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ABSTRACT

For every tonne of china clay produced in the UK, nine tonnes of waste material is generated. A limited quantity of the coarser waste has beneficial use as a building stone or secondary aggregate in concrete and asphalt, but there are currently limited uses for the finest waste fraction. “Mica” waste is a mix of fine minerals and is one of the forms of the waste with little beneficial use other than the restoration of old quarries. With an aim of new commercially viable and low environmental impact uses in construction, this paper is focused on studying the use of china clay waste as an aggregate in alkali-activated(AA) cement mortar. Based on a preliminary analysis on the compressive strength of binders using slag and fly ash, the optimum binders were selected to produce mortars using mica and other forms of china clay waste as aggregate and compared in compression with control specimens using standard sand, with a goal to replacing standard sands with wastes in low impact construction materials. Although the results show that the test mortars are generally weaker than the control samples, there are opportunities for its use.

LIST OF NOTATIONS

AA: Alkali-activated
AAS: Alkali-activated slag
M: Mica waste
CCS: Sand derived from China clay works used as secondary aggregate
SS: Standard sand
GSS: Ground standard sand
GGBS: Ground Granulated Blastfurnace Slag
FA: Fly Ash
PC: Portland cement
XRD: X-ray diffraction
SEM: Scanning electron microscopy

KEYWORDS

Concrete technology & manufacture; Recycling & reuse of materials; Strength and testing of materials

1. INTRODUCTION

For every tonne of china clay (almost pure kaolin) produced in the UK, approximately nine tonnes of waste is generated.(Thurlow, 2005) The production of china clay and its associated waste have permanently altered the landscape in parts of Cornwall. Based on the UK production of approximately 1 million tonnes per year (Brown et al., 2012), this equates a waste quantity of approximately 9 million tonnes per year which is well below the UK primary aggregate use of approximately 145 million tonnes. (BGS, 2013)

There are three main forms of china clay waste: Stent which is coarse, unaltered granite with a diameter of up to 2m, sand which derives from the same rock and is fragmented due to weathering and crushing, and mica, the finest waste fraction with particle size just above 0.5mm. Surprisingly with its name, the latest does not comprise pure mica but it contains less than 10% mica flakes along with other minerals (predominantly quartz). The current waste streams are comprised approximately of 50% stent, 39% sand and 11% mica.

Less than 20% of the live feed waste production of stent and sand is sold to commercial enterprises, who make 'secondary aggregates' out of it for applications as ready-mixed concrete, in asphalt bases and surface courses, in precast concrete products and as plain aggregates for fills, capping, in hydraulically bound and unbound mixtures. (Thurlow, 2005) That percentage could be increased if the cost and environmental impact of transport to more distant markets could be reduced. About 70% of aggregates used in Cornwall for road construction are derived from china clay pits. Previous investigation on the alkali-silica reactivity of china clay stent from Littlejohn quarry in Cornwall showed "Low reactivity by BRE Digest 330 classification". (Marsh, 2006)

The "mica" waste stream currently has little beneficial use and is generally used for backfilling mines. Because of the large quantities of this material which are produced, it was determined that a bulk use in building products should be investigated. This material has the advantage that high energy crushing is not required before use as an aggregate should it be suitable for this use, but the fine grading means that it does not meet current specifications for sands in cementitious mixes.

As part of the Cornwall Eco-Town development near St Austell, a desire to develop construction materials based on the china clay waste was expressed. It was intended that these should be used in the construction of low-impact dwellings in the area, and a potential bulk use of the waste as an aggregate in cement bound construction materials (blocks and roofing tiles) was identified. Rather than only investigating the use of the waste with Portland cement (PC) binders, the use of the china clay waste with potentially lower impact alkali-activated binders was investigated. Alkali-activated binders or geopolymers were identified by the Intergovernmental Panel on Climate change (IPCC) as one of two feasible alternative binders which could produce a significant reduction in the global CO_2 emissions from cement manufacture. (Metz, 2007)

Before embarking on a detailed investigation of the use of china clay waste in bound construction materials, the waste was characterised along with potential additives, notably Ground Granulated Blastfurnace Slag (GGBS), fly ash and PC.

2 CHINA CLAY WASTE

2.1. Available forms

The waste used in this study was obtained from IMERYS Minerals ltd. in Cornwall. Two forms of the waste are used in this paper: mica waste (M) and china clay sand (CCS) which is commercially available as a secondary aggregate. The mineralogy of the waste differs slightly between the different

forms and also may vary from batch to batch. It generally comprises five minerals: quartz, feldspar, schorl, mica mineral and leftover (non-recovered) kaolinite as shown in Table 1. An XRF analysis indicating the oxide composition is shown in Table 2 and the particle size distribution of the mica waste is illustrated in Figure 1, along with the particle size distribution for a standard mortar sand in EN 196-1. Although the particle size distribution of the china clay sand can be altered in the plants in which it is processed, Figure 1 presents the particle size distribution for the CCS used in this study.

Mica is a family of minerals. More specifically the mica mineral present in this waste stream consists mainly of muscovite with some biotite and zinnwaldite. According to BS EN 1097-6:2013, clause 9, the apparent particle density of this fine waste is 2.71Mg/m^3 and the water absorption is 1.5%, while standard siliceous sand conforming to BS EN 196-1 is estimated to have apparent particle density and water absorption of 2.62Mg/m^3 and 0.5% respectively.

2.2 Technical specifications for use as aggregate

China clay sand does not require extensive modification to conform to BS EN 12620 Grade 0/4 (MP) (formerly BS 882 Grade M sand) due to its manufacturing process and is suitable for use in concrete as it has low silt content.(WRAP, 2004) In addition, concrete formed using stent or china clay sand conforms to BS 8500 and BS EN 206-1.(Marsh, 2007) Because it is a plentiful secondary aggregate, china clay sand is low cost. It is immune to alkali-silica reaction (ASR) and the thaumasite form of sulphate attack (TSA). It does, however, need a higher water content in concrete mixes because of the mica mineral present, which can split into very thin flakes because of the perfect cleavage parallel to the basal plane of the mica crystal. This increases the surface area of the fine aggregate and results in an increase in the water demand of the concrete. Hence, for a given concrete strength and compared to other standard sands, the china clay sand concrete mix needs higher cement content. To overcome this issue china clay sand may be blended with high quality sand from natural land-based sand deposits or washed marine sand. This cost can be offset by the low cost of the material which is exempt from the Aggregates Levy.(WRAP, 2004)

In Lea's chemistry of cement and concrete (Sims and Brown, 2003) muscovite and biotite micas are described to have "disadvantageous effects" when used in fine aggregate. "*When mica occurs as discrete (or 'free') flaky grains in fine aggregates, it usually increases the water demand of concrete and also reduces the cohesiveness of the mix, which can adversely affect the final strength and durability of the hardened concrete"* (Sims and Brown, 2003). Dewar (1963) studied granite-derived sands from southwest England and reported that for a typical concrete mix the compressive strength might be decreased up to 5% for presence of 1% by weight muscovite mica in the total aggregate. A study by Fookes and Revie (1982) demonstrated the impact of mica on strength, workability and w/c ratio in Portland cement concrete; for mixes of constant workability, the compressive strength reduces by approximately 45% on the 28th day if 6% of total aggregate –an equivalent of 18% in fine aggregate- is replaced by mica minerals.

This previous work did not distinguish between the effect of changing particle size distribution and the effect of adding mica mineral, and this was also only focussed on using mica mineral in PC based concretes. It did, however, indicate that the "mica" waste stream has potential to be used as a fine aggregate in mortars, but that this may lead to reduced strengths. This current work has attempted to quantify the effect of particle size distribution as well as mica content on the performance of both PC and alkali-activated binder mortars. The behaviour between PC and alkali-activated may be different for two main reasons:

- Portland cement based mortars require water for hardening reactions, while alkali-activated geopolymers require water for dissolution but can produce water during hardening (Duxson et al., 2007). As noted earlier, the addition of mica affects the water demand of the mix which could therefore affect the hardening of the different binders in different ways.

- Micas are aluminosilicate mineral which could affect the Al:Si ratio in the alkali-activated materials and thereby affect their strength. (Davidovits, 2011) Although the micas were not converted to a dehydroxylated state through calcination, there is still some dissolution of micas under alkali conditions and this is affected by temperature, dissolved Al and pH. (Oelkers et al., 2008)

3. EXPERIMENTAL WORK

A series of tests were undertaken to determine how the waste performs as an aggregate in PC and alkali-activated binders.

3.1 Materials

Two series of alkali-activated mortars were produced: one based on FA and one on GGBS and these were compared to a control based on PC. The samples were tested in compression after 7, 28, 90 and 180 days curing.

GGBS

Ground Granulated Blastfurnace Slag (GGBS) was provided by the Hanson Heidelberg cement group from the Port Talbot works. Its chemical analysis is shown in Table 3. In the XRD pattern (Figure 2), the halo and the absence of distinct peaks which would correspond to impurities indicate it is highly amorphous, unlike the Fly Ash which showed distinct peaks (Figure 3) and is discussed in the following section.

FA

Cemex 450-S was the type of Fly Ash (FA) used in the tests and its chemical composition is shown in Table 3. An XRD (Figure 3) showed distinct peaks for quartz, mullite and hematite in addition to the amorphous materials.

Sodium Silicate and Sodium Hydroxide

The sodium silicate ($Na_2O{\cdot}nSiO_2$) used for the research was supplied by Tennants Distribution Ltd. It was in solid (spray-dried powder) form and comprised Na_2O, SiO_2 and H_2O at 27.05, 53.5 and 19.45 wt.% respectively. Dry Sodium Hydroxide (NaOH) pellets were used and both this and the $Na_2O{\cdot}nSiO_2$ were mixed with distilled water and cooled before use.

PC

Portland cement mortars were produced for comparison. In order to achieve high strength, comparable to the strength of the alkali-activated cement mortars, CEM I 52.5N by Cemex was used. This is a free of mineral additives Portland cement, chosen in order to minimise the effect of mineral additives.

Sand

Clause 5.1 EN standard 196-1 specifies that a standard sand for production of mortars contains at least 98% silica and has a particle size distribution with maximum 2% passing the 0.08mm sieve, as shown in Figure 1. This standard sand (SS) was used in the testing.

The effect of particle size distribution was assessed through comparing mixes using aggregates of equivalent particle size: SS with at least 98% silica was ground and sieved (GSS) to have approximately the same particle size distribution of M and the coarser waste, sand from the china clay extraction (CCS), was prepared to the same particle size distribution as the SS (Figure 1). By reducing the role of particle size through materials with the same particle size distribution, the effect of sand mineralogy can be assessed.

3.2 Scanning electron microscopy (SEM)

A JEOL SEM6480LV was used for imaging the alkali-activated mortars after 6months of curing. All samples are fragments stored in a desiccator before imaging and were tested in low vacuum. For that reason the samples were not coated.

3.3 Procedures for the preparation of samples

As there are no EN standard procedures for the preparation of geopolymers, the following were used.

3.3.1 Composition of the binder

For the production of the alkali-activated binders, the NaOH and $Na_2O{\cdot}nSiO_2$ solutions were prepared separately and left to cool before use. For the slag-based series, the synthesis of the solution can be expressed as $1Na_2O{:}1.25SiO_2{:}35.90H_2O$. After the addition of slag and assuming the dissolution is complete, the whole geopolymeric system had the composition: $1Na_2O{:}7.3SiO_2{:}1.6Al_2O_3{:}35.90H_2O$.
For the FA geopolymer series, the synthesis of the solution can be expressed as $1Na_2O{:}1.0SiO_2{:}12.2H_2O$. After the addition of FA and again with the assumption of full dissolution, the whole geopolymeric system had the composition: $1Na_2O{:}6.6SiO_2{:}1.6Al_2O_3{:}12.2H_2O$. In these ratios it was assumed that FA and GGBS are entirely amorphous (although the XRD graph of FA shows some crystalline material). The silica in the “mica” waste was considered non-reactive and excluded from the ratios presented above. These mix ratios were determined through an initial study where the binder strength and workability was assessed with different ratios of $Na_2O{:}SiO_2{:}Al_2O_3{:}H_2O$ and the binders selected for this study were those which produced the required strength of about 30 MPa or more while having the lowest environmental impact and therefore fulfilling the overall project aims. Because of space restrictions, the full results of this initial study are beyond the scope of this paper.

The initial setting time of the slag based binder is 40 minutes and the final setting time is 50 minutes. For the FA based series the initial setting time is 1 hour and 45 minutes and the final setting time is approximately 2 hours. While some studies on the potential for this material to participate in geopolymeric or pozzolanic reactions in an unprocessed and calcined form have been undertaken, the hydration kinetics of these reactions are beyond the scope of this paper.

3.3.2 Composition of the alkali-activated binder mortars

The composition of the mortar by mass is shown in Table 4 where “binder” (B) equals to GGBS or FA plus Na_2O plus SiO_2 (from NaOH and $Na_2O{\cdot}nSiO_2$) and where “water” equals to H_2O in NaOH and $Na_2O{\cdot}nSiO_2$ plus the total amount of water added in the mortar.

The control mortar using standard sand follows the BS EN 196-1:2005 and uses “binder to aggregate” ratio equal to 1:3 specified in the standard. However, all the other mixes incorporate a ‘volume factor’. This is because the finer sands have lower bulk density and fill the regular prismatic mould with less material than what is indicated in mass (g) in the standard. Table 4 shows the mix ratios including the ‘volume factors’ which results in the same mass of binder for each mould, regardless of sample density. Interestingly, although GSS and M have the same particle distribution, their different particle shape leads to different density and, consequently, different mixing ratios.

The SS control mortar specimens make minimum use of water, especially in the case of FA series. All the other sands have greater apparent water absorption and therefore extra water had to be added to the other mixes to achieve similar workability. Even the CCS that had the same particle size distribution as the SS needed extra water which shows the impact of particle shape and mineralogy in surface area and water absorption.

In the GGBS based series, the SS control specimen have a “water to binder” ratio of 0.47 and the flow table test according to BS EN 1015-3 provided a flow of 134mm which is between the limits of 120mm and 175mm in BS EN 1015-2. For a “water to binder” ratio of 0.60, the mixes containing CCS and

GSS had approximately the same flow (±10mm). The mix using M had similar flow values of about 114mm.

The FA series visually appeared very dry in spite of having relatively high water content. All these mixes were too dry to accurately test using the flow table and this demonstrates the problem of transferring standard tests and mix designs developed for PC binders to alternate binders.

The full mix designs are presented in Table 5.

3.3.3 Mixing and curing

The separately prepared solutions were mixed for 30 seconds in the mixer and then the precursor was added. Mixing was first at slow speed and after 2 minutes at high speed, the binder was mixed for 5 minutes in total. Later, sand and any extra water was added before an additional 10 minutes of mixing. Cylindrical moulds of 36mm height and 18mm diameter were used. All test results are presented as the averages of three replicates. The GGBS based series was cured at room temperature and RH>90%. The FA based series was oven cured at 80°C until testing as the FA series did not harden under ambient conditions as noted by Shi et al. (2012) for FA based geopolymers.

3.4 Comparing performance with Portland cement mortars

One series of Portland cement mortar was produced for comparison using the same sands. The binder:water:sand ratio was exactly the same as for the slag based series in Table 4 which is close to the standard mortar mix in EN 196-1 which has a binder : water : sand ratio of 1 : 0.5 : 3. As with the alkali-activated binder samples, a higher water content was required to ensure similar workability for the samples with finer aggregate and with the CCS of different mineralogy, and the proportion of sand was reduced for the finer sand to account for different volume factor and to ensure the amount of binder in each sample was consistent. Mixing and curing were followed as specified in BS EN 196-1 but the moulds used were not the prismatic moulds specified but the cylindrical 36mm height and 18mm diameter moulds used for the other mixes. Portland samples were tested in compression after 7 and 28 days curing. The initial setting time for the Portland cement paste is 4 hours and 5 minutes and the final setting time is 4hours and 45 minutes (without immersion of the sample in water as the reference method in BS EN 196-3:2005 indicates).

4. RESULTS AND DISCUSSION

4.1 GGBS mortars

The results of the compression test of the GGBS series is presented in Figure 4. As expected all samples gain strength over time.

At 7 days all samples which had a higher water content to achieve a similar workability as the SS samples had low strength compared to the SS samples. The impact of high water content decays over time as geopolymerisation continues. As a consequence, the difference in strength between the CCS mortar and the SS control mortar decreased from the initial 29.6% on day 7 to 5.2% difference by 6 months. Generally, the medium-coarse aggregates produce mortars of higher strength than the fine-medium aggregates.

Figure 5 shows images of the SS, M and CCS samples. The binder matrices in all geopolymer samples have common characteristics: highly amorphous, with a number of undissolved particles of slag and microfissures. Although it is possible that some of the microfissures formed due to drying shrinkage during the hardening of the mortar, it is most probable that they appeared during storage in the dessicator during sample preparation for SEM, as indicated previously by Palacios and Puertas

(2011).The SS sample (Figure 5,a) has thicker and more distinct microfissures than the samples with higher water content, M and CCS (Figure 5,b and c). The more rough particle surface for the CCS compared with the SS (Figure 5, c and a) provides an explanation why a higher water content was required with the CCS to achieve a similar workability to the SS. Figure 5,d belongs to the CCS mix and shows in high magnification the vitreous nature of the matrix while the different intensity of grey indicates the progressive dissolution of slag particles. Mica mineral particles could be detected during the SEM analysis.

4.2 PC mortars

Figure 6 shows the mixes with Portland cement mortar. For the specific Portland based cement used, the values of strength are of the order of 20-30 MPa. The ratio of strength between the mixes does not vary significantly on day 7 and 28. CCS performs as well as the control mortars and M has less than 8% difference to the strongest mixes, GSS and SS, on day 28.

4.3 FA mortars

The results of FA mortars were disappointing: the mortars as average did not gain strength over time and all apart from the SS control mortar showed extremely low performance (Figure 7). Due to the poor performance testing stopped after 28 days. To understand why the samples using CCS,M and GSS (with a higher water / binder ratio as shown in Table 4) achieved such low strengths, the SS control mortar was repeated with an increased water content, so that the binder : water : sand ratio was 1 : 0.55 : 3 (not included in Table 4 and Figure 7). This produced a mix which was too fluid and this resulted in segregation of the sand and binder, a trend not noted with the finer sands. The specimens were tested after 7 days and the strength was 9.66 MPa which indicates it is most likely the extra water required to obtain the desired workability which reduced the strength of the mortar. Therefore, without use of a water reducing admixture, use of a significantly higher B:A ratio or increased activator content the strength of the alkali-activated FA mortar using the china clay waste cannot be improved. Increasing the activator content or B:A ratio will result in an in cost and environmental impact, which would defeat the aim of the research and as a result, the research in to the FA mortars was not taken further.

Figure 8 shows images of the M and SS samples. The topography of M is not glassy, is inhomogeneous and the aggregate can easily be detected behind the loosely structured fly ash particles which shows limited dissolution when used with the M sand. The binder with the SS sand is largely amorphous and dense indicating dissolution and formation of a geopolymeric structure. The completely different nature of the binders is shown even more intensively in high magnification (Figure 8, c and d). The lack of dissolution may be because the increased water required for the M samples resulted in a lower concentration activator which limited dissolution, indicating the difficulty of extrapolating binder results to mortars for alkali-activated geopolymers.

4.4 Discussion

Through the materials used (Table 1), it is not possible to effectively distinguish the effect of micas and kaolin on the strength of the mixes. Previous work by Fernandes et al. (2007) has shown replacing silica sand by up to 20% kaolin has limited effect on the compressive strength of PC based mixes. As this 20% kaolin content is much higher than that of the materials used for this paper and as micas have been shown to affect PC based concrete mixes at much lower contents, Fookes and Revie (1982) this discussion has focussed on the effect of mica rather than kaolin on the compressive strength of the material.

As the FA based alkali-activated binders performed so poorly and because this was demonstrated to be related to the water:binder ratio, rather than the aggregate type, these mortars are excluded from this discussion. The discussion is therefore focussed on the PC and alkali-activated slag (AAS) binders. For the mixes of different water content but of adjusted aggregate content (incorporating the

'volume factors'), Portland cement binders resulted in mortars of similar strength while the alkali-activated based mortars showed greater diversity, justifying the initial assumptions that behaviour would be different.

Data on the effect of mica content on the compressive strength of PC based cements was obtained from Fookes and Revie (1982) and the data on the effect of water:binder ratio on the compressive strength of both PC and AAS concretes was obtained from Yang et al. (2012). The work by Fookes and Revie represents mixes with different mica contents which have similar workability and different water:binder ratios as used for this study, but a limitation of the previous study by Fookes and Revie is that the binder content per unit volume was different as the different volume factors were not accounted for. The work by Yang was based on concrete mixes with the same volume of water per unit volume concrete, so as the water: binder ratio increased, the binder content per unit volume of concrete also decreased. This work was also focussed on calcium hydroxide / sodium silicate based AASs rather than the sodium hydroxide / sodium silicate based ASSs used here.

Figure 9 and 10 show the data for this study along with that from Fookes and Revie and Yang et al. The data is shown as a percentage reduction in compressive strength from a reference case with no mica for each mix design. The data shown for Yang et al. does not include mica content but rather represents the reduction in compressive strength as the water:binder ratio (Table 4) increases from the baseline case with no mica (GSS and SS for the medium-fine and medium-coarse gradings), to the case with 9% mica (CCS and M respectively).

As shown in Figure 9 for the medium-fine sand, the strength reduction with increased mica content or water:binder ratio for both the AAS and PC mortars is considerably lower than that indicated by the work of Fookes and Revie or Yang et al. This is most likely because the authors of both these previous studies varied the binder content per unit volume by not accounting for volume factors or by fixing the volume of water (rather than the volume of binder) in the mixes. As the mica flakes have a higher bulking factor than the more cubic quartz used for the ground standard sand (Table 4), not accounting for bulking would result in a decreased binder content per unit volume as the mica content was increased which would lead to a reduction in strength. This demonstrates the importance of considering bulking when investigating different aggregates and of maintaining the same binder content per unit volume when considering the water:binder ratio. This is a particularly important consideration when attempting to manufacture low-impact PC or AAS concretes where the binder provides the greatest contribution to impact.(Habert et al., 2011)

As shown in Figure 10 for the medium-coarse sand, the strength reduction with increased mica content or water:binder ratio for both the AAS and PC mortars is again much lower than that predicted by Fookes and Revie (1982) and is generally close or lower than the strength reduction which can be attributed to the increase in water:binder ratio.(Yang et al., 2012)

5. CONCLUSIONS

The high water demand of the china clay waste has a negative impact on strength for Portland cement and geopolymer binders, but this effect varies depending on the specific mix design.

The china clay waste performed poorly with FA based geopolymer binders and this was largely attributed to the high water content required for mixing. It is unlikely that these mixes could be used unless an effective plasticizer is incorporated in the mixture or/and the mix is redesigned for higher alkalinity or higher ratio of B:A, but this will increase environmental impacts and costs.

The use of fine china clay waste in slag based alkali-activated cement is possible and there is potential for optimisation. The samples incorporating china clay waste initially develop strength slowly

but in the long term they tend to approach the strength of the control mortars with quartzitic sand. In particular, based on the results of compression testing after 6 months, samples with china clay sand of standardised particle distribution have the same strength as samples with standard sand. The reduction in strength with increased water content to obtain the required workability with these waste materials is not as high as expected from previous research. Although the use of the waste does result in slight strength decreases compared with the control sand, an overall environmental and cost benefit may result through use of this waste material.

Using the china clay waste with Portland cement appears to have very little strength reduction compared to standard sand. This is contrary to previous research which indicated larger strength reductions with increasing binder contents. This previous research was based on mixes which did not account for the increase in volume for the waste material, which provided a net decrease in binder content per unit volume. This aspect of different bulking or volume factors must be accounted for if an accurate assessment of different wastes is to be undertaken.

Although “mica” waste stream is finer than materials typically used as aggregate in cementitious products, it may provide adequate strength for certain applications without the high energy crushing process required for the production of sand from coarser china clay waste streams. The overall environmental impact of this approach and durability of these materials should be assessed before use.

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PRACTICAL RELEVANCE AND POTENTIAL APPLICATIONS

This publication is the first step to the establishment of the china clay waste as an alternative type of aggregate used in alkali-activated (AA) cement, looking at mechanical strength. While strength can provide an indication of potential suitability for use in concrete blocks and roof tiles, studies should be conducted to assess durability. Benefits arise from the reuse of the china clay waste, the reuse of by-products as FA and GGBS and the low CO_2 emission of manufacturing alkali-activated binders. In addition, making mortar using different forms of the waste implies great variety of applications in construction and would advance the local Cornish economy. Scaling up to manufacturing of AA concrete and durability tests related to the freeze-thaw behaviour and water absorption are the future goals of the research exploring potential applications.

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Tables

Table 1 Mineralogical analysis by X-Ray diffraction.

Constituents (wt%)	M	CCS
Kaolinite	8	4
Mica	9	9
Quartz	50	58
Feldspar	22	21
Schorl	11	8

Table 2 Chemical analysis of waste by X-Ray fluorescence.

Constituents (wt%)	M	CCS
SiO_2	81.23	84.30
Al_2O_3	10.95	9.20
K_2O	3.21	3.11
Fe_2O_3	1.89	1.58
MgO	0.32	0.23
Na_2O	0.29	0.32
TiO_2	0.22	0.14
CaO	0.05	0.05
LOI	1.79	1.03

Table 3 Chemical analysis of precursors by X-Ray fluorescence.

Constituents (wt%)	GGBS	FA
SiO_2	35.15	49.00
Al_2O_3	13.07	23.50
Fe_2O_3	0.28	8.70
CaO	39.60	2.40
MgO	8.47	1.40
SO_3	0.17	0.80
Na_2O	0.14	3.06
K_2O	0.51	0.87
TiO_2	0.66	
MnO	0.44	
P_2O_5		1.10
LOI	0.97	4.40

Table 4 Mixing ratio of mortars by weight.

Ratios of binder : water : sand			Series based on: GGBS / PC	Series based on: FA
aggregate type	medium-fine	M	1 : 0.65 : 2.3	1 : 0.55 : 2.3
		GSS	1 : 0.60 : 2.6	1 : 0.40 : 2.6
	medium-coarse	CCS	1 : 0.60 : 3	1 : 0.50 : 3
		SS	1 : 0.47 : 3	1 : 0.27 : 3

Table 5 Mixing composition.

			Composition (in g)		
			GGBS series	Portland	FA series
BINDERS		GGBS	100.0	-	-
		FA	-	-	100.0
		Portland	-	111.0	-
		Na_2SiO_3 powder	11.3	-	16.3
		NaOH pellets	2.5	-	5.9
		Water added in binder	49.4	52.2	27.3
MORTARS	M	Aggregate	255.4	255.4	270.7
		Extra mix water	20.0	20.0	33.0
	CCS	Aggregate	333.1	333.1	353.1
		Extra mix water	14.4	14.4	27.1
	SS	Aggregate	333.1	333.1	353.1
		Extra mix water	-	-	-
	GSS	Aggregate	288.7	288.7	306.0
		Extra mix water	14.4	14.4	15.3

Figure captions

Figure 1 Particle size distribution of the types of sand used.

Figure 2 XRD pattern of GGBS

Figure 3 XRD pattern of FA (Q: quartz, H: hematite, M: mullite)

Figure 4 Compressive strength development of slag based mortars.

Figure 5 SEM images of the GGBS series mortars (a: SS/ b: M/ c,d: CCS)

Figure 6 Compressive strength development of Portland cement mortars.

Figure 7 Compressive strength development of fly ash based mortars.

Figure 8 SEM images of the FA series mortars (a,c: SS / b,d: M)

Figure 9 Reduction of strength for increasing content of mica mineral for fine materials.

Figure 10 Reduction of strength for increasing content of mica mineral for coarse materials.

Figure 1

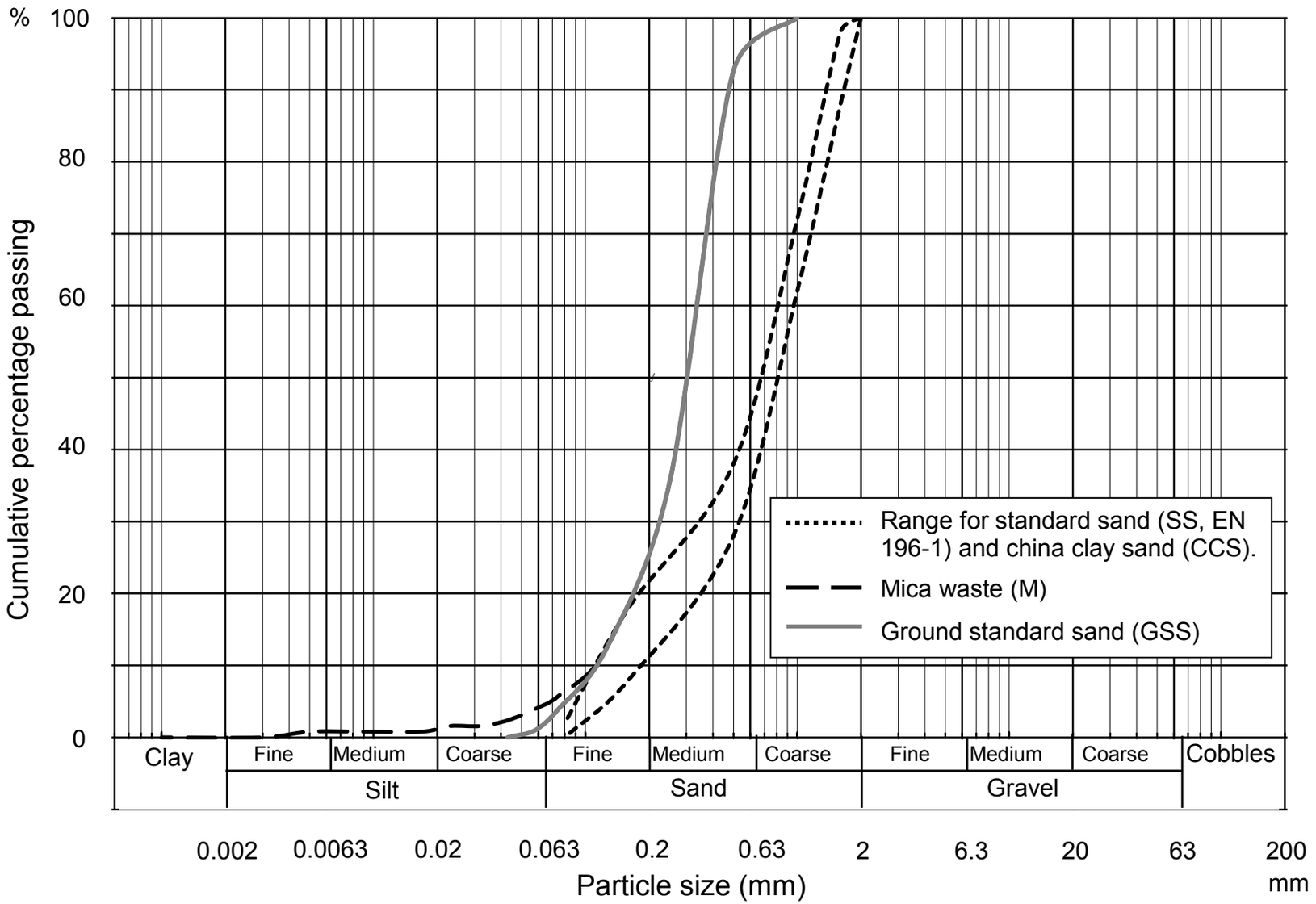
%
100
80
60
40
20
0
Cumulative percentage passing
Range for standard sand (SS, EN 196-1) and china clay sand (CCS).
Mica waste (M)
Ground standard sand (GSS)
Clay
Fine
Medium
Coarse
Fine
Medium
Coarse
Fine
Medium
Coarse
Cobbles
Silt
Sand
Gravel
0.002
0.0063
0.02
0.063
0.2
0.63
2
6.3
20
63
200
mm
Particle size (mm)

Figure 2

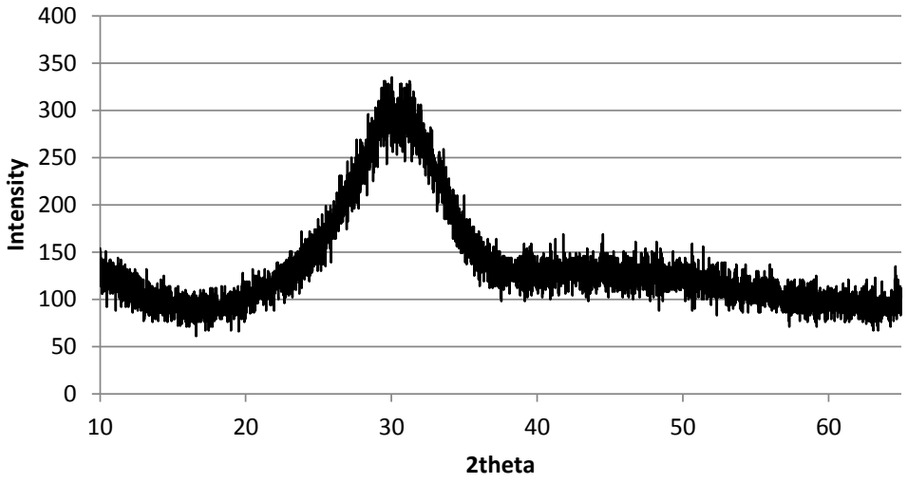
400
350
300
250
200
150
100
50
0
Intensity
10
20
30
40
50
60
2theta

Figure 3

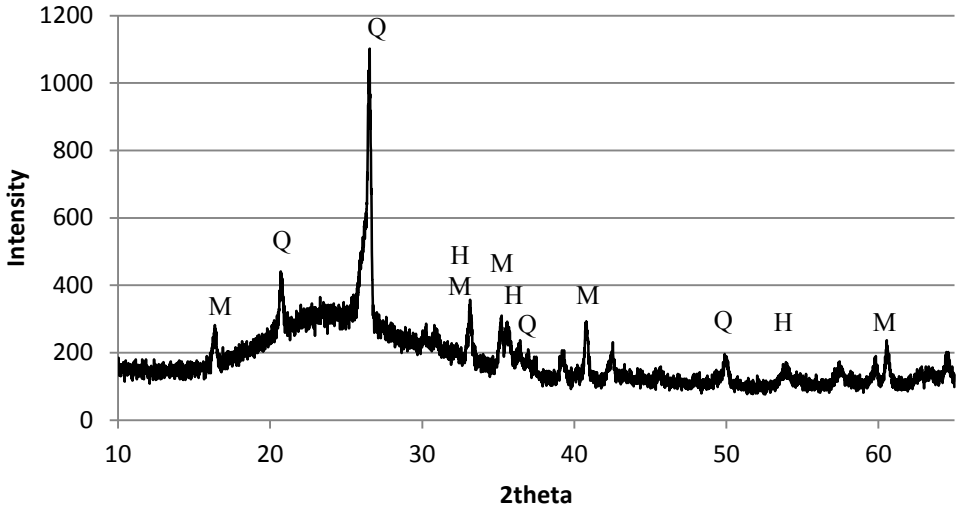
1200
1000
800
600
400
200
0
Intensity
10
20
30
40
50
60
2theta
Q
Q
H
M
M
H
Q
M
M
Q
H
M

Figure 4

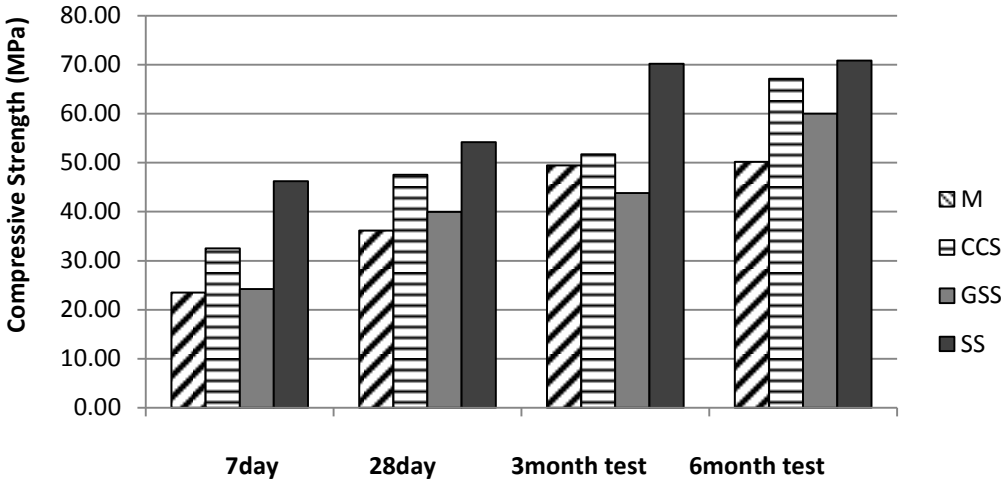
Compressive Strength (MPa)
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
7day
28day
3month test
6month test
M
CCS
GSS
SS

Figure 5a
Click here to download high resolution image

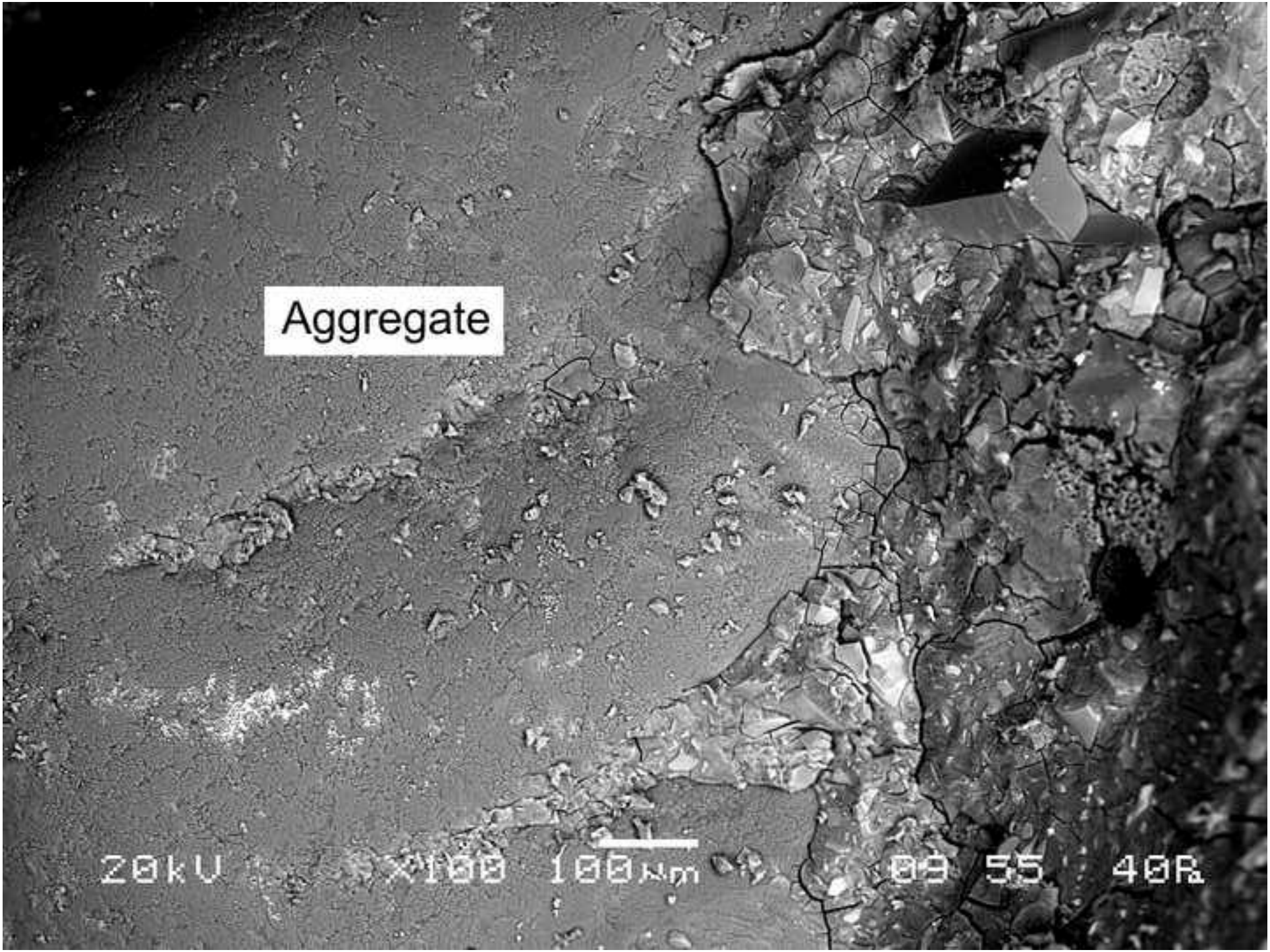

Figure 5b
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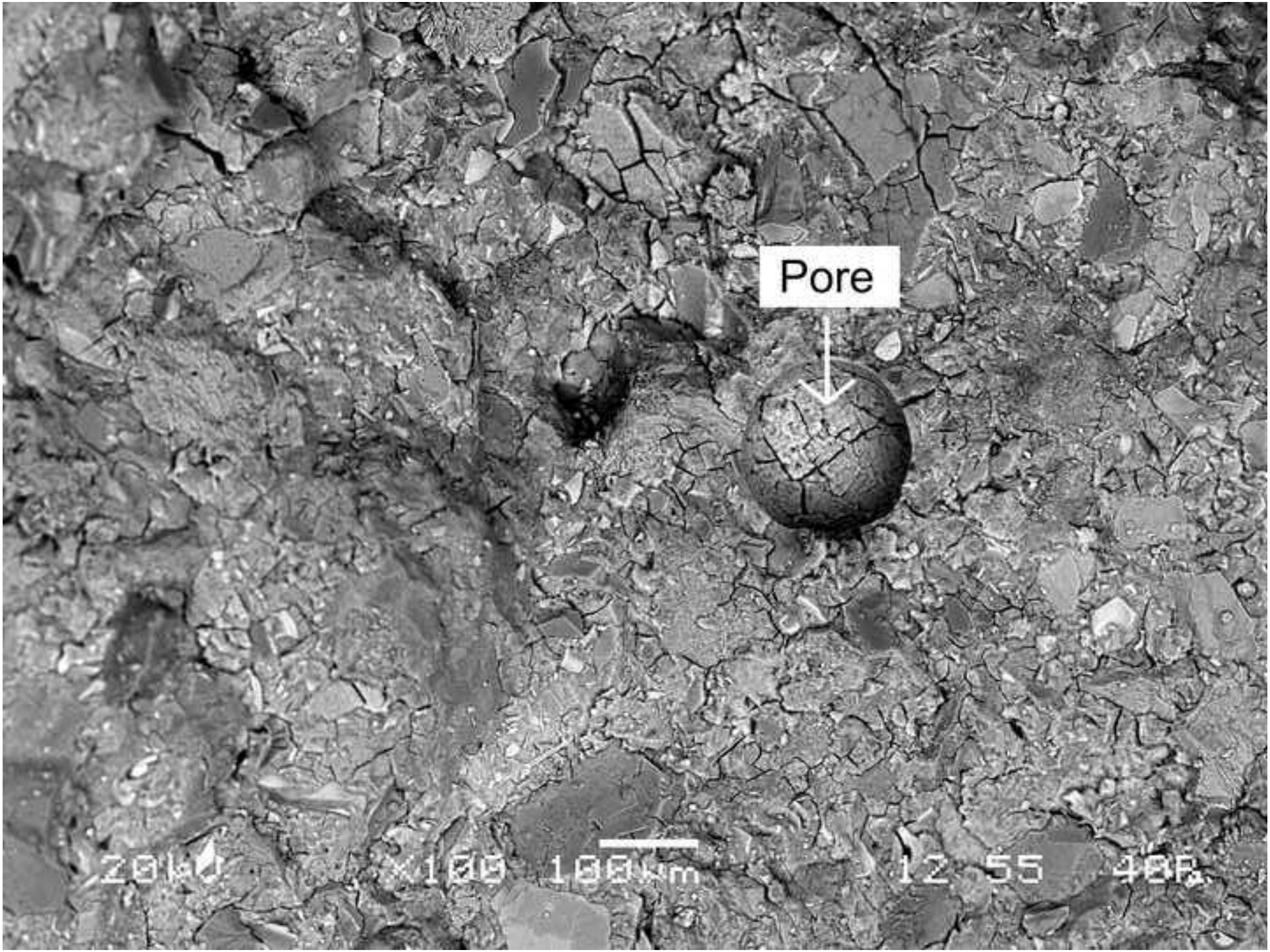

Figure 5c
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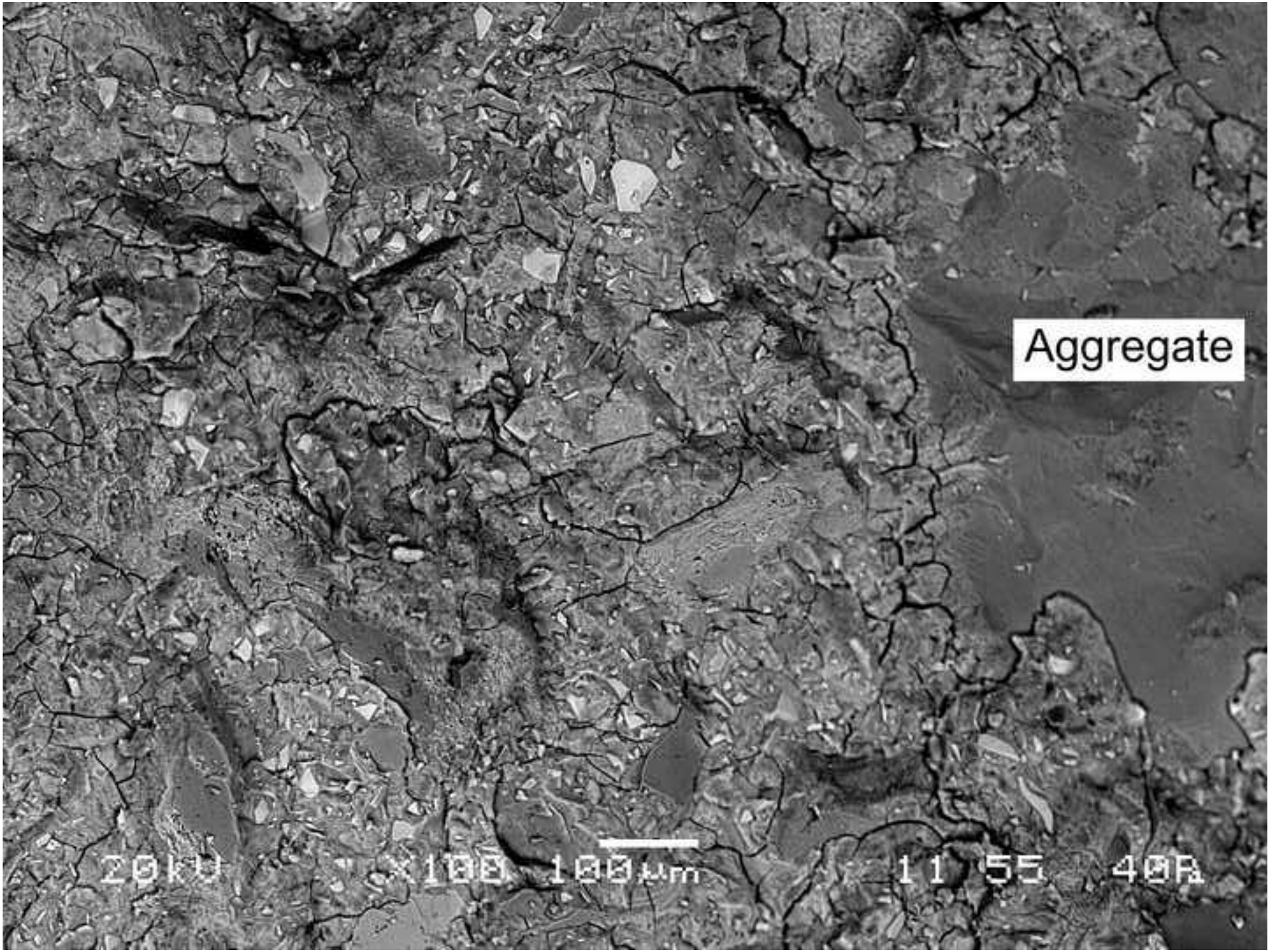

Figure 5d
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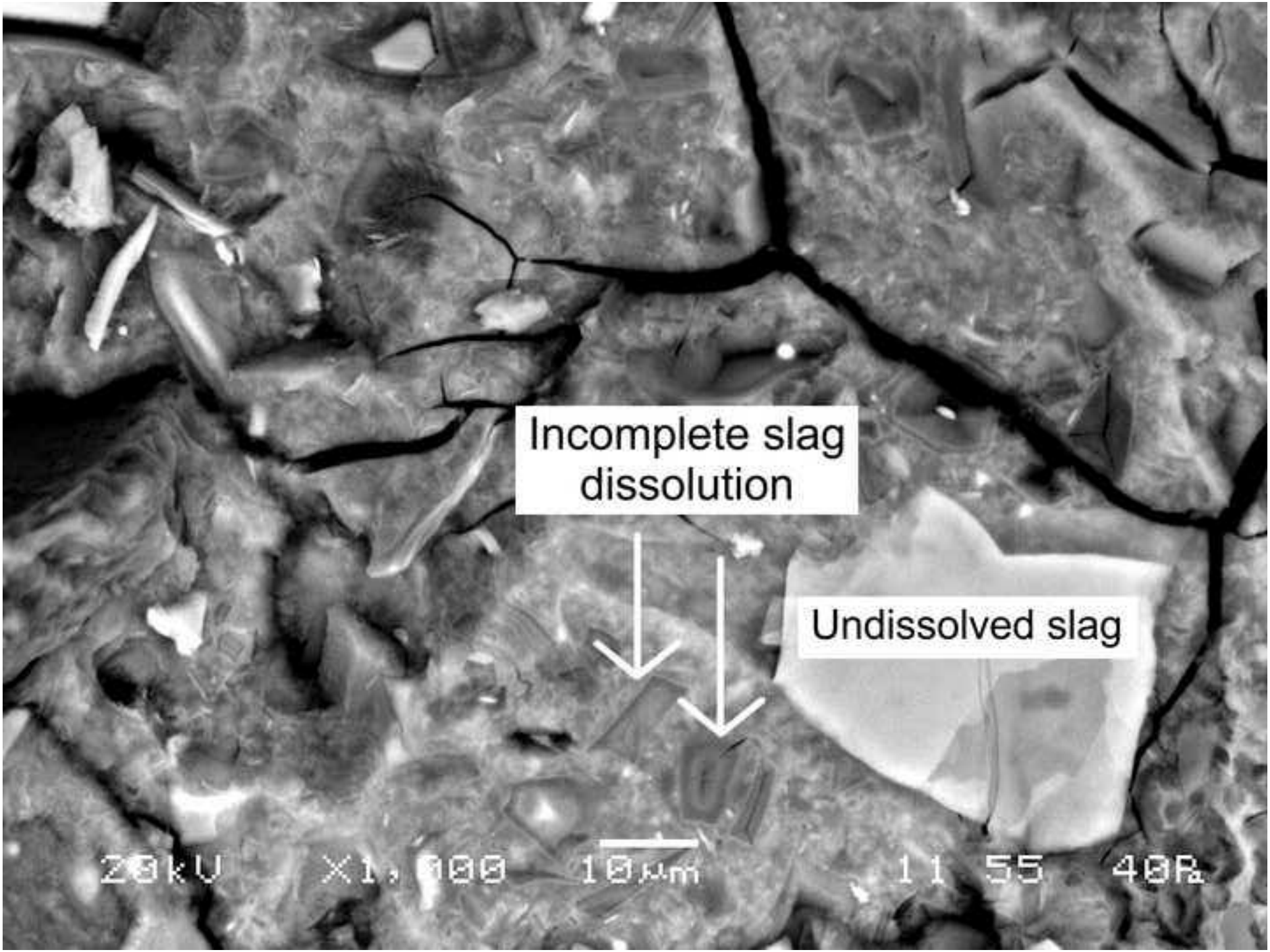

Figure 6

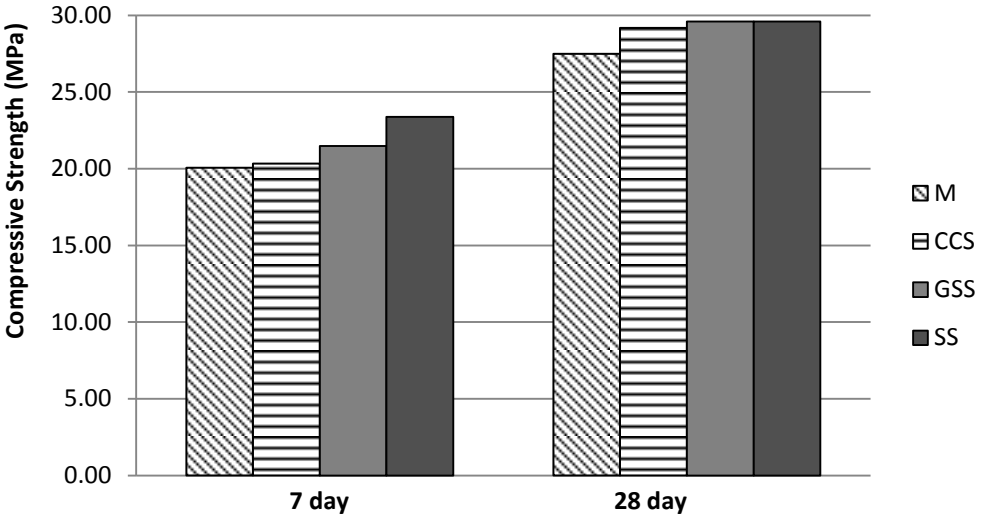
Compressive Strength (MPa)
30.00
25.00
20.00
15.00
10.00
5.00
0.00
7 day
28 day
M
CCS
GSS
SS

Figure 7

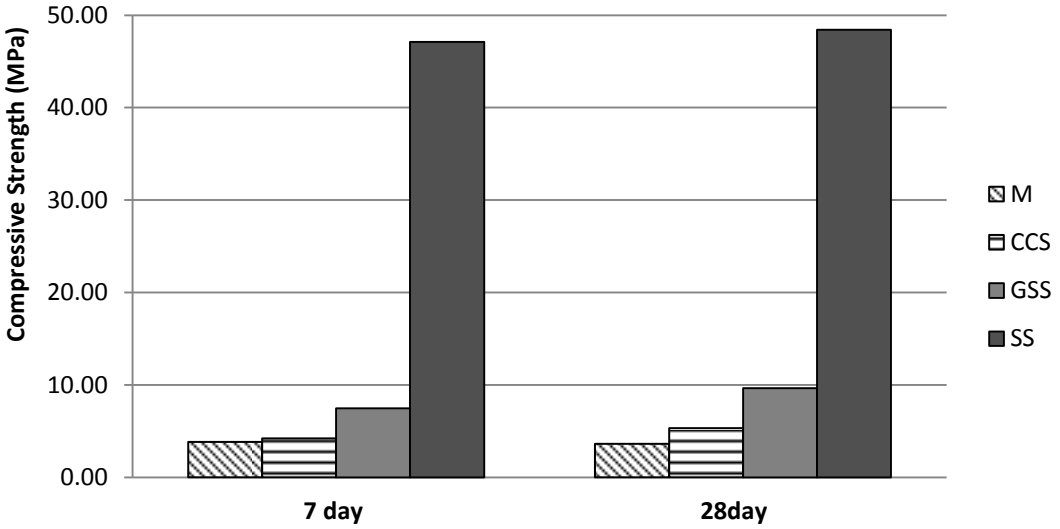
Compressive Strength (MPa)
50.00
40.00
30.00
20.00
10.00
0.00
7 day
28day
M
CCS
GSS
SS

Figure 8a
Click here to download high resolution image

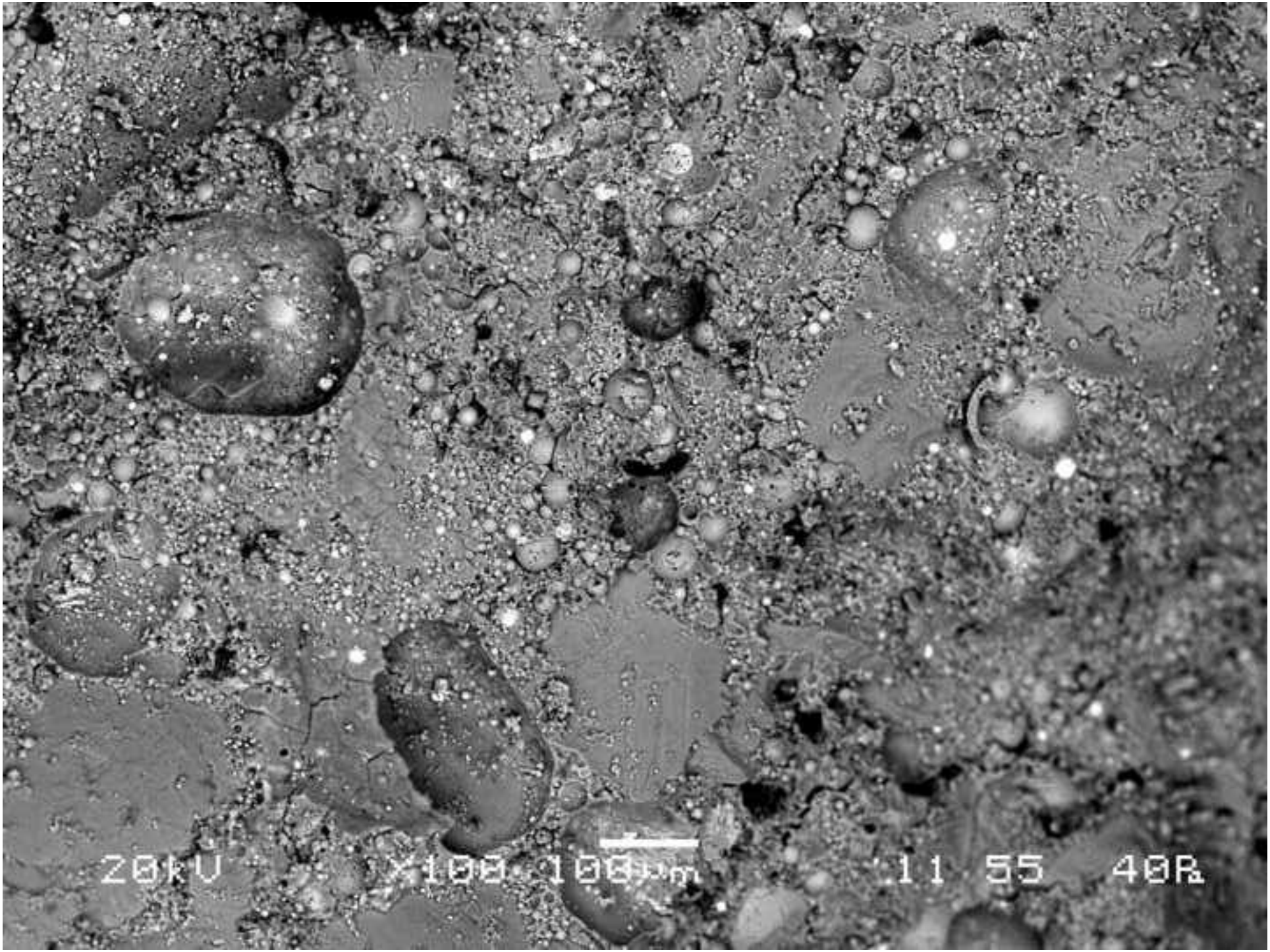

Figure 8b
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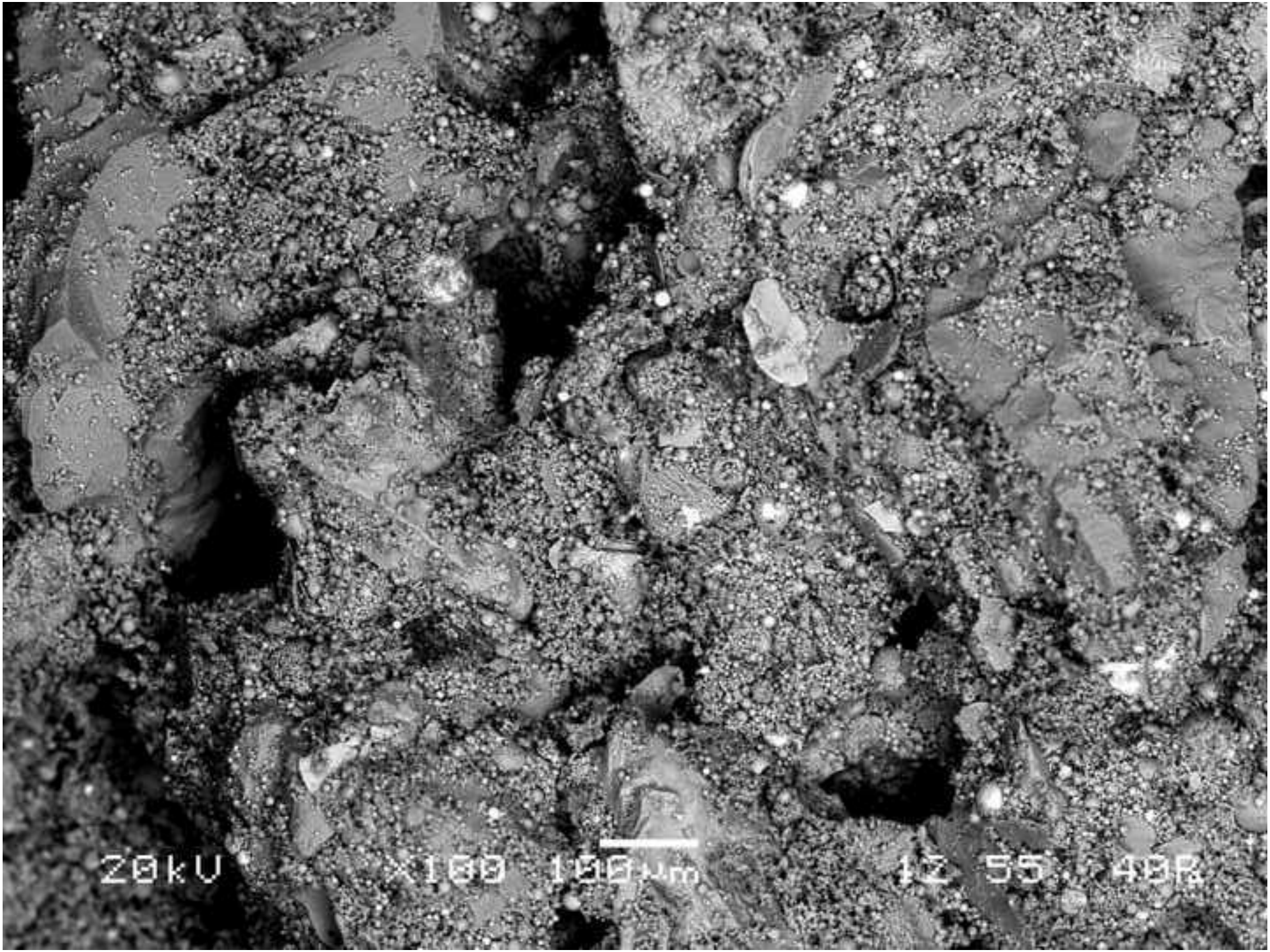

Figure 8c
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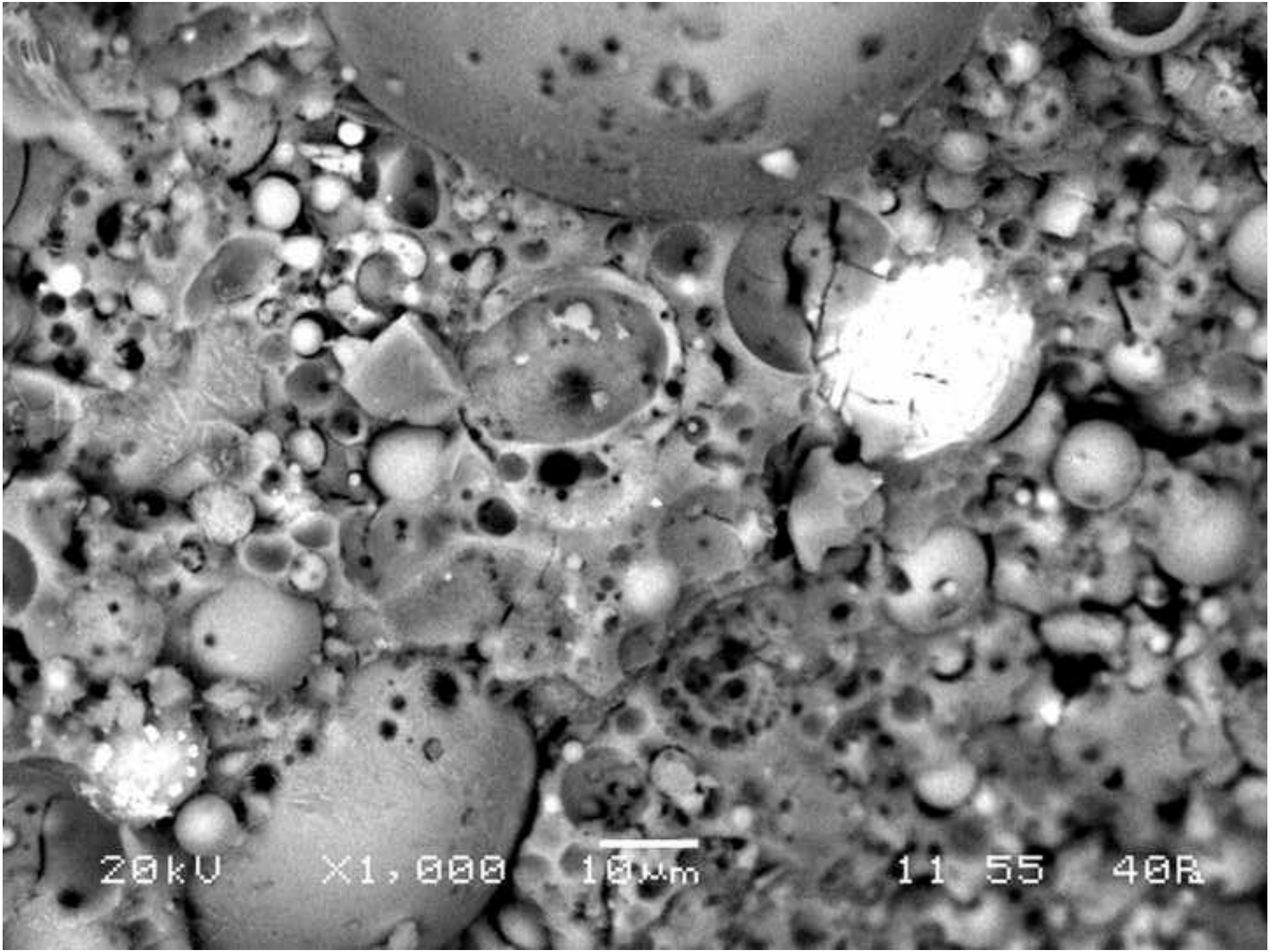

Figure 8d
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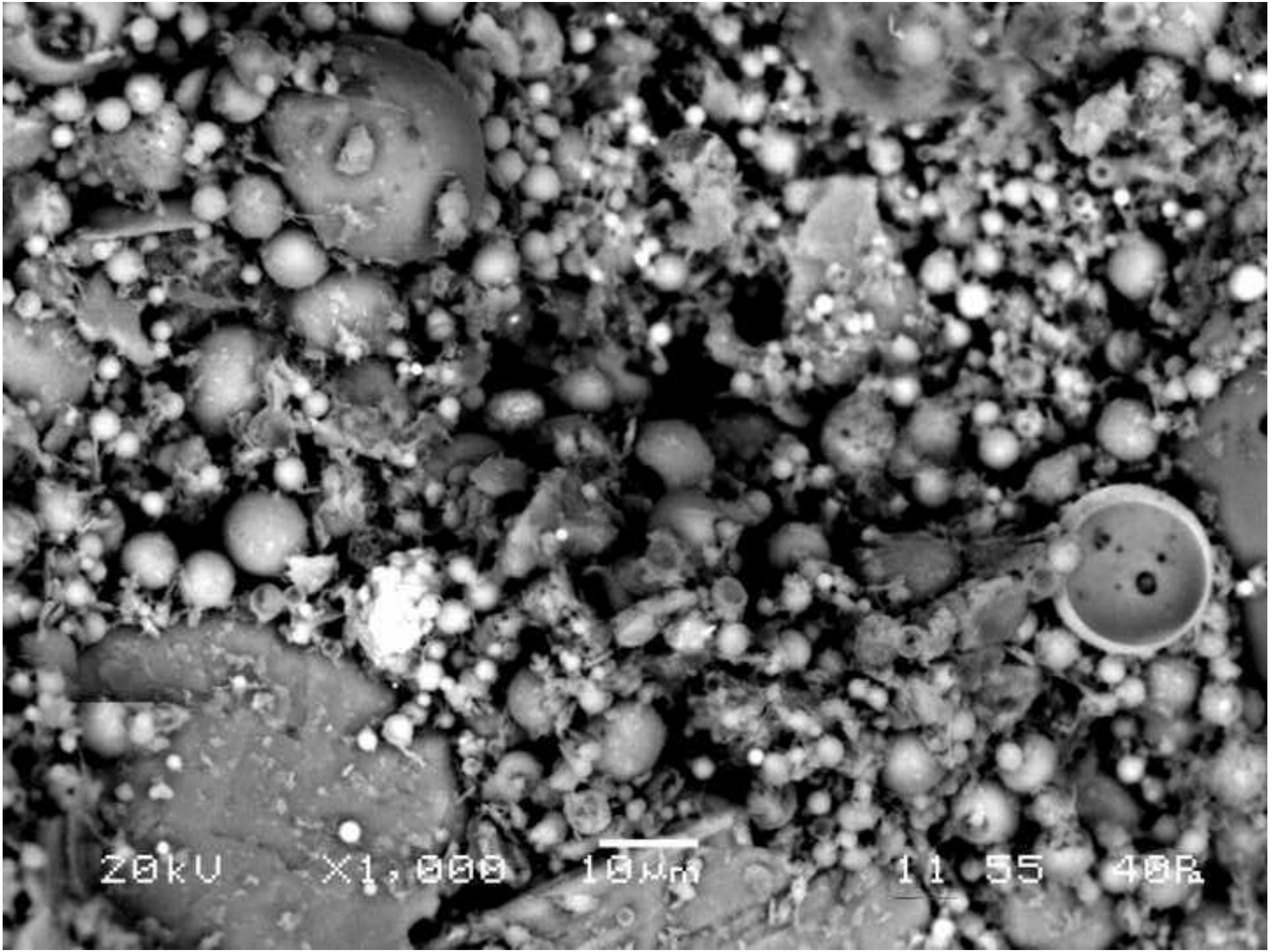


Figure 9

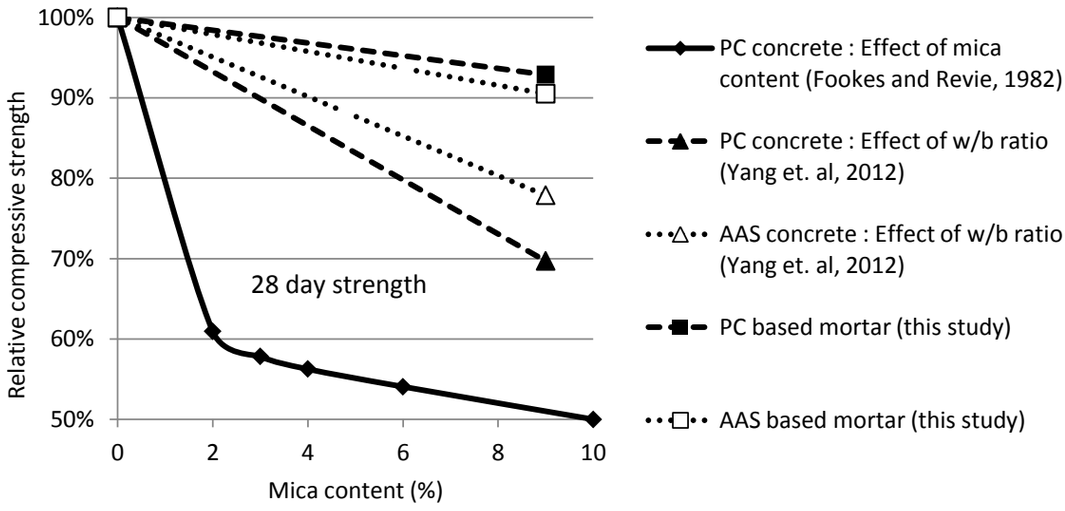
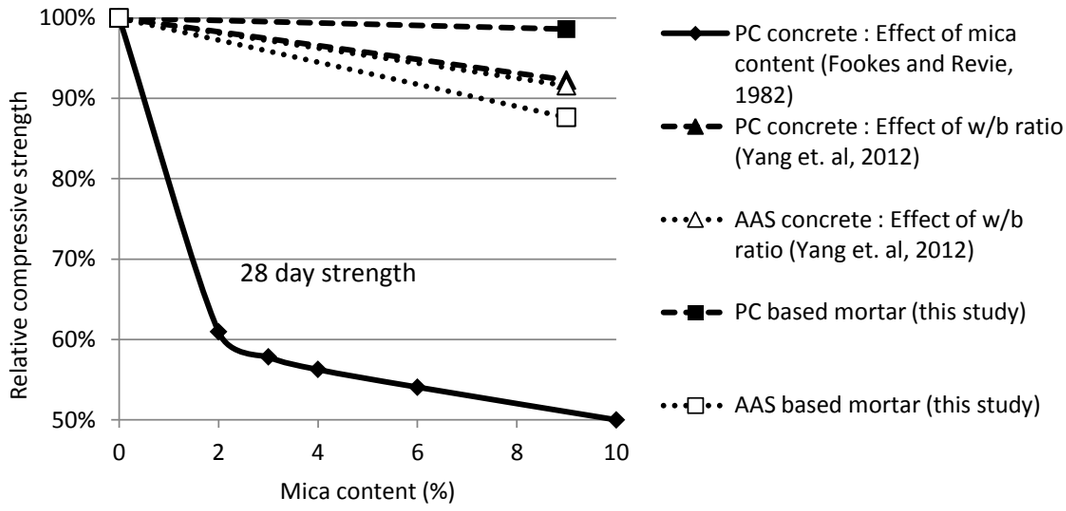

100%
90%
80%
70%
60%
50%
Relative compressive strength
28 day strength
0
2
4
6
8
10
Mica content (%)
PC concrete : Effect of mica content (Fookes and Revie, 1982)
PC concrete : Effect of w/b ratio (Yang et. al, 2012)
AAS concrete : Effect of w/b ratio (Yang et. al, 2012)
PC based mortar (this study)
AAS based mortar (this study)

Figure 10


100%
90%
80%
70%
60%
50%
Relative compressive strength
28 day strength
0
2
4
6
8
10
Mica content (%)
PC concrete : Effect of mica content (Fookes and Revie, 1982)
PC concrete : Effect of w/b ratio (Yang et. al, 2012)
AAS concrete : Effect of w/b ratio (Yang et. al, 2012)
PC based mortar (this study)
AAS based mortar (this study)