Physical properties of demolition waste material

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Abstract: Demolition waste materials, such as crushed concrete and bricks, have been utilised by the UK construction industry for applications such as the production of concrete, low level backfill and road sub-base. There has been increased research on the properties of the recycled aggregates in the past decade but it mainly concentrates on the strength of these types of materials through shear box and triaxial tests. Little research has been undertaken on the physical properties of recycled materials, such as particle shape, water absorption and freeze-thaw resistance. This paper addresses the investigation of the physical properties of demolition waste materials for the purpose of them being reused as engineering fill. It presents the physical characteristics of three types of commercially crushed concrete and brick materials, two of them being similarly based crushed concrete materials with different degrees of processing and one being crushed brick. Characteristics such as particle size distribution, particle shape, large scale compaction, resistance to freeze-thaw and aggregate impact and crushing values were established. The results show that there are similarities and differences between the two concrete based materials. The characteristics of the brick based materials are significantly different from the crushed concrete materials.

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Title: Physical Properties of Demolition Waste Material

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Abstract

Demolition waste materials, such as crushed concrete and bricks, have been utilised by the UK construction industry for applications such as the production of concrete, low level backfill and road sub-base. There has been increased research on the properties of the recycled aggregates in the past decade but it mainly concentrates on the strength of these types of materials through shear box and triaxial tests. Little research has been undertaken on the physical properties of recycled materials, such as particle shape, water absorption and freeze-thaw resistance. This paper addresses the investigation of the physical properties of demolition waste materials for the purpose of them being reused as engineering fill. It presents the physical characteristics of three types of commercially crushed concrete and brick materials, two of them being similarly based crushed concrete materials with different degrees of processing and one being crushed brick. Characteristics such as particle size distribution, particle shape, large scale compaction, resistance to freeze-thaw and aggregate impact and crushing values were established. The results show that there are similarities and differences between the two concrete based materials. The characteristics of the brick based materials are significantly different from the crushed concrete materials.

1. INTRODUCTION

The UK construction industry consumed about 235 million tonnes of primary aggregates in 2005 for applications such as pavement engineering, concrete production and engineering fill[1]. At the same time it produces huge amounts of demolition and construction waste that are being disposed in landfill sites. There are environmental and economic concerns that arise for the continuous extraction of natural aggregates, production and landfilling of demolition waste and haulage of these materials from the production to the construction and disposal sites. It makes both environmental and economical sense therefore to recycle / reuse the demolition waste products, particularly crushed concrete and bricks, since it will both reduce the amount of primary aggregates extracted and waste landfilled.

The use of the demolition wastes in the production of concrete has been researched in the past 15 years around the world. It has been shown that crushed concrete can be used in the production of concrete and concrete masonry blocks.[2] Adding to the investigations of recycling / reusing crushed concrete, the research on the utilisation of other demolition waste, such as fine crushed bricks has gained momentum in the past years.[3]

Parallel to the investigations on the reuse of demolition waste in the production of concrete, research undertaken in the past decade (e.g. Sivakumar *et al*[4]; Aurstad *et al*[5]) has shown that structural concrete and bricks have adequate strength characteristics to be utilised as general bulk backfill and / or road sub-bases. The behaviour of granular materials during shearing depends on many parameters such as their particle size distribution and particle shape. Little research has been undertaken into quantifying these characterisation parameters for recycled materials and to determine if the differences in their composition (brick or concrete based waste) and degree of processing affect these parameters.

The three recycled materials, two similarly based crushed concrete materials and one crushed brick, tested in this investigation were chosen specifically to address these issues. These were all obtained from commercial demolition and crushing processes, instead of being produced in the laboratory by crushing bricks and concrete cubes. This was done in order to obtain representative recycled materials used by the construction industry. The first type of concrete (CC1) was produced from the demolition of a late 20th century building in the city centre of Sheffield, UK. It contained mainly crushed concrete and the majority of architectural and structural components of the building were removed prior to demolition. The second type of material (CC2) was also crushed concrete from a different demolition site; it had been removed from the demolition site and was further processed on a crushing site. The third type of recycled materials (CB1) was brickwork rubble (crushed bricks) and was processed at the same site as material CC2. Both these materials were sourced from unknown demolition sites and they were crushed to comply with the requirements of RCA (ii) of Table 1, Digest 433 B.R.E.[6] (CC2) and RCA (i) of Digest 433, B.R.E.[6] (CB1). All three materials were crushed with the use of jaw crushers.

2. TESTING PROCEDURES

The materials were transported to the laboratory where particles larger than 50 mm were discarded. It would have been desirable to test the whole range of particle sizes but that would have been impossible with the size of equipment available for testing. Similar maximum particle sizes have been investigated by many researchers (Charles and Watts[7]; Indraratna *et al*[8] and Indraratna *et al*[9]) for the investigation of the properties of engineered fills.

In order to determine the percentage of impurities (plastic, cables, timber and different types of metals) in the materials it was decided to test a quantity of 100 kg of each of the materials. This quantity was sieved and the impurities were removed from each size fraction of the materials and weighted. The impurities were found to be were found to be less than 1 % (range 0.2 - 0.8 %) in weight of the materials.

The grading curves of the materials were determined by using the mechanical dry sieving method[10] in preference to wet sieving. This was done due to the need to perform sieving tests on large quantities of materials to achieve repeatability, given the variability of recycled materials. It was considered impractical, due to time restrictions, to wet sieve large quantities of the materials, since the wet sieving procedure is hugely time consuming. However, a small quantity of each of the three types of materials was wet sieved at the same stages of the project in order to verify the results of the dry sieving process. To establish the exact dry sieving procedure, it was necessary to perform some initial trials to check the time required for the materials to pass the apertures and to be retained by the right sieve. Different sieving duration sessions were performed with test times varying from 2.5 minutes to 17.5 minutes in increments of 2.5 minutes. From this, it was determined that 15 minute duration was satisfactory. Sieving for 17.5 minutes showed that the results were the same as with 15 minutes sieving, therefore sieving for more than 15 minutes was not necessary.

A total of two tonnes of each of the materials was dry sieved and 100 kg were wet sieved to compare the two types of sieving processes. A quantity of 10 kg was mechanically sieved at a time for 15 minutes.

The particle shape of the materials was determined with two methods:

1. Flakiness (F_I) and Elongation (E_I) Indices according to BS 812-105.1[11] and BS 812-105.2[12] respectively. The flakiness and elongation indices are simple to determine and are widely employed to characterise the shapes of aggregates.
2. The method according to Rösslein[13]. Rösslein[13] determined the flatness (p) and elongation (q) ratios from Eqs. (1) and (2):

$$p = c/b \qquad \text{Eq. (1)}$$

$$q = b/a \qquad \text{Eq. (2)}$$

where a, b and c are the longest, intermediate and shortest lengths of the particle respectively. The values of p and q are plotted in a chart as shown in Fig.1 and the shape of the particle is determined.

As the materials tested are not homogeneous it was considered necessary to produce results not only for the whole of the material but also for each of the individual particle sizes fractions in order to establish the effect of size on the shape of the materials.

The water absorption and particle density of the materials were also determined according to BS 812-2.[14] The aggregate impact value (AIV) and aggregate crushing value (ACV) were established according to BS 812-112[15] and BS 812-110[16] respectively and the resistance to freezing - thawing according to BS EN 1367-1.[17] Materials of maximum particle size of 50 mm and minimum of 10 mm underwent freezing and thawing cycles, and materials of particle sizes between 14 and 10 mm were frozen and thawed to determine the effect of weathering on strength by conducting AIV and ACV tests.

A large scale compaction test method was adopted using a 300 mm diameter mould to accommodate maximum particle sizes up to 50 mm. Marachi *et al*[18] and Indraratna *et al*[9] have suggested that the ratio of diameter to maximum particle size be at least 6 to render particle size effects negligible. The materials were compacted using a Kango K900 vibrating hammer with an output of 1050 W. The force applied to the vibrating hammer (with the tamper attached to it) was 350 ±10 N. The specimen was formed in the compaction mould in two layers of about 200 mm each. Water was measured and added to the dry fresh material to achieve the required moisture contents (3 to 9% and 11%). After both layers had been compacted, the specimen occupied about three-quarters of the mould depth of about 300 mm. Every single specimen was sampled after compaction and again tested for its moisture content. Each layer was compacted for a number of periods of 30 (± 1) seconds. Between each time period of compaction the depth of the sample from the top of the compaction cell was measured at five different points (centre and four points on the sample's edges, forming a cross) so that its volume and, therefore, its dry density could be determined. The compaction testing procedure was designed to enable determination of:

(a). the effect of moisture content on compaction behaviour.

(b). any possible differences between the two layers of compaction.

3. RESULTS AND DISCUSSION

3.1. Particle size distribution

The dry and wet sieving particle distribution curves of materials CC1, CC2 and CB1 are shown in Fig. 2. Figs. 2(a), 2(b) and 2(c) show that the differences in percentage passing between the wet and dry sieving processes are quite small. This indicates that dry sieving can be an acceptable way of determining the particle size distribution of crushed concrete and bricks if the sample mass is sieved for a significant amount of time (15 minutes) and the quantity of materials is small (10 kg). The dry sieved grading curves of the materials can, therefore, be considered an accurate representation of the materials' particle size distribution. The dry sieved particle distribution curves of all three materials are shown in Fig. 2(d) and the grain size characteristics of test materials are summarised in Table 1. The results show that even though there is a difference in the effective sizes of the particles in Materials CC1 and CC2, their Uniformity Coefficient (C_u) values are almost identical. The Uniformity Coefficient is the ratio of the grain size that is 60% finer by weight to the grain size that is 10% finer by weight on the grain size distribution curve and it measures how well materials are graded. The higher the values the better the materials are graded. There is a larger range of particle sizes in Material CC2 than in Material CC1 and CC2, and a larger C_u. This is also verified by their Coefficient of Curvature (C_z) which is a measure of the shape of a grading curve. Materials CC2 and CB1 that had been further processed are well graded as they both are within the limits of 1 – 3 for well-graded soils[19]. Material CC1 has a value of C_z of 0.7, and may be described as poorly to well graded. The difference in materials CC1 and CC2 may be a result of the artificial selection at the site and therefore solid conclusions can not be made.

3.2. Particle shape

The F_I and E_I of the three materials in relation to their particle size are shown in Fig. 3. The mean F_I values for material CC1, CC2 and CB3 are 12.9, 7.3 and 10.9 and the mean E_I values are 23.9, 13.1 and 20.8 respectively. All three materials can be characterised as equidimensional since 64% of Material A, 74% of Material B and 55% for Material C, fall within this category (Figs. 4, 5 and 6). The results show:

1. The F_I and E_I of material CC2 decrease by 5.6% and 10.8% respectively in comparison to material CC1.
2. There is a 10 percent increase in equidimensional particles in material CC2 compared with material CC1.

The most likely explanation for these observations is the manner in which the materials fracture when subjected to mechanical crushing. Lade *et al*[20] found that particles fracture easier along their smaller dimensions, and Yamamuro and Lade[21] observed that the concentration of stresses at the angular points of particles causes fracture more easily than at non-angular points. It is, therefore, possible to infer, although further testing is required, that angular and flaky particles will tend to break into more equidimensional particle shapes during crushing. Since material CC2 has undergone more processing (i.e. more crushing) it would have particles that are less flaky and / or elongated than similarly based crushed concrete materials (CC1) that have not been further processed.

The F_I and E_I values for material CB1 fall between those for materials CC1 and CC2. The most possible explanations for this are the way the materials crush and the degree of processing. The particles are less flaky and elongated compared with material CC1 due to greater processing they have undergone, and more flaky and elongated than material CC2. Though both materials have undergone similar processing, material CC1 (furthered processed crushed concrete) probably crushes more easily and therefore produces "more rounded" particles. Further testing is recommended to verify this conclusion, since no individual particle strength/hardness tests were performed in this investigation.

The F_I reduces with particle size for all materials. This may be a result of the larger particles losing their flaky and angular parts during processing (demolition and crushing) or simply larger particles crushing into smaller ones. For example, a 60 mm particle can crush into two smaller pieces that will have the same width but half the length and, therefore, be less flaky and more equidimensional than the original particle.

Another interesting observation is that there are almost no particles that can be characterised as blades (particles described as being elongated and flaky) in any of the three materials. This is most probably a result of the processing / crushing of the materials that breaks the angular edges of the particles.

3.3. Particle density and water absorption

The calculated particle densities of the materials are 2.2 Mg/m^3 for both the concrete based materials (CC1 and CC2) and 1.9 Mg/m^3 for the crushed bricks. The water absorption of the concrete based materials is 5.5 % and for CB1 13.2%. The results for the concrete based materials, CC1 and CC2, are identical. This indicates that despite the differences in the degree of processing similarly based crushed concrete materials have identical values of properties that depend on the composition of the particles. The value of water absorption is higher and particle density is lower for the crushed brick material compared to the crushed concrete and this is generally also true for uncrushed concrete and bricks. This suggests that these two properties depend on the original structures that were demolished and provided materials CC1, CC2 and CB1. However, since materials CC2 and CB1 originated from unknown structures this statement can not be verified.

At this stage it needs to be noted that the self-cementing characteristics of demolition waste can affect the water absorption results obtained from the standard test procedures. Despite this though this procedure was chosen and used as an initial indication of the water absorption of the three materials as it can be easily replicated and utilised by the industry, without the need for expensive equipment and complicated procedures.

3.4. Aggregate impact and aggregate crushing value tests

The average dry AIV results (from five tests) of materials CC1, CC2 and CB1 are 17.7%, 29.5% and 27.8% respectively. The average (from five tests) dry ACV results are 25%, 28.6% and 33.3% respectively. The highest percentage number indicates the most breakage during testing. The AIV results show that the particles tested (range 10-14 mm) of material CC1 are the strongest and of Material CC2 the weakest. The ACV results show that the particles tested (range 10-14 mm) of material CC1 are still the strongest but for this test the particles of material CB1 are the weakest.

The AIV and ACV tests have been widely used in characterising the strength of natural homogeneous materials. Since the three types of materials investigated in this project are not homogeneous, it is possible that the AIV and ACV results presented are not representative of the materials as a whole. Tests that can provide information about the strength of the materials as a whole (full gradings) are currently being completed by the authors and a comparison with the AIV and ACV results will be presented in a future paper.

3.5. Freeze-thaw resistance

The materials were passed through a 5 mm sieve after ten freezing and thawing cycles. The average results of five tests show that 2%, 2.4% and 2.1% of the mass of materials CC1, CC2 and CB1 respectively passed through the 5 mm sieve. These results only provide an indication of the effect of freezing and thawing and the effect on strength can be determined by conducting AIV and ACV tests on materials after the weathering (freeze-thaw) process. Table 2 summarises the results of the AIV and ACV tests before and after the freezing-thawing process and the percentage reductions in their values. All materials show a reduction in strength after freeze-thaw cycles.

The crushed concrete which was exposed to further crushing process (CC2) is affected more by the freezing-thawing process than the crushed concrete obtained straight from the demolition site (CC1). This is likely to be a result of micro-cracking caused by the further processing of material CC2, filling of the micro-cracks with water and rapid disintegration caused by the freezing and thawing of the water in the microcracks. Microscopic analysis of the materials in order to investigate this suggestion was not feasible due to the time frame of this investigation.

A comparison of all AIV results shows that the crushed brick materials are affected more by the freezing and thawing than material CC1 but less than CC2. This may indicate that the further processed concrete is affected more by the weathering process than further processed crushed brick. This is true only for the specific types of materials tested in this investigation and further testing with more types of demolition waste is needed to generalise this conclusion.

3.6. Compaction tests

The results for the one and two layer large scale compaction tests are shown in Figs. 7(a) and 7(b) respectively. The dry density increased steadily with time for about the first three minutes of the procedure and, thereafter, any additional compactive effort had little or no effect on the dry density. The values plotted in Fig. 7 are averages of 5 tests at each moisture content, after compacting the specimens for 8 periods of 30 seconds each. It is apparent from the compaction results that the two crushed concrete materials, CC1 and CC2, have similar maximum dry densities at similar moisture contents and this is possibly due to the identical values of particle density and water absorption. The similarity in the compaction results of Materials CC1 and CC2 shows that the differences in the values of other parameters such as C_u, C_Z, F_I, E_I do not affect the compaction characteristics of the two crushed concrete Materials. However, this is only true when the same compaction procedure is applied and for Materials CC1 and CC2. More crushed concrete materials need to be investigated if this conclusion is to be generalised. Material CB1 behaves differently to CC1 and CC2. Its maximum dry density is lower than the crushed concrete and this is attributed to their lower particle density. The maximum dry density of CB1 is achieved at higher moisture contents than for CC1 and CC2, something that was also observed by O'Mahony[22] for similar materials. This is most probably a result of the higher water absorption values of the demolition debris/crushed bricks than crushed concrete. As Material CB1 have higher values of water absorption than CC1 and CC2, more water needs to be added to achieve the "lubrication" needed for the closer packing of particles during compaction.

4. CONCLUSIONS

The following conclusions are based on the results of this investigation:

(a) Dry sieving is an acceptable method for determining the grading curves of recycled materials as long as the mass tested is small (less than 10 kg) and the duration of sieving long (more than 15 minutes).

(b) Materials that have not been further processed have more angular / flaky particles and the flakiness of particles reduces with reducing particle size.

(c) The two crushed concrete based materials that have been processed in different degrees have identical values on properties that depend on their composition, such as particle density and water absorption.

(d) Materials with similar particle density and water absorption behave similarly during the large scale compaction tests.

There are similarities between crushed concrete aggregates that have been further processed or obtained straight from the demolition site. These similarities mainly apply to properties that depend on the composition of the materials. Brickwork rubble has significantly different properties than the crushed concrete materials. The main conclusion therefore is that the findings of research on one demolition waste do not apply to all recycled materials, since there are so many different types produced. The conclusions of this paper apply to the three types of materials tested in this investigation.

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Table 1. Summary of grain size characteristics of test materials

	Characteristics						
Material	d_{max}	d_{10}	d_{30}	d_{50}	d_{60}	C_u	C_z
CC1	50 mm	0.47 mm	4.6 mm	10.1 mm	13.5 mm	32.9	0.7
CC2	50 mm	0.62 mm	8.5 mm	17.9 mm	23.6 mm	33.3	2.1
CB1	50 mm	0.29 mm	1.8 mm	12.9 mm	18.3 mm	46.6	1.0
C_Z is the Coefficient of Curvature and C_u the Uniformity Coefficient							

Table 2. ACV and AIV for all the materials before and after the freeze-thaw

	Before Freeze-Thaw		After Freeze-Thaw		Reduction (%)	
Material Type	AIV (%)	ACV (%)	AIV_w (%)	ACV_w (%)	AIV	ACV
Material A	17.7	25.0	19.5	27.6	10.2	10.4
Material B	29.5	28.6	33.9	32	14.9	11.9
Material C	27.8	33.3	30.9	35.9	11.2	7.8

FIGURE CAPTIONS

Fig. 1. Shape categories determined by elongation and flatness ratios (Rösslein[10])

Fig. 2. Particle size distribution curves; (a) material CC1; (b) material CC2; (c) material CB1; (d) all three materials

Fig. 3. Particle shape of materials; (a) flakiness index; (b) elongation index

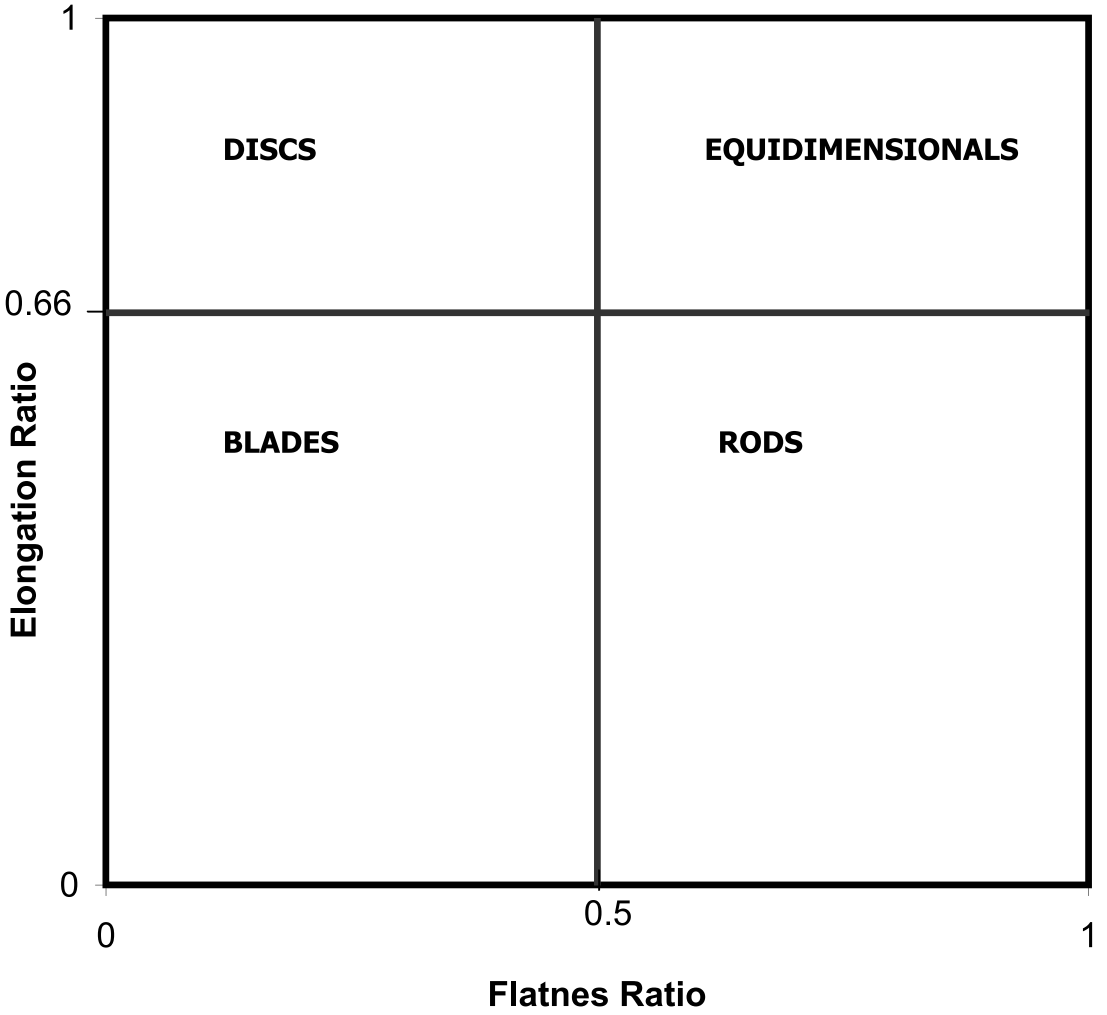
Fig. 4. Shape characterisation for material CC1 (after Rösslein[10])

Fig. 5. Shape characterisation for material CC2 (after Rösslein[10])

Fig. 6. Shape characterisation for material CB1 (after Rösslein[10])

Fig. 7. Compaction behaviour of materials; (a) one layer compaction; (b) two layer compaction

Figure 1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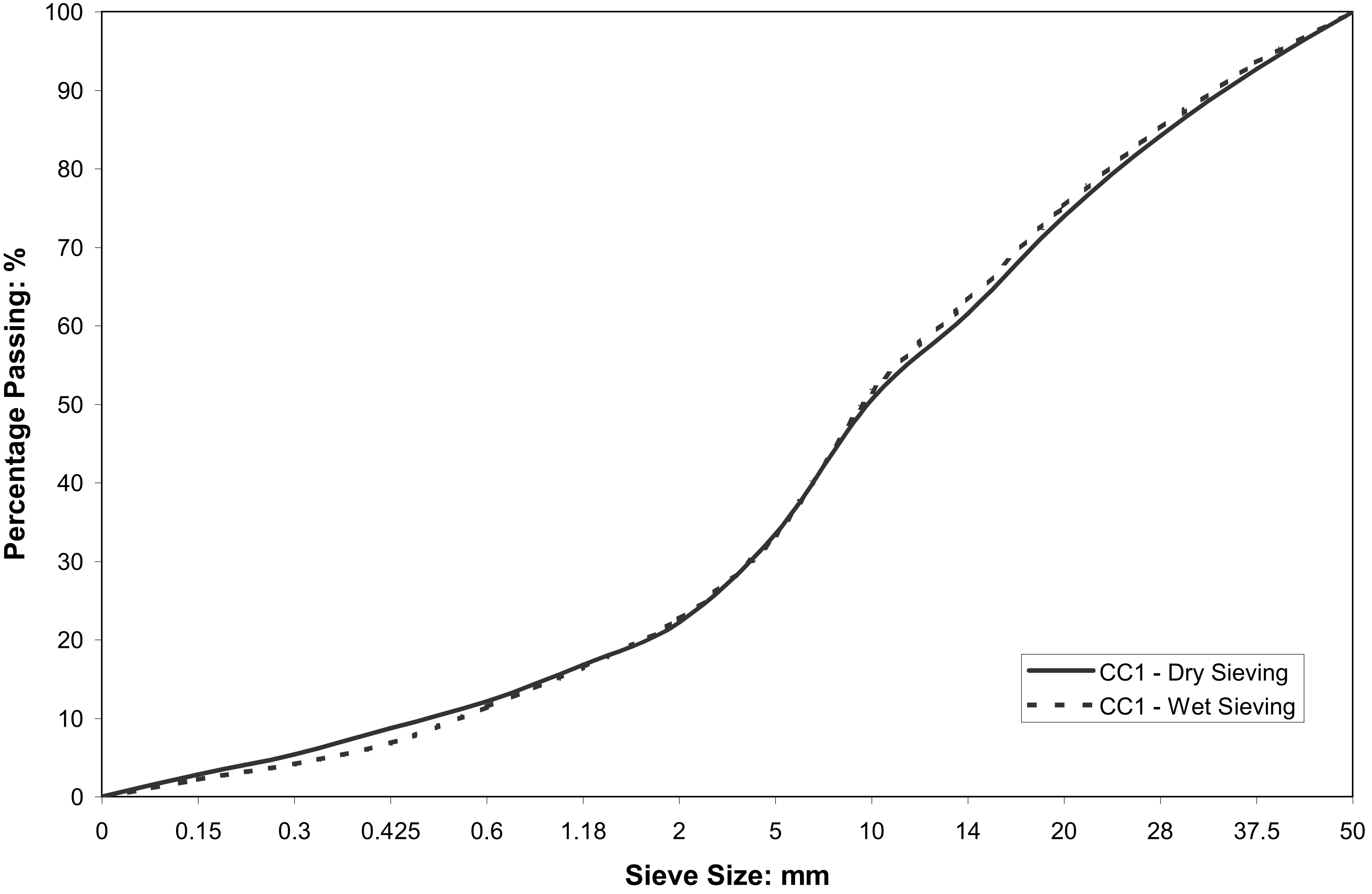
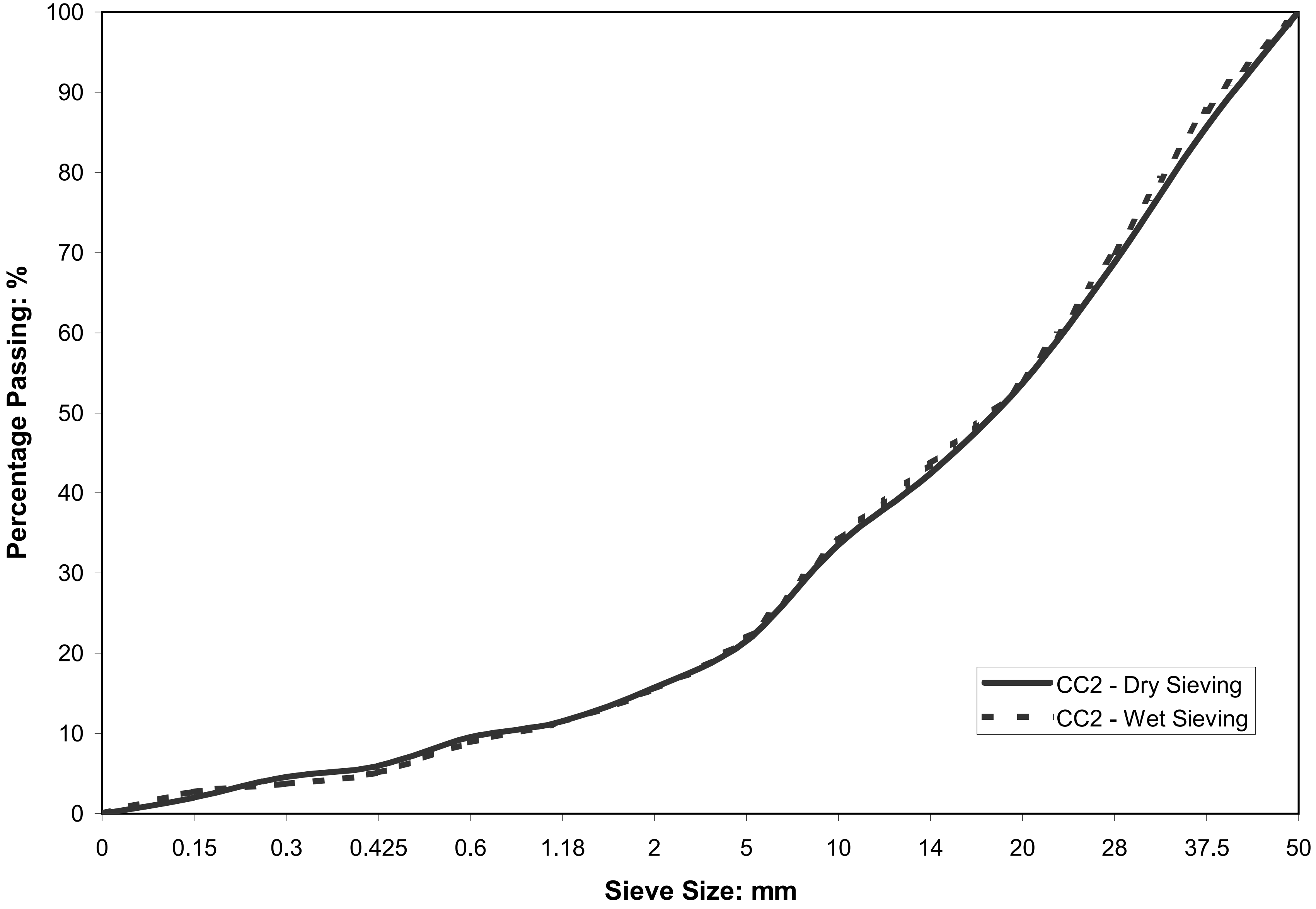
0.66
0
DISCS
EQUIDIMENSIONALS
BLADES
RODS
Elongation Ratio
0
0.5
1
Flatnes Ratio

Figure 2a



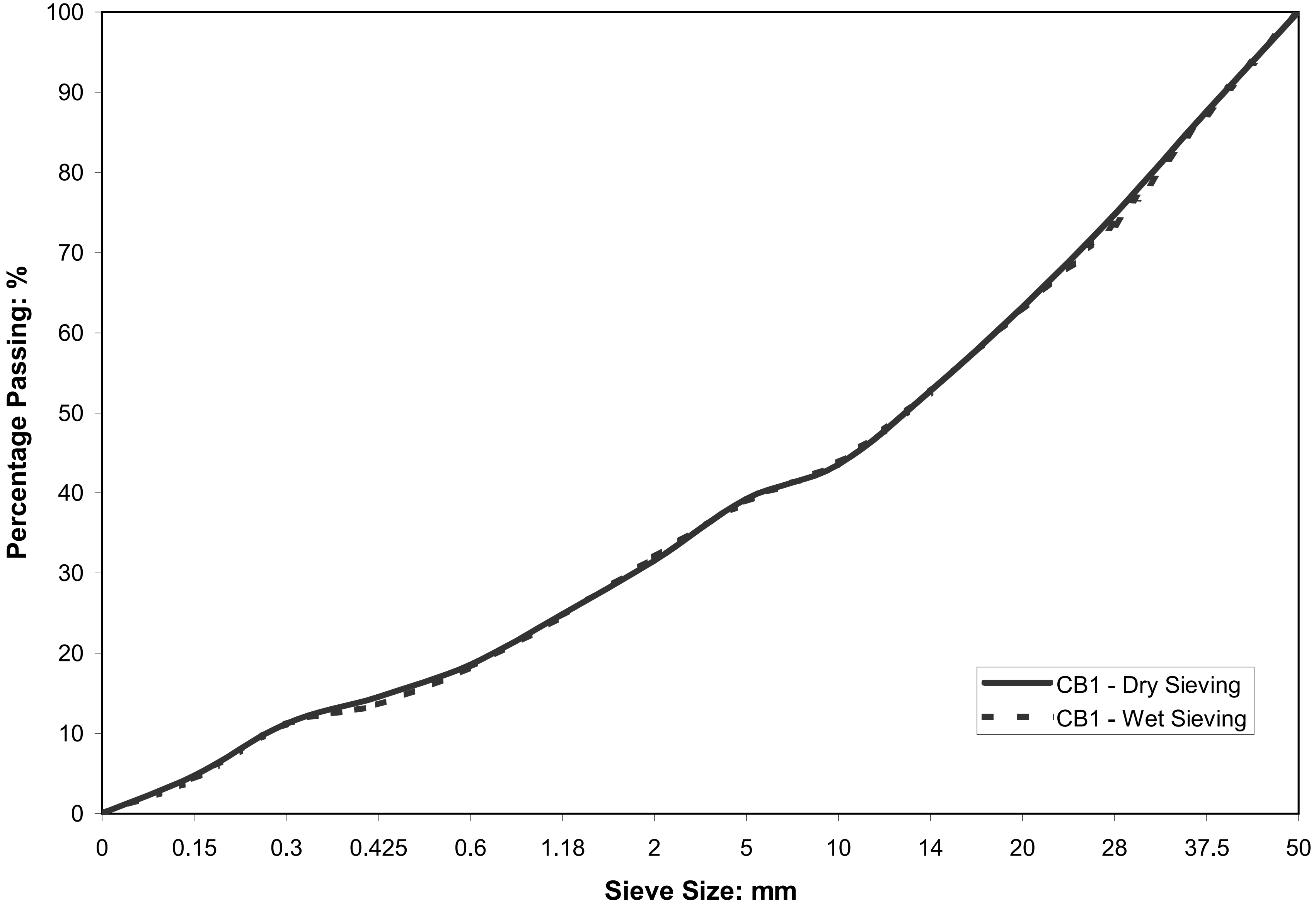
100
90
80
70
60
50
40
30
20
10
0
Percentage Passing: %
0
0.15
0.3
0.425
0.6
1.18
2
5
10
14
20
28
37.5
50
Sieve Size: mm
CC1 - Dry Sieving
CC1 - Wet Sieving

Figure 2b



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

Figure 2c



Percentage Passing: %
100
90
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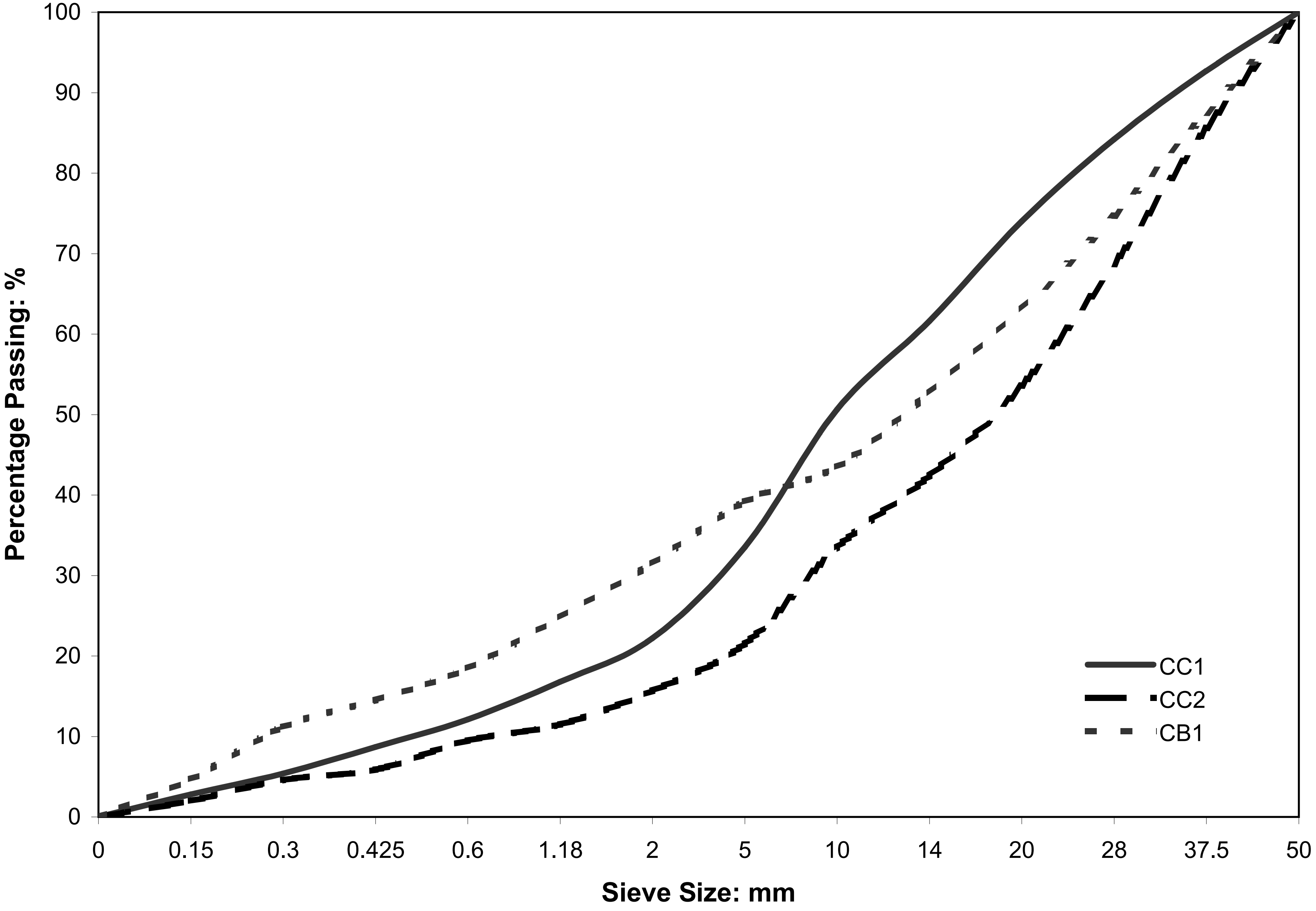
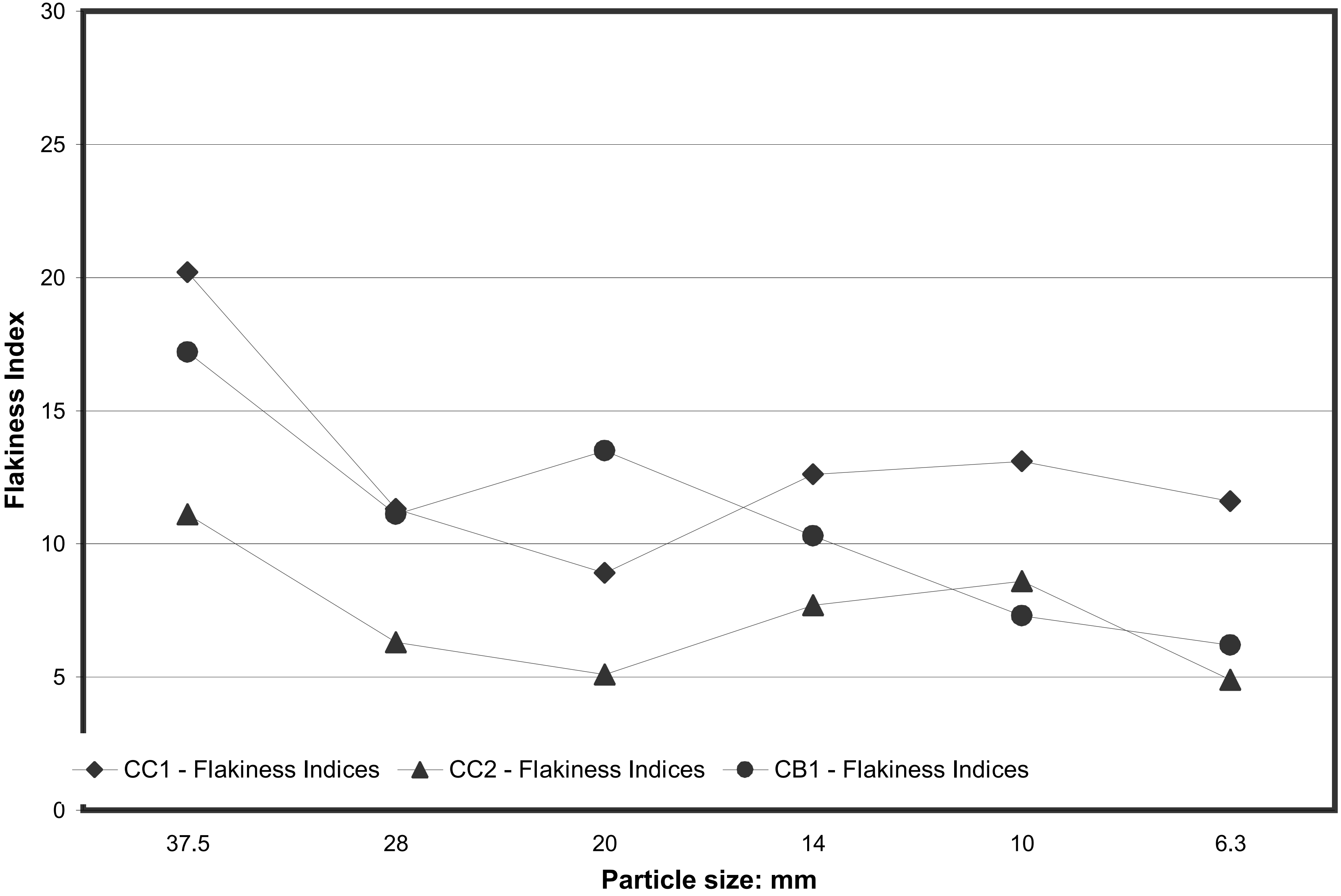
20
10
0
0
0.15
0.3
0.425
0.6
1.18
2
5
10
14
20
28
37.5
50
Sieve Size: mm
CB1 - Dry Sieving
CB1 - Wet Sieving

Figure2d



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

Figure 3a



30
25
20
15
10
5
0
Flakiness Index
◆ CC1 - Flakiness Indices
▲ CC2 - Flakiness Indices
● CB1 - Flakiness Indices
37.5
28
20
14
10
6.3
Particle size: mm

Figure 3b

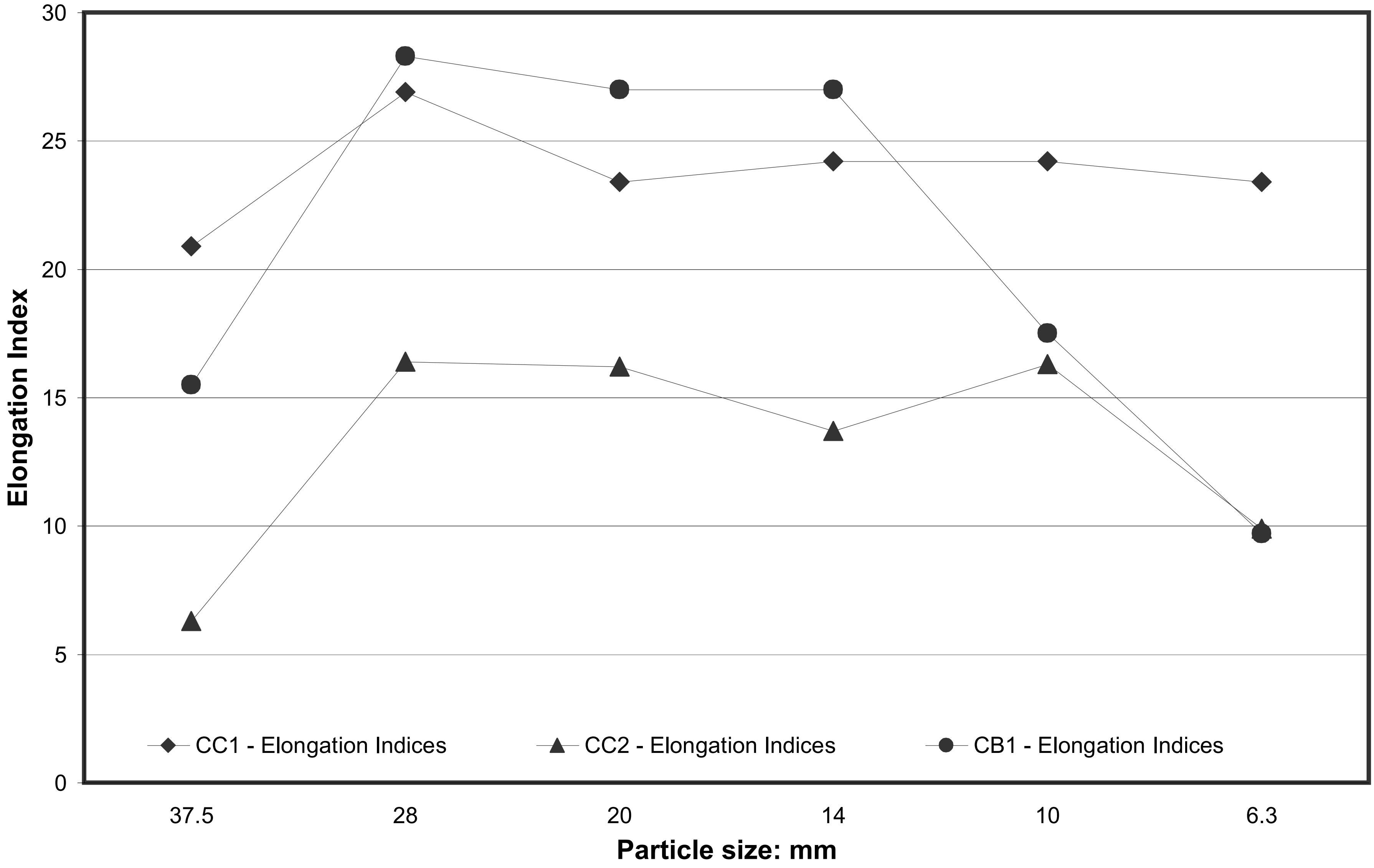

30
25
20
15
10
5
0
Elongation Index
37.5
28
20
14
10
6.3
Particle size: mm
CC1 - Elongation Indices
CC2 - Elongation Indices
CB1 - Elongation Indices

Figure 4

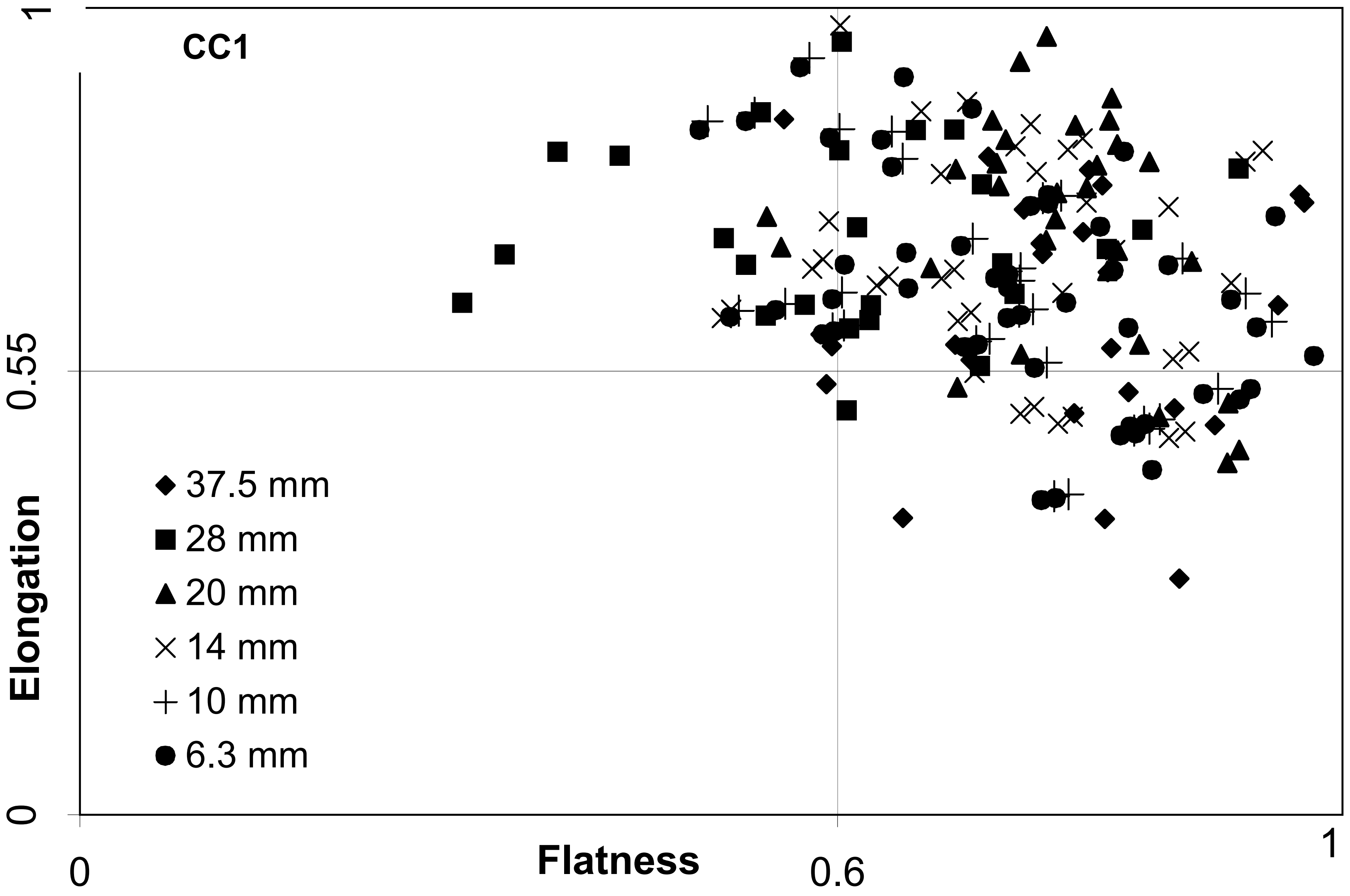

CC1
Elongation
Flatness
0
0.55
1
0
0.6
1
◆ 37.5 mm
■ 28 mm
▲ 20 mm
× 14 mm
+ 10 mm
● 6.3 mm

Figure 5

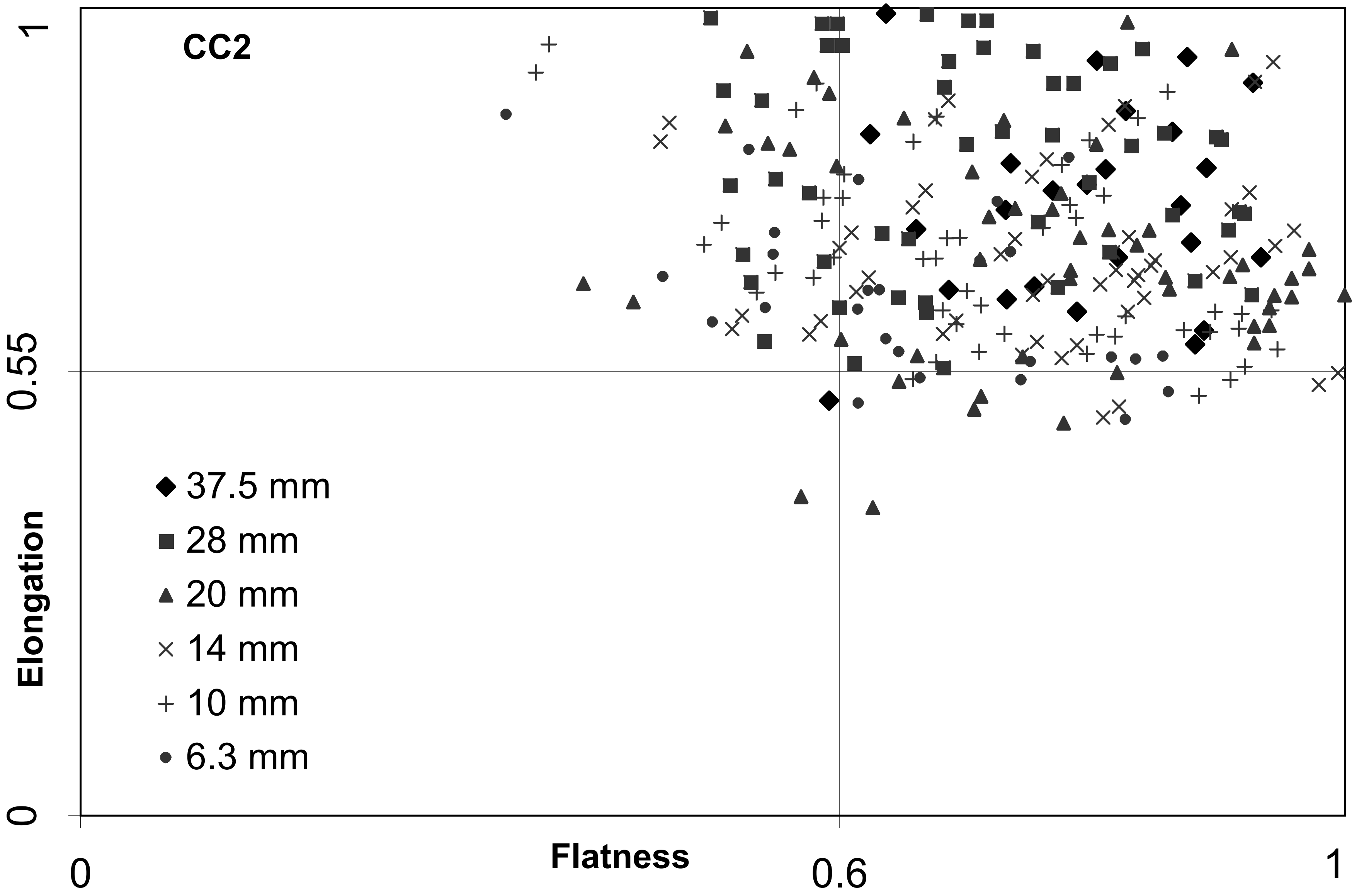

CC2
Elongation
Flatness
0
0.55
1
0
0.6
1
◆ 37.5 mm
■ 28 mm
▲ 20 mm
× 14 mm
+ 10 mm
● 6.3 mm

Figure 6

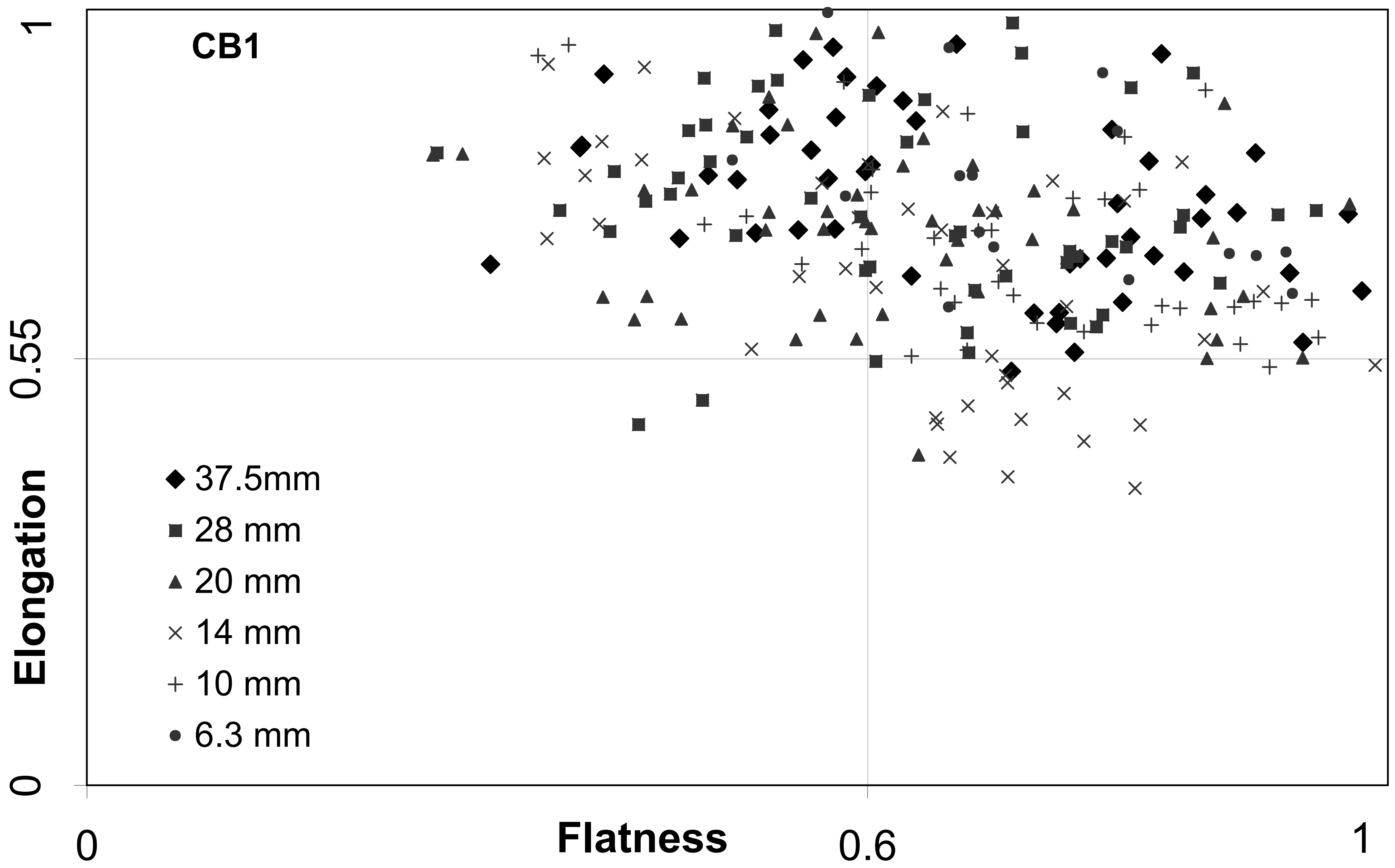

CB1
Elongation
Flatness
1
0.55
0
0
0.6
1
◆ 37.5mm
■ 28 mm
▲ 20 mm
× 14 mm
+ 10 mm
● 6.3 mm

Figure 7a

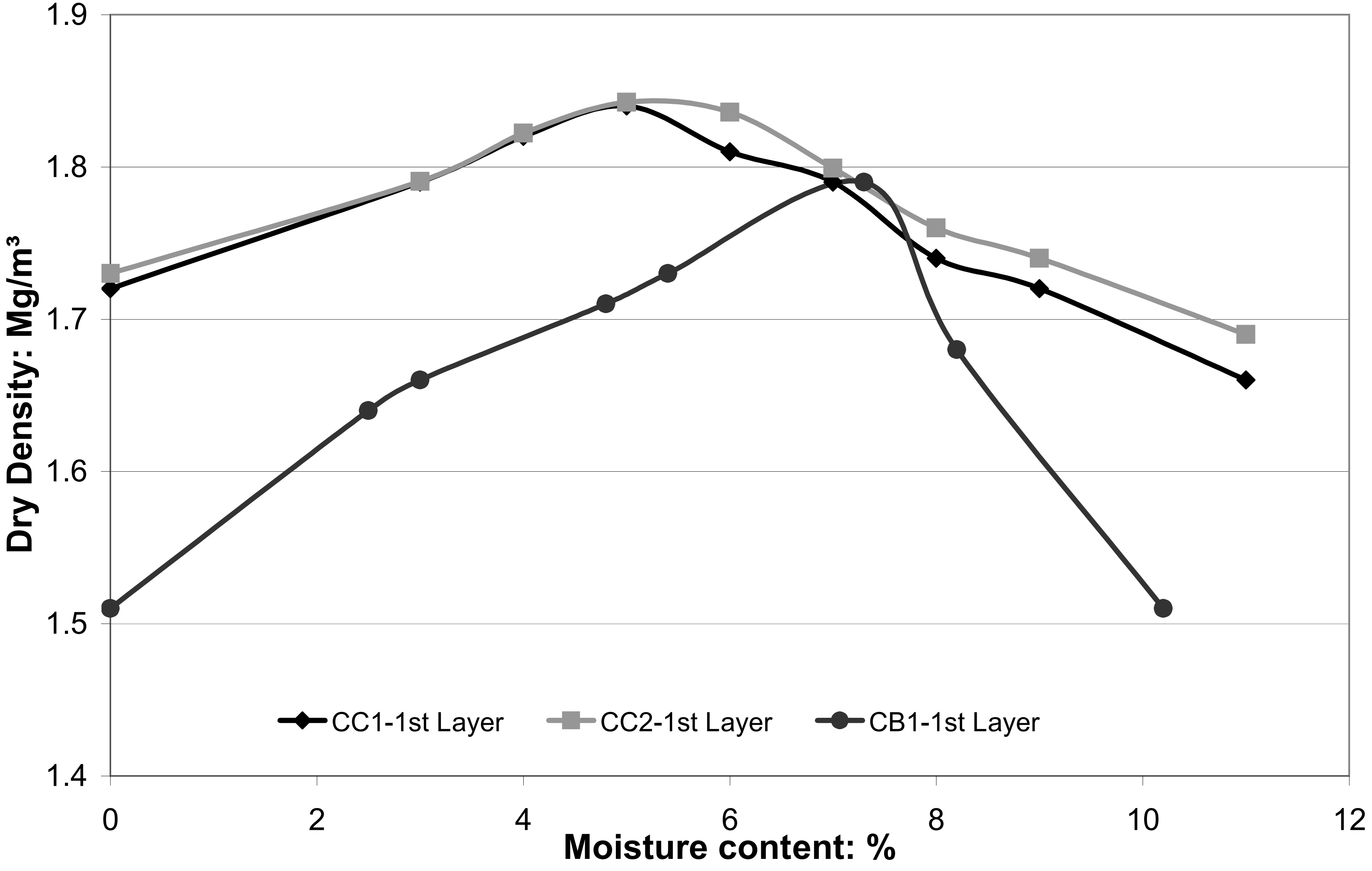
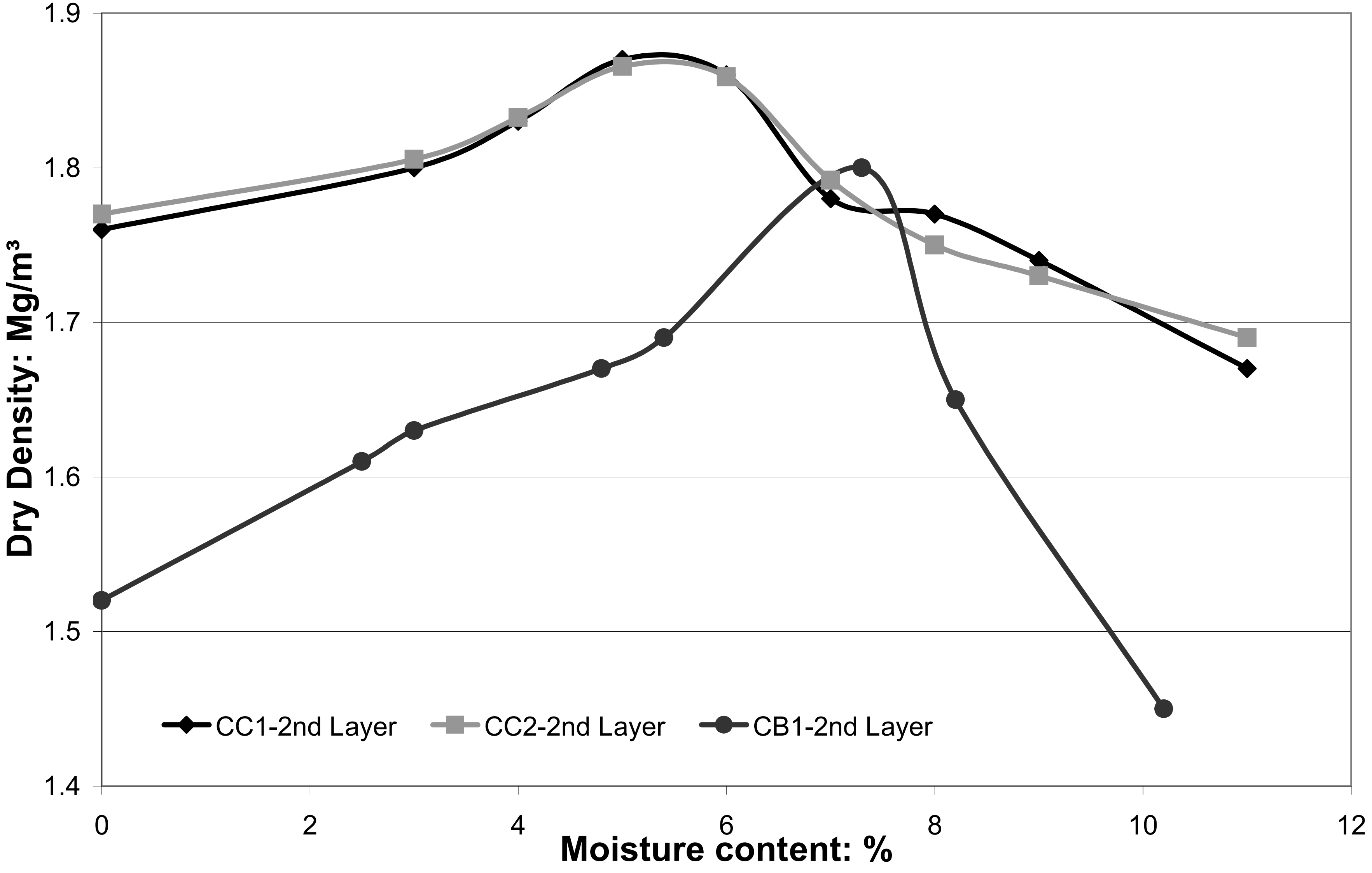

1.9
1.8
1.7
1.6
1.5
1.4
Dry Density: Mg/m³
0
2
4
6
8
10
12
Moisture content: %
CC1-1st Layer
CC2-1st Layer
CB1-1st Layer

Figure 7b



Dry Density: Mg/m³
1.9
1.8
1.7
1.6
1.5
1.4
0
2
4
6
8
10
12
Moisture content: %
CC1-2nd Layer
CC2-2nd Layer
CB1-2nd Layer

*** Response to Reviewer and Editor Comments**

The following Text contains the Authors' response to the comments made by the Editorial Panel and how they were addressed (Responses in red)

Regards

The Editorial Panel only had one comment (below):

Is there a need for a clarity in Figure 2(d)- for effective/ meaningful black/white production?
- All graphs have been made in black colour for more clarity