregates and, therefore, accumulated data from research into the properties of such natural aggregates has been extrapolated and applied to recycled materials used in

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industry. There are differences between natural aggregates and demolition waste though, especially crushed concrete and bricks, with the most significant being that the latter are non-homogeneous and its composition varies depending on the different particle size fractions.

It is important, therefore, to investigate the behaviour of demolition produced crushed concrete and bricks in comparison with natural aggregates before these materials can be confidently utilised in geotechnical applications.

2. DESCRIPTION OF MATERIALS

The three material types tested in this investigation were purposefully selected as being representative of commercial crushing processes used in demolition and processing sites in preference to the crushing of the materials in the laboratory using artificial procedures. The first type of crushed concrete (CC1) was produced at a Sheffield city centre location from the demolition of a late 20th century concrete building in 2001. The demolition waste was crushed on site using heavy demolition plant and mainly comprised crushed concrete, as the demolition and processing methods adopted on site had led to the removal of the vast majority of other structural components.

The second type of crushed concrete (CC2) and the brickwork rubble (CB1) were obtained from a crushing site. Both the concrete and brick had been originally sourced from unknown developments, and subsequently transported to and processed at the crushing site. A range of commercial products are prepared at the site, and the products used in this research project were selected as being compliant with industry standard specifications. CC2 was selected as meeting the grading requirements of RCA (ii) of Table 1 of Digest 433 B.R.E.[3], whilst CB1 was chosen to meet the grading requirements of RCA (i) of Digest 433 B.R.E.[3]

The removal of all the impurities, such as timber, metal, plastic, (sizes from 40 mm to fine particles) would be a lengthy and costly procedure for industry. Typically only large particles such as timber and metals are removed in practice, the latter via the use of magnets. It was therefore decided to similarly test the materials without removing any impurities other than metal components and large pieces of timber. The quantity of the impurities after the sieving tests (100 kg of each material were sampled) was found to be less than 1 % (range 0.2 - 0.8 %).

Fig. 1 presents the grading curves for all three materials. Table 1 lists the three materials under investigation (col. 1) and summarises some of their physical characteristics obtained in the laboratory (cols. 2-5). The coefficients of uniformity (C_u), a measure of the variation in particle size, are 32.9, 33.3 and 46.6 for material CC1, CC2 and CB1 respectively, Table 1, col. 6.

3. EXPERIMENTAL EQUIPMENT AND PROCEDURE

The shear box equipment used in the test programme is shown in Fig. 2. The apparatus is free-standing and consists of a rigid base frame supporting a central horizontal loading jack. The thrust from the jack is applied to the lower half of the ball track mounted shear box, measuring 316 mm square by 160 mm high. The upper half of the shear box is attached to another horizontal loading jack, which is connected in turn to a 50 kN capacity load cell. The horizontal loading jacks are driven via a multi-speed gear box mounted within the base of the machine. Vertical load is applied to each specimen through a rigid loading plate and a vertical loading frame. The lower crosshead of the loading frame passes beneath a horizontal loading beam, which transfers dead load from the end of the beam at a ratio of 20:1.

The complete testing programme required a very large quantity of each material to be prepared, but due to storage limitations it was not feasible to obtain sufficient amount of the material from the suppliers to allow quartering of the samples strictly in accordance with BS requirements. Rather, the entire mass of each material required for the shear box tests was placed on a clean concrete floor. The materials were passed through a 37.5 mm sieve and the fraction coarser than 37.5mm was then removed to reduce the ratio between the minimum dimension of the test specimen and the maximum particle size to within acceptable limits. The remainder was then mixed thoroughly on a clean concrete floor. The mixed material was sub-divided to prepare each sub-sample in turn via a process of quartering, with the remaining sample being retained each time for further re-mixing and quartering for the preparation of the next samples.

To ease specimen preparation and avoid damage to the shear box frame, compaction of the materials in the shear box was undertaken with the shear box removed from its frame and placed on a concrete floor. Both halves of the shear box were secured together with the locating screws and a vibrating hammer was used to compact the materials into the box in three layers to achieve the target dry density for each test specimen of 1.8 ± 0.04 Mg/m^3. Three layers were adopted to avoid coexistence of the shear plane with layer interfaces, and to promote a uniform density throughout the specimens. All the materials were tested in their natural moisture content, which was measured before and after each test and was found to be 2.0 ± 0.2 %. After the required density was achieved, the top plate was placed in position and the shear box placed within the test frame. The locating screws and four clamps placed on each side of the shear box ensured that the disturbance of the sample during its placement in the test frame was kept to a minimum.

Five different vertical stresses were applied varying from 95 kPa to 317 kPa (the maximum that could be applied without damaging the shear box apparatus). A rate of displacement of

0.125 mm/minute was used to shear the samples. Sivakumar *et al*[4] have used faster rates (1.5 mm/minute) for shearing recycled materials but the slow rate used in this investigation allowed more detailed observations to be made. Measurements of the load applied (measured through the load cell) and the vertical and horizontal displacements (measured through low voltage displacement transducers) were logged by the computer at one minute intervals with the help of a custom made analogue interface box.

The tests were carried out until the real time graph showed that the ratio of shear strength to horizontal displacement was reducing due to time restrictions of the research. This allowed for the large number of tests necessary to minimise the effects of the materials' variability but did not allow for analytical observations of the post peak behaviour of the materials, as this was not the scope of the research. Ten tests were performed per different vertical stress for CC1 (50 tests in total) and five tests per different vertical stress for CC2 and CB1.

All the materials were sieved after the shear box tests and their grading curves established. The sum of positive differences between the percentages passing from each of the individual sieves before and after testing provided a measure of particle breakage (Breakage Index, B_g) according to Marsal[5].

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1. Particle breakage

The breakage indices of the materials, which could indicate the strength of individual particles, were found to be 8.8, 12.1 and 4.3 for material CC1, CC2 and CB1. Lade *et al*[6] have shown that increased angularity increases particle breakage, as the stresses can concentrate along their smaller dimension and fracture it more easily. Yamamuro and Lade[7] have found that well-graded soils break less, probably because when more particles surround each particle, the average contact stress tends to decrease. The recycled brick material crush the least ($B_g = 4.3$) but they are neither the most flaky nor the most elongated from the three and, therefore, it appears that particle shape is not the dominant factor in the particle breakage of the materials. Material CB1, though, has the highest Cu value and that appears to be in agreement with the findings of Yamamuro and Lade[7]. Particle strength may be another reason for the differences between the particle breakage of the materials but McDowell *et al*[8] found that found that no correlation was obtained between degradation and particle strength for ballast, especially for box tests. As an individual particle strength test was not performed in this research, the effect of this parameter can not be established.

4.2. Stress- displacement behaviour

The results of the shear box tests for material CC1, CC2 and CB1 are shown in Figs. 3, 4 and 5 respectively as plots of shear stress and vertical displacement against horizontal displacement.

The gradual decrease of shear stress with horizontal displacement after peak, shown in Figs 3(a), 4(a) and 5(a), suggests the strain-softening behaviour of the materials which has also been reported for natural aggregates (Indraratna *et al*[9]). The crushed brick material, Figs. 5a, 5b exhibit higher stress-horizontal displacement ratios and this is attributed to lowest particle breakage index and greater particle interlock due to higher value of Cu (Table 1). The results indicate that the amount of strain at failure (peak of shear stress / horizontal displacement, Figs. 3a, 4a, 5a) increases with normal stress, something that has been observed by others (Indraratna *et al*[9]; Charles and Watts[10]; Varadarajan, *et al*[11]) when testing granular materials.

All three materials exhibit volumetric expansion (dilation) in the later stages of the tests where failure (peak of shear stress / horizontal displacement graph) occurs as shown in

Figs. 3(b), 4(b) and 5(b). The amount of dilation, though, reduces with the increase in normal stress levels. This phenomenon is attributed to the increase amounts of particle crushing at higher normal stresses (Varadarajan, *et al*[11], Lade *et al*[6]). This can not be verified for the three materials investigated since the quantification of particle crushing was calculated for the complete samples CC1, CC2 and CB1 (for al the tests for the different normal loads) and not for each of the individual normal stresses. The type of the material displaying the highest value of vertical displacement at failure changes depending on the normal stress applied. The differences between the amounts of dilation appear to be the lowest at 317 kPa normal stress. These observations indicate that for the three specific types of materials tested, the normal stress is the dominant factor in controlling the amount of vertical displacement, something that has been observed by Indraratna *et al*[12] for natural rockfill material too.

4.3. Shear stress and angles of internal friction

The strength envelopes of the crushed brick and two types of crushed concrete materials are shown in Fig. 6. They display curvature and pass through the origin of the axes (zero cohesion). The curvature phenomenon has been observed in shear strength investigations for natural granular materials by others (Indraratna *et al*[9]; Charles and Watts[10]; Indraratna *et al*[12]; Marachi *et al*[13]).

The angles of internal friction, φ', based on a straight line from the origin to the measured shear at 317 kPa, were calculated as 55°, 57° and 57° for CC1, CC2 and CB1 respectively. The values of φ' appear to be quite high but values of about 60° have been observed by Charles and Watts[10] for sandstone and basalt of maximum particle size of 38 mm. Indraratna *et al*[9] have found friction angles of 66° and 67° for basalt at low normal stresses and attributed them to the inter-particle stresses being less that the crushing strength of the materials and the ability of particles to dilate more. Further, Fannin *et al*[14] have calculated friction angles up to 71° performing in situ tests in mountain soils at British Columbia.

Sivakumar *et al*[4] investigated the shear behaviour of crushed concrete obtained from crushing concrete tubes and crushed brickwork containing at least 95% bricks and mortar with vertical stresses varying from 60 kPa to 300 kPa. Both materials were sieved and had particle sizes between 20 and 40 mm. The angles of internal friction (φ') of both materials were 43°. These values are significantly lower than φ' calculated for CC1, CC2 and CB1 in this investigation. This is attributed to better packing of particles of material CC1, CC2 and CB1 due to their broader gradation and existence of smaller particles. Aurstad *et al*[15] have tested crushed concrete with particles ranging from 0-63 mm and from 20-63 mm in a large triaxial apparatus (diameter 300 mm and height 600 mm). They found that the angles of internal friction were 48° and 60° for the materials with minimum particle size of 20 and 0 mm respectively.

McKelvey *et al*[16] investigated the behaviour of two types of recycled aggregates under repeated load on a series of shear box tests and vertical stresses varying from 60 kPa to 300 kPa. The first type of material (named S1 for this discussion) was crushed concrete obtained from crushing concrete cubes. The second type of materials (named S2) was crushed brickwork containing bricks (of at least 95%) and mortar. The friction angles, determined from a straight line from the origins to the value of shear stress for 300 kPa, were and 39° for S1 and 37° for S2. These values are significantly lower than the ones obtained for Material A, B and C at 317 kPa for all types of shear box. McKelvey *et al*[16] state that the particle crushing of the materials was high but do not give specific values. The lower values of friction angles of S1 and S2 are most probably due to:

1. Their higher level of particle crushing and/or
2. The fact that Materials A, B and C have broader grading curves

Material S1 and S2 behave similarly volumetrically with Material A, B and C since they exhibit dilatancy at low normal stresses that reduces with increasing normal stress levels.

Apart from affecting the shear stress, it has been well documented (Marsal[5]; Indraratna *et al*[12]; Marachi *et al*[13]; Fannin *et al*[14]) that an increase in normal stress reduces the internal angle of friction of granular materials. Fig. 7 shows the values of friction angle in relation to the five normal stresses under consideration (95, 143, 190, 238 and 317 kPa). The friction angles are based on a straight line from the origin of the axes to the measured shear stress at the individual normal stresses (Fig. 6). The friction angles of CC1 and CC2 reduce by 6.5° and 3.4° respectively (from the value of φ' at 95 kPa normal load to the value of φ' at 317 kPa). The friction angles of CB1 reduce by 8.7° for the same differences in normal loads. This is close to reductions observed by Charles and Watts[10] (friction angle of basalt from about 60° to 50° from 100 kPa to 300 kPa normal stresses). On the other hand though, the reductions, though significant, appear to be less striking than the ones observed by Indraratna *et al*[9] who noticed reductions in friction angles from 67° to 46.8° at normal stresses from 20 kPa to 250 kPa.

The crushed brick (CB1) appear to have higher friction angles at low normal stresses. This is thought to be a result of the higher Cu value (Table 1, col. 6) that provides better packing of particles and / or having the least particle crushing and, therefore, higher stiffness. There are other parameters, such as basic surface friction and individual particle strength, that may cause these differences in friction angle values, but they were not investigated in this research. Further testing is required to identify if any other possible reasons for these differences exist.

The differences of the friction angles of Material CB1 with those of the concrete based materials reduce as the level of normal stress increases. It is believed, though, further testing is needed, as there may be a specific level of normal stress that the friction angles of the materials are similar despite their differences in individual properties. This indicates that at high normal stresses, the differences in the properties of the three types of recycled materials (such as particle shape, grading and particle crushing) may not play a significant role and the normal stress dominates their behaviour under shear.

5. CONCLUSION

This investigation has examined the potential use of two types of crushed concrete and one type of crushed brick for utilisation as an engineering fill. It found that:

- the recycled materials resemble the stress-strain and volumetric behaviour of natural aggregates, as depicted in this paper by using shear stress-horizontal displacement and vertical displacement-horizontal displacement relationships
- although the angles of internal friction of the recycled materials are high, they are similar to those found in investigations on natural aggregates.
- the three types of recycled materials meet the strength requirements for general engineering fill but more research (e.g. permeability, cyclic loading) is needed to provide a complete picture of the properties of these materials.
- the friction angles of the three recycled materials under investigation vary with those obtained from other types of recycled aggregates. This shows that it is very difficult to find two investigations that test the same type of recycled aggregates since they are too variable and almost certainly are obtained from different sources.
- The lack of ability to characterise a specific type of recycled aggregates and then extrapolate the data to all demolition waste remains the biggest problem in recycled aggregates research. Despite these differences in the types of recycled aggregates tested, in different investigations, it is clear that recycled aggregates exhibit the strength required to be utilised as engineering fill for a variety of purposes.

Further testing with different types of demolition waste (but with identical maximum and minimum particle sizes) is therefore needed to being able to confidently state that recycled aggregates in general can be utilised for engineering fill. It is also important to test recycled aggregates for other properties such as their permeability and ability to withstand cyclic load in order to obtain a more complete picture of their behaviour.

6. ACKNOWLEDGEMENTS

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TABLES

Table 1. Characteristics of the materials.

Characteristics					
1	2	3	4	5	6
Material Type	Water Absorption (%)[1]	Particle Density (Mg/m^3)[2]	Flakiness Index (%)[3]	Elongation Index (%)[4]	Particle Variation (Cu)
CC1	5.5	2.2	11.5	24.4	32.9
CC2	5.5	2.2	6.5	14.5	33.3
CB1	13.2	1.9	9.7	21.9	46.6

[1] and [2] determined using BS 812-2, 1995
[3] and [4]determined using BS 812-105.1, 1989 and BS 812-105.2, 1990 respectively.

FIGURE CAPTIONS

Fig. 1. Particle size distributions of the three materials

Fig. 2. Large shear box apparatus

Fig. 3. Behaviour of material CC1 during shearing; (a) shear stress-horizontal displacement and (b) vertical displacement-horizontal displacement

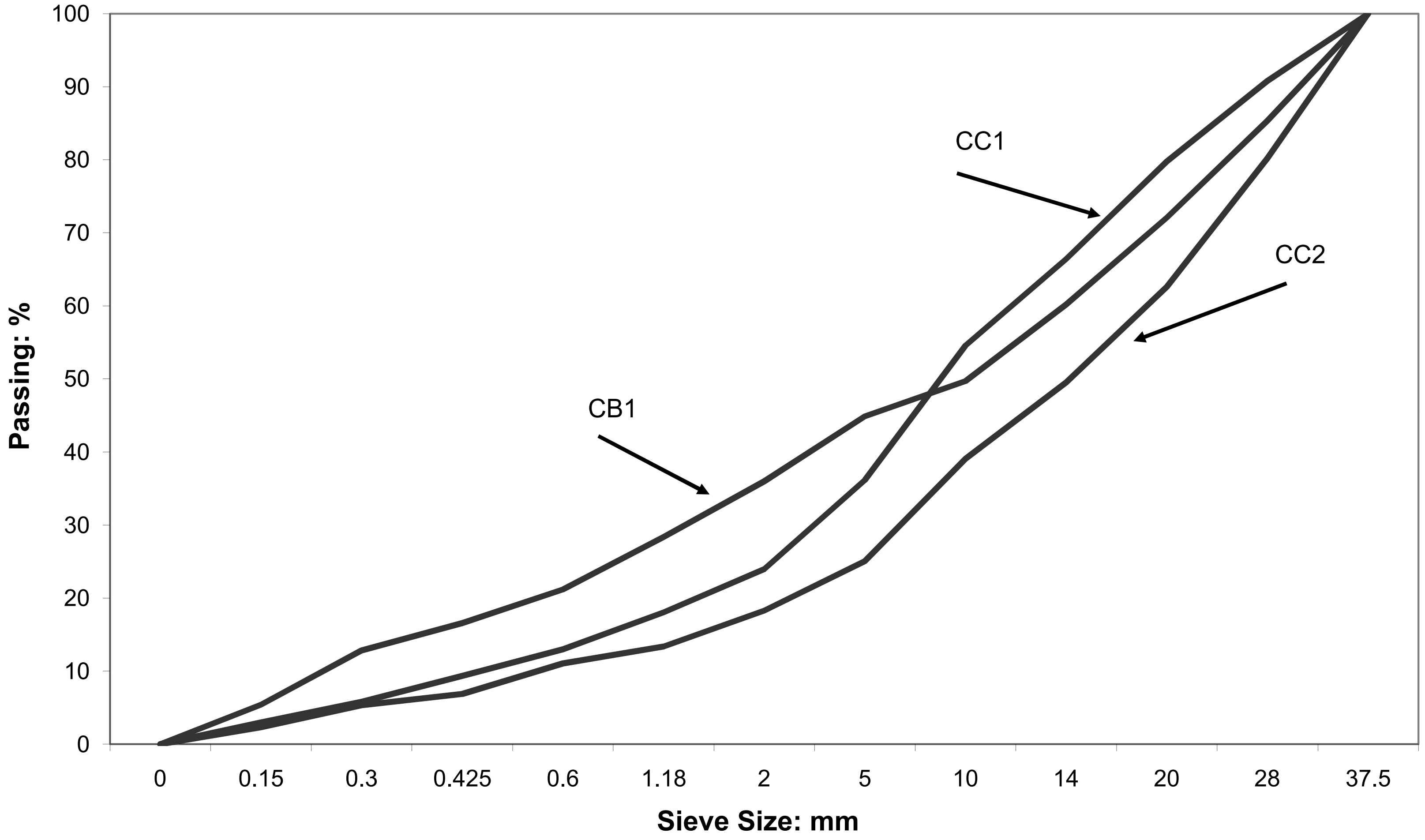
Fig. 4. Behaviour of material CC2 during shearing; (a) shear stress-horizontal displacement and (b) vertical displacement-horizontal displacement

Fig. 5. Behaviour of material CB1 during shearing; (a) shear stress-horizontal displacement and (b) vertical displacement-horizontal displacement

Fig. 6. Strength envelopes of the three materials

Fig. 7. Friction angles against normal stress

Figure1

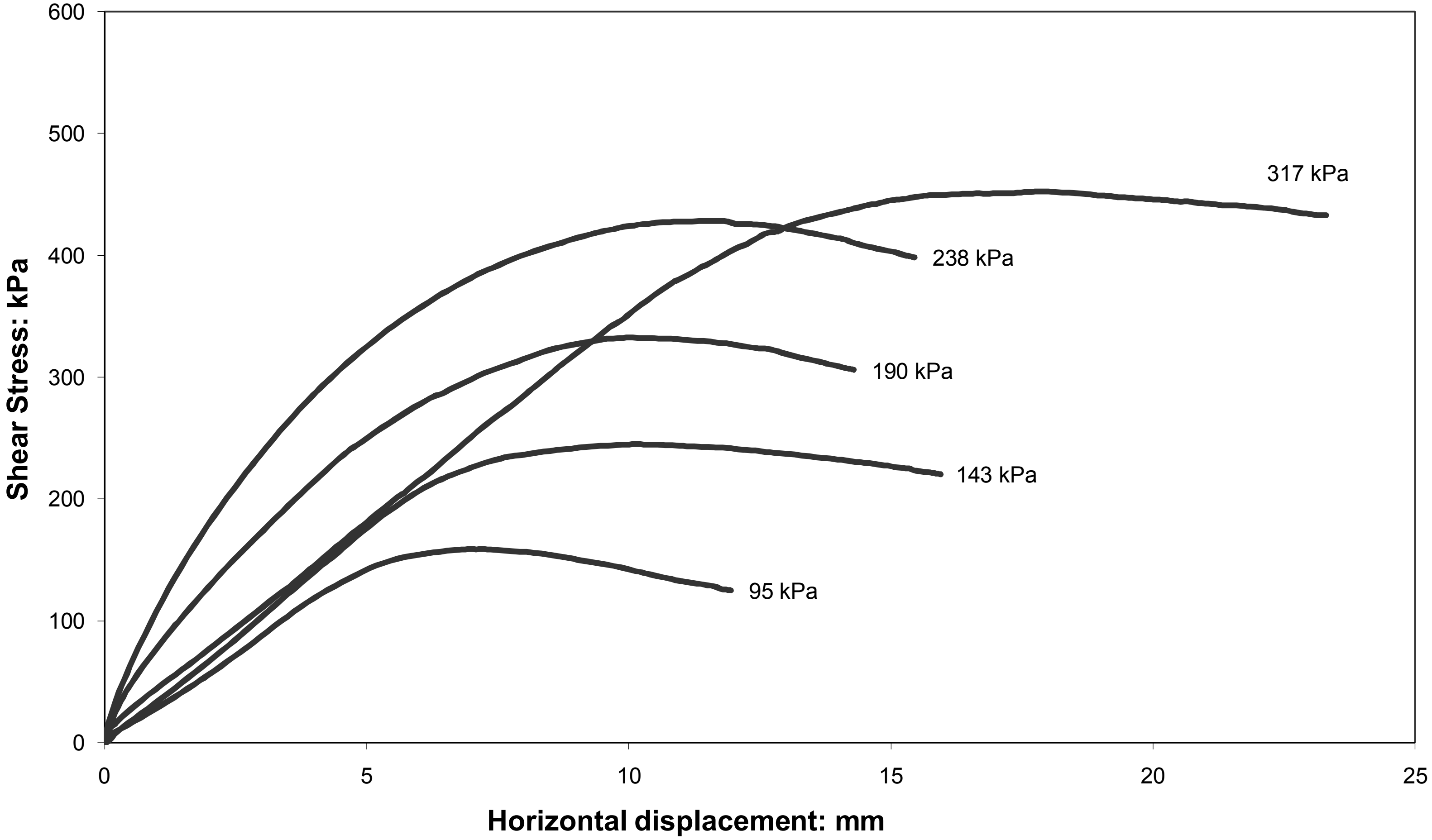


100
90
80
70
60
50
40
30
20
10
0
Passing: %
CC1
CC2
CB1
0
0.15
0.3
0.425
0.6
1.18
2
5
10
14
20
28
37.5
Sieve Size: mm

Figure 2

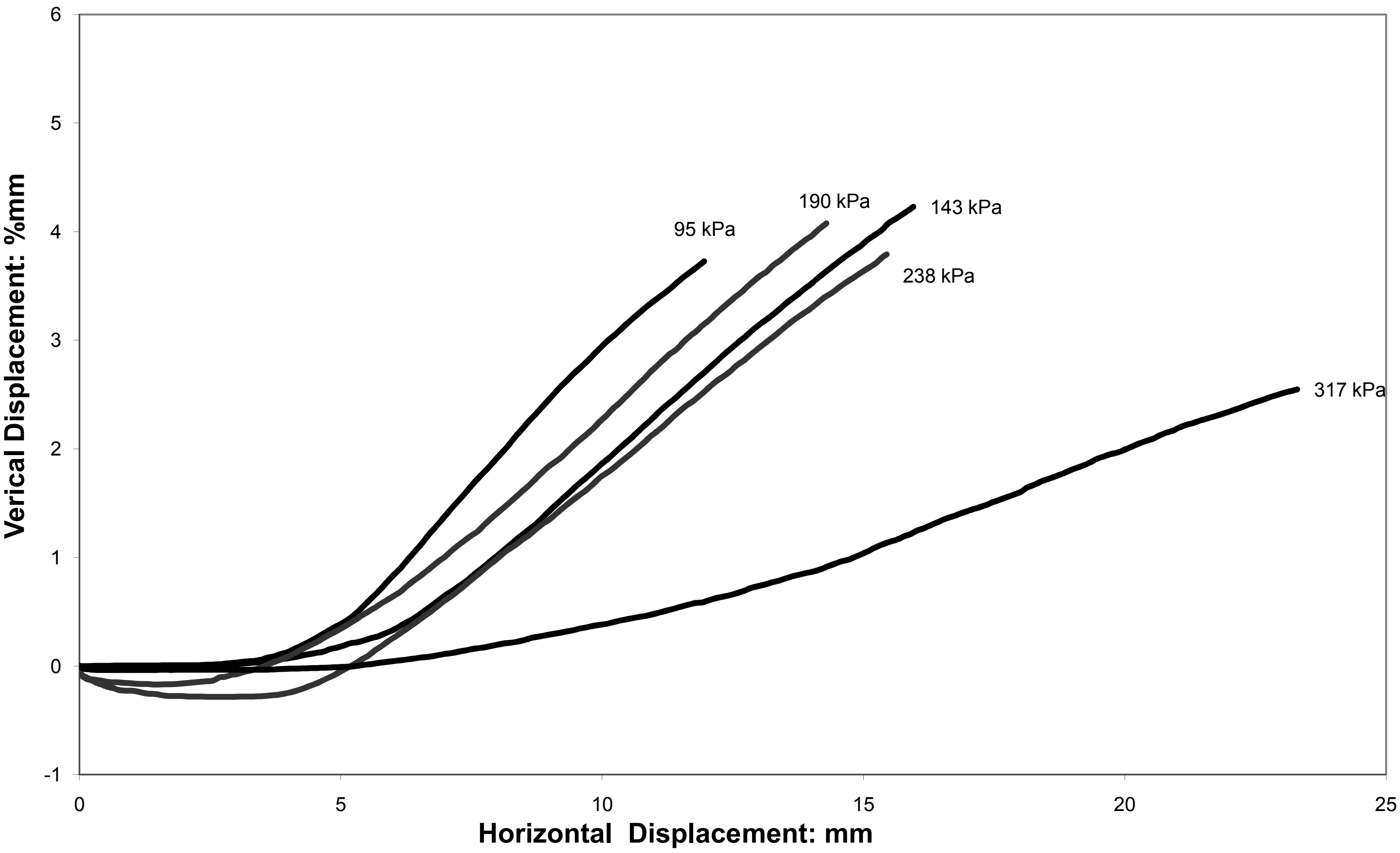
Click here to download high resolution image

Figure 3a



600
500
400
300
200
100
0
Shear Stress: kPa
0
5
10
15
20
25
Horizontal displacement: mm
317 kPa
238 kPa
190 kPa
143 kPa
95 kPa

Figure 3b



95 kPa
190 kPa
143 kPa
238 kPa
317 kPa
6
5
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Verical Displacement: %mm
0
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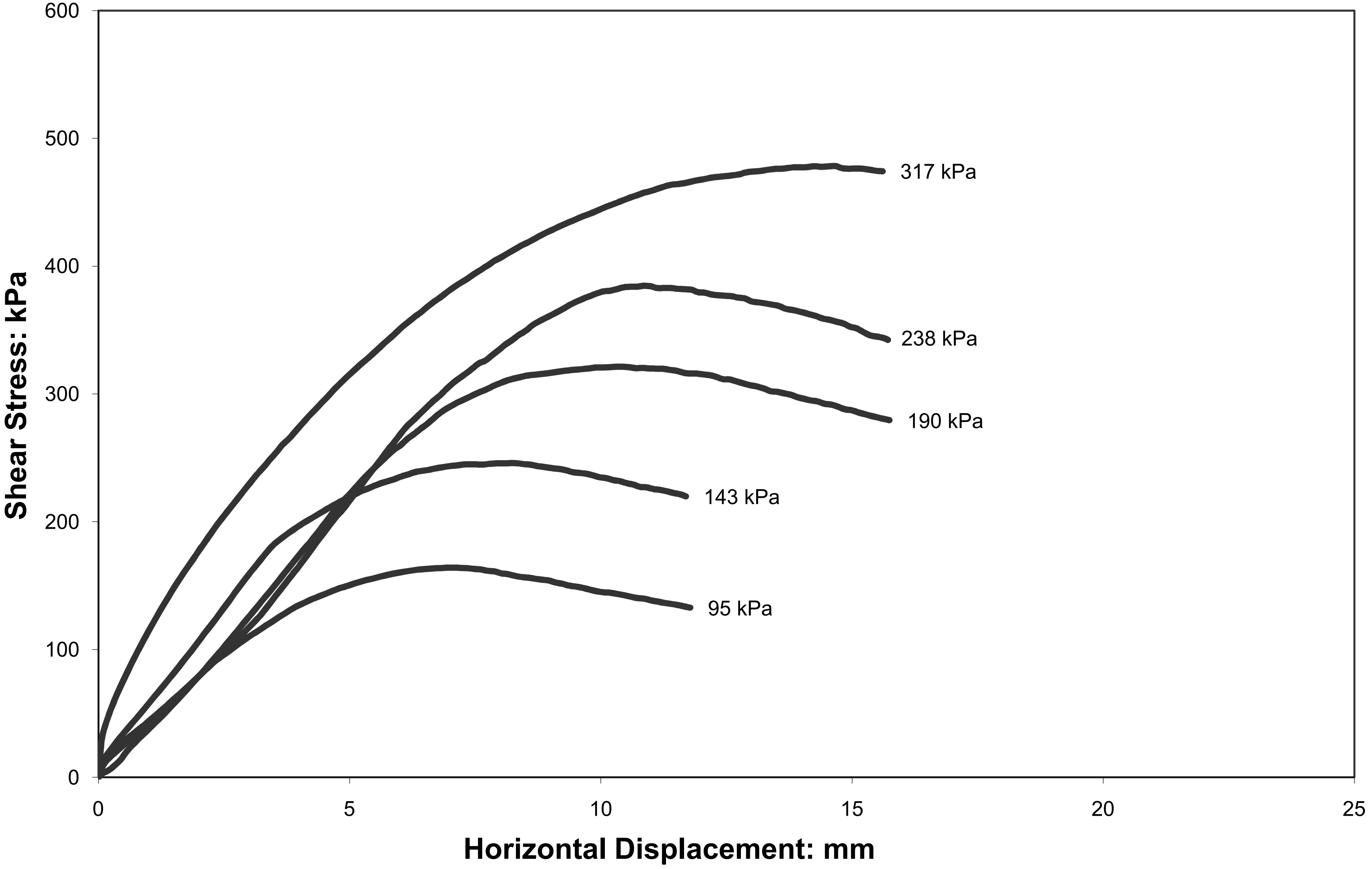
10
15
20
25
Horizontal Displacement: mm

Figure 4a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Shear Stress: kPa
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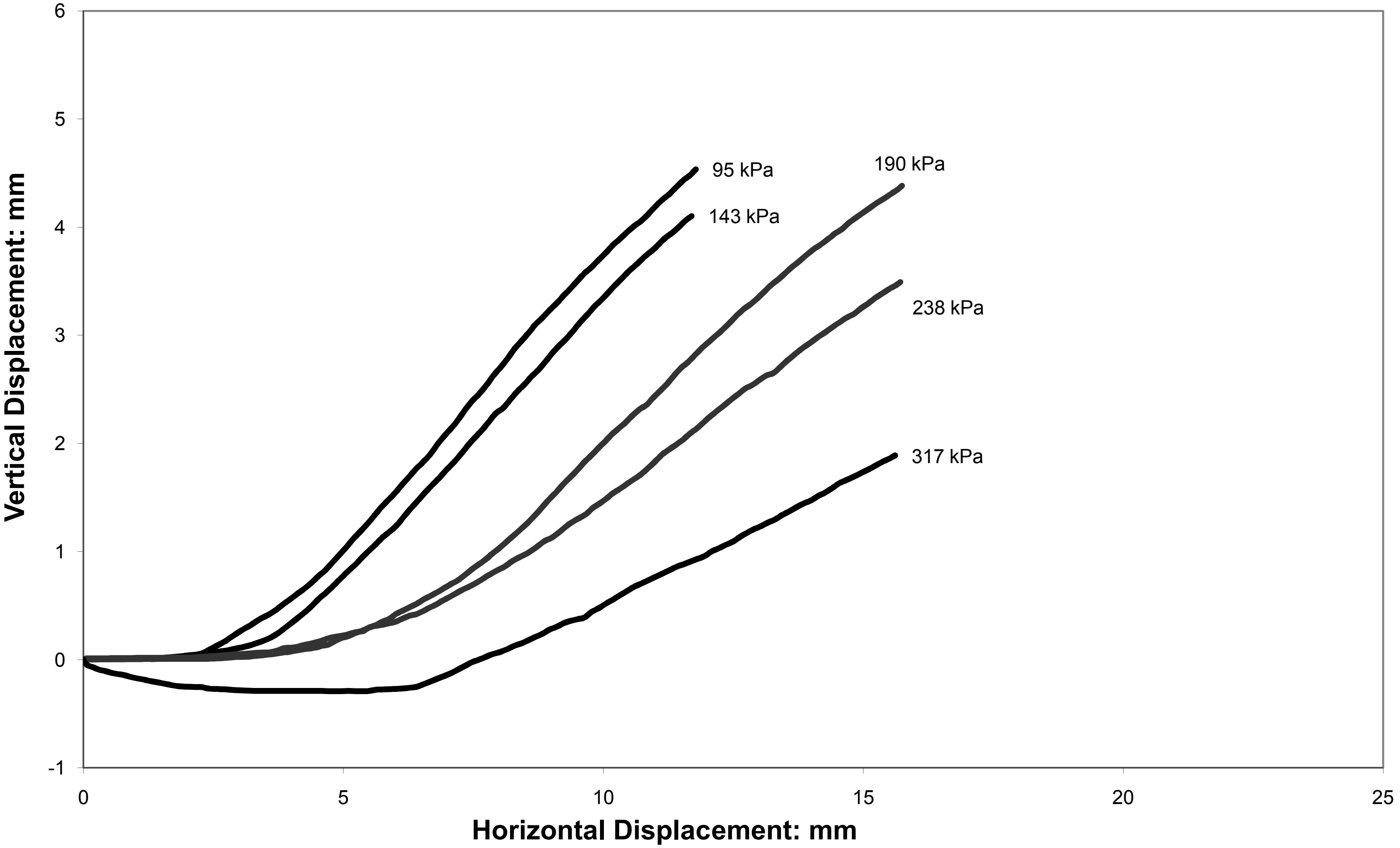
Horizontal Displacement: mm
317 kPa
238 kPa
190 kPa
143 kPa
95 kPa

Figure 4b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Vertical Displacement: mm
Horizontal Displacement: mm
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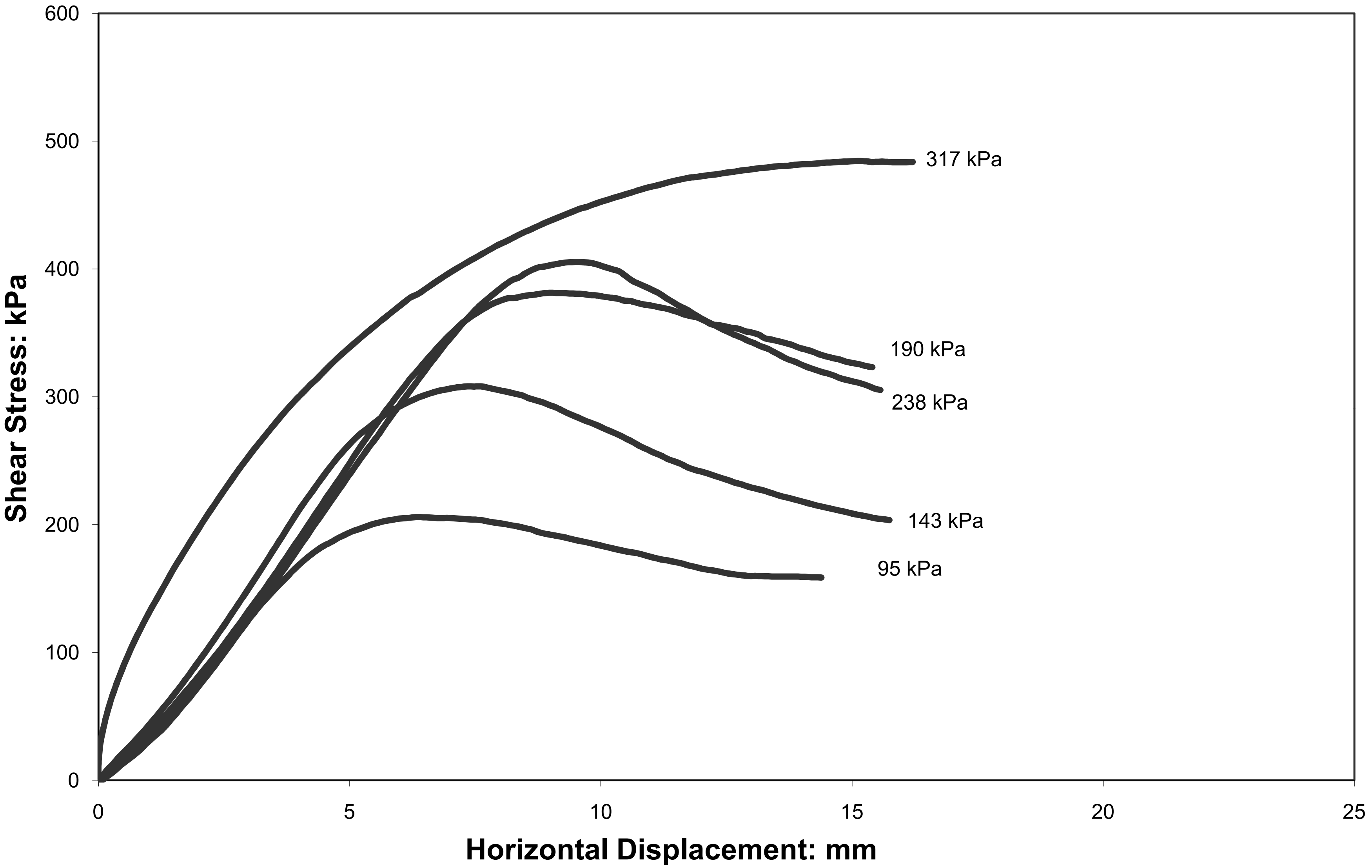
143 kPa
190 kPa
238 kPa
317 kPa

Figure 5a



600
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Shear Stress: kPa
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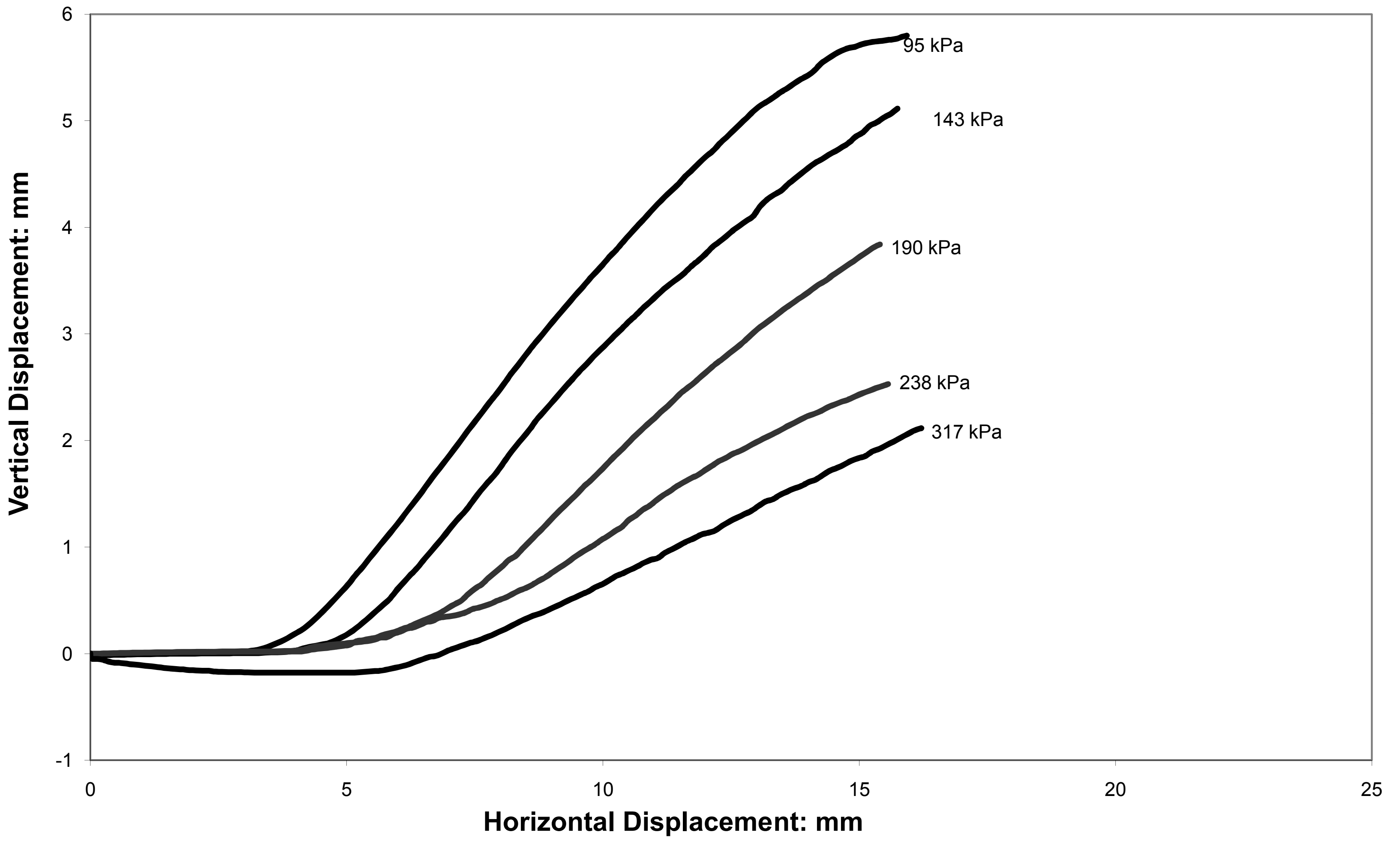
25
Horizontal Displacement: mm
317 kPa
190 kPa
238 kPa
143 kPa
95 kPa

Figure 5b



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Vertical Displacement: mm
Horizontal Displacement: mm
95 kPa
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238 kPa
317 kPa

Figure 6

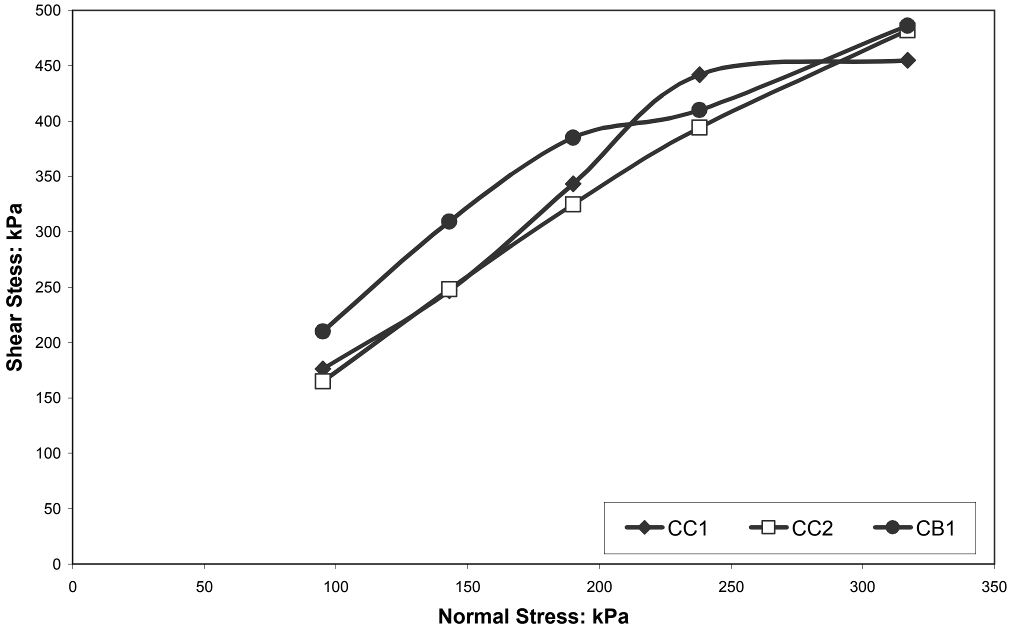
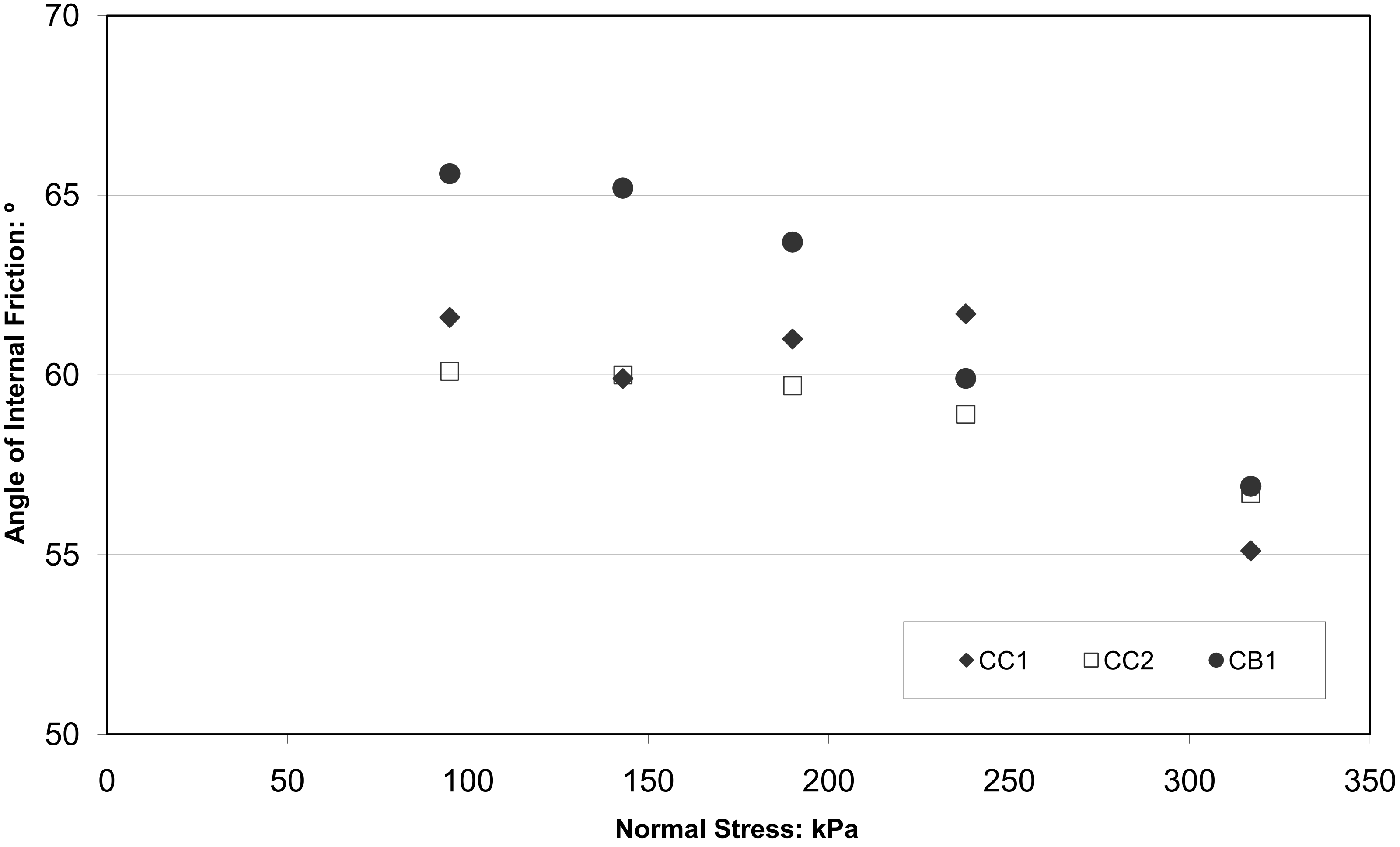

500
450
400
350
300
250
200
150
100
50
0
Shear Stess: kPa
0
50
100
150
200
250
300
350
Normal Stress: kPa
CC1
CC2
CB1

Figure 7


70
65
60
55
50
Angle of Internal Friction: °
0
50
100
150
200
250
300
350
Normal Stress: kPa
◆ CC1
□ CC2
● CB1

Title: Shear behaviour of crushed concrete and bricks Article number: COMA-D-08-00046

REPLY TO PEER REVIEW COMMENTS

Comments on Revision 1

Figs 1, 3(a)&(b), 4(a)&(b) and 5(a)&(b) should be re-plotted and references in the test changed.
Corrected

Fig 1 shows the particle size distribution. It should be a simple plot of y vs log x. At the moment it appears to be a sort of bar chart.
The same style of graph has been used in a previous paper so it has to remain the same in order for any reader to be able to see that the materials are the same.

CB3 needs to be corrected to CB1.
Has been corrected

Figs 3(a), 4(a) and 5(a) need to be plotted as shear stress vs horizontal displacement. Normalised horizontal displacement is a meaningless term. Peak shear stress would occur at the same horizontal displacement irrespective of the length of the shear box, so it is the horizontal movement which is the important parameter, not the normalised value. See BS 1377 Part 7 1990 clause 4.6.3 (a)
Corrected

Figs 3(b), 4(b) and 5(b) need to be plotted as vertical displacement vs horizontal displacement, not as normalised displacements. The plot then has meaning and can be used to determine the dilation angle (slope of displacement line). See BS 1377 Part 7 1990 clause 4.6.3 (b)
Corrected

Page 10 - end of 1st para. - should be ....20mm and 0 respectively.
Corrected