Strength development of soil-fly ash geopolymer: Assessment of soil, fly ash, alkali activators and water

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Abstract

In this study, fly ash was added to residual soil to produce soil-fly ash geopolymer bricks. This study investigated the effects of fly ash/soil, alkali activator/ash, Na_2SiO_3/KOH (or NaOH), additional water content, curing condition and curing temperature on the compressive strength of soil-fly ash geopolymer. The results showed that the optimum compressive strength was obtained when the ratios of alkali activator/ash, Na_2SiO_3/KOH (or NaOH) and additional water were 0.6, 0.5 and 10 % respectively. Higher amount of alkali activators was required for strength development in soil-fly ash geopolymer than conventional fly ash-based geopolymers. The formation of the rigid structure at low ratios of alkali activator/ash and Na_2SiO_3/KOH (or NaOH) was unlikely. Compressive strength decreased when additional water was increased. High curing temperature and long curing duration showed negative effect on strength development. The compressive strength of soil-fly ash geopolymer varied as different mixing sequences of raw materials were used, indicating the importance of the formation of geopolymer gel in the structure.

Compressive strength results obtained in this study demonstrate that soil-fly ash geopolymer can be a potential alternative to traditional clay fired brick.

Keyword

Soil; fly ash; geopolymer; alkali activators; compressive strength

Introduction

Clay fired brick is commonly used as construction material. The making process requires firing process which is kilned under high temperature for strength development. During the firing process, it consumes high energy derived by burning charcoal to increase the temperature. Carbon dioxide emission due to high energy consumption pollutes the atmosphere by contributing to the greenhouse effect. Developing a greener material can effectively reduce the exposure of hazard to the surrounding environment, thus being more environmentally friendly. Different types of industrial by-product such as fly ash, sawdust, waste bricks, biomass waste and olive pomace ash have been reported and added into fired clay brick by other researchers (Bories et al. 2015; Casa and Castro 2014; Velasco et al. 2014a; Zhang 2013).

Fly ash, an aluminosilicate material, is an industrial by-product from the combustion of coal at power stations. Geopolymer, an inorganic aluminosilicate polymer, is produced by activating the aluminosilicate materials such as fly ash, bottom ash, metakaolin and slag in an alkaline environment at the low curing temperature (Davidovits 2008). Various types of alkali activator can be used to activate fly ash such as sodium hydroxide, sodium silicate, potassium hydroxide etc. (Criado et al. 2007; Heah et al. 2012; Nematollahi and Sanjayan 2014; Ryu et al. 2013) to produce geopolymer gel. The combined use of sodium hydroxide and sodium silicate as alkali activators for making geopolymer exhibited good compressive strength (Hardjito and Rangan 2005). The formation of three-dimensional polymer chains can be attributed to three main stages, i.e. dissolution of silica and alumina from the aluminosilicate source, reorganisation and polycondensation (Davidovits 2008). The formation of geopolymer gel in the structure was confirmed through the microstructure images (Komljenovi et al. 2010; Tennakoon et al. 2014), contributing to the strength development. Geopolymer has been used as a sustainable construction material in structural elements of buildings such as beams, columns and piles (Power Pile 2013; Sarker 2008; Shrest 2013; Uretek 2014), besides also being viable as a ground treatment method when mixed with weaker clayey soils (Cristelo et al. 2013; Cristelo et al. 2012; Zhang et al. 2013). Being an environmentally friendly construction material, the production of geopolymer emits 80 % less carbon dioxide than manufacturing traditional Portland cement (Duxson et al. 2007).

Other than making fly ash based geopolymer, fly ash can be used to produce clay-fly ash geopolymer (Phetchuay et al. 2014; Sukmak et al. 2013a; Xu et al. 2005). Sukmak et al. (2013a) reported that the amount of alkali activators and fly ash/clay content correspond directly to its compressive strength. The maximum compressive strength was obtained at the ratio of alkali activator/ash of 0.5 to 0.6 and the ratio of Na_2SiO_3/NaOH of 0.7. The increase of amorphous phase of SiO_2 and the Al_2O_3 due to higher ratios of fly ash increases the strength capability (Lingling et al. 2005). However, SiO_2 and Al_2O_3 in clay particles are mostly of the crystalline phase (Phetchuay et al. 2014), indicating the formation of geopolymer gel due to the chemical reaction amongst the clay particles and alkali activators is unlikely. The water content within the sample influent the compressive strength of geopolymer (Phetchuay et al. 2016).

Diop et al. (2014) reported that different curing temperature and curing time led to different strength capability. High curing temperature and long curing time corresponded to higher compressive strength. The formation of geopolymer gel due to better geopolymerisation enhanced the strength capabilities (Phetchuay et al. 2014; Phummiphan et al. 2016a). The geopolymer structure became more rigid after curing for certain period in comparison to its early stage (Diop et al. 2011). This could be due to the geopolymer that formed became more stable as the curing time increased. Zhang et al. (2012) explained the importance of pre-curing process at room temperature. As water content within the sample evaporated during the pre-curing process, cracking at the later curing stage at high temperature was prevented. Hence, strength development was improved. The formation of sponge-like aluminosilicate species was observed amongst the clay particles in the geopolymer structure (Ogundiran and Kumar 2015). The formation of geopolymer gel in clay-fly ash geopolymer was confirmed through scanning electron microscopy by researchers (Diop et al. 2014; Phetchuay et al. 2014; Phummiphan et al. 2016b; Sukmak et al. 2013a; Xu et al. 2005). It bound the clay particles together thus forming a rigid structure (Diop et al. 2014). However, the morphology studies on the soil-fly ash geopolymer at different ratios of fly ash/soil and additional water content are found to be rather limited.

In this study, residual soil is used to produce soil-fly ash geopolymer. The main purpose of this study is to assess the effect of the ratio of fly ash/soil, the ratio of alkali activator/ash, the ratio of Na_2SiO_3/KOH(or NaOH), additional water content, curing condition and curing temperature on the compressive strength of soil-fly ash geopolymer. This study aims to develop further the application of fly ash other than producing the conventional fly ash-based geopolymer, utilizing the method, which is analogous to the brick-making industry to produce soil-fly ash geopolymer.

Experimental Procedure

Materials

Fly ash

In this study, Sarawak fly ash which is available in the local industry was used. It was obtained from Sejingkat Power Station, which is located in the Sarawak state capital of Kuching in Malaysia. Sarawak fly ash has been successfully used in a handful of studies (Leong et al. 2015; Leong et al. 2016a; Leong et al. 2016b). **Table 1** shows the chemical compositions of the fly ash using WD-X-ray Fluorescence Spectrometer (WD-XRF). It is classified as Class F type in accordance to ASTM-C618 (2005), containing low calcium content and hence having poor self-cementing properties. Alkali activators are essentially required to activate the fly ash content for geopolymerisation and strength development.

Soil

The residual soil was sourced from the outskirt of Kuching city, Malaysia. It is classified as reddish brown slightly sandy silt with a natural moisture content of 53 %. It consists of 11 % gravel, 13 % sand, 34 % silt and 42 % clay. The liquid limit, plastic limit and plasticity index of the residual soil are 66 %, 36 % and 30 % respectively. The optimum moisture content (OMC) and the maximum dry density (MDD) of the residual soil are 47 % and 1184 kg/m^3. The chemical compositions of the residual soil are tabulated in **Table 1**. It contains relatively lower SiO_2 content but relatively higher Al_2O_3 and Fe_2O_3 contents than fly ash. **Fig. 1** shows the morphologies of fly ash and soil under a scanning electron microscopy (SEM). As seen in the SEM images, fly ash mainly consists of spherical shape whereas soil shows irregular shapes and exhibits porous-like structures. The particle size distributions of both fly ash and soil are plotted in **Fig. 2**. It demonstrates that fly ash has much smaller particle sizes than soil. However, the latter has wider distributions of particle size. It is mainly due to the physical and chemical weathering processes of the parent rock to form the residual soil, making it behaves more heterogeneous rather than homogenous (Wesley 2010). The difference of particle size distributions of both fly ash and soil is postulated to be an important factor for strength development, which will be discussed further in the next section.

Alkali activators

8M potassium hydroxide (KOH) solution and 8M sodium hydroxide (NaOH) solution were prepared (Leong et al. 2016a) from KOH pellets (brand: Merck) and NaOH pellets (brand: Hudson) respectively. The combined use of potassium hydroxide or sodium hydroxide and sodium silicate (Na_2SiO_3) (17% Na_2O and 35% SiO_2 by weight) was used as the alkali activators in this study. This combination is the most common used in practice in terms of cost effectiveness to produce geopolymer with good compressive strength than the sole use of alkali silicate or hydroxide (Hardjito & Rangan 2005). High concentrations of alkali are essential to activate fly ash particles to form geopolymer gel for strength development. It also facilitates a greater degree of geopolymerisation (Diop, Grutzeck & Molez 2011). 8M NaOH exhibits the optimal concentration for the optimum compressive strength in term of long term performance (Diop et al. 2014).

Sample Preparation and Mixture Proportions

Different ratios of fly ash/soil were studied (0, 0.3, 0.6, 0.8 and 0.9). The ratio of alkali activator/ash was varied in the range of 0.4 to 0.7 and Na_2SiO_3/NaOH (or KOH) = 0.5, 1 were studied. The residual soil was placed in the oven for it to be dried out for 24 hours at 100 °C. The effect of water content on compressive strength of geopolymer was investigated by adding additional water content (i.e. 10 %, 20 %, 30 % and 40 %) into the mixture. The dry soil was initially premixed with fly ash in a mixer. The alkali activators and additional water content were added into the mixture for further mixing until homogenous state was obtained. The mixture was poured into the modified cube mould (50 mm × 50 mm × 120 mm) as presented in **Fig. 3a**. The compression machine was used to press the sample into cubes with dimensions of 50 mm × 50 mm × 50 mm (see **Fig. 3b**) at a press load of 10 kN as shown in **Fig. 3c**. This press load was fixed at 10 kN due to the limitation of the modified cube mould. The mould might deform if a press load higher than 10kN was applied. The samples were then demoulded and cured in an oven at different curing temperatures (i.e. 60 °C, 100 °C or 200 °C) to investigate the effect of different curing temperatures on compressive strength of geopolymer. Different curing time of the samples was also studied (i.e. dried at room temperature for 2 days then cured in oven for 1 day, direct cured in oven for 1 day and direct cured in oven for 2 days). **Table 2** shows the designations of soil-fly ash geopolymers studied in this study.

Test

Workability

The mixture was placed into the conical mould on top of the flow table for the workability test immediately after finishing the mixing process. The test was conducted in accordance to ASTM-C1437 (2013).

Compression test

Samples were tested for compressive strength after oven curing. The compressive strength of the samples was obtained using compression test machine in accordance to ASTM-C109/C109M (2005).

Particle Size Distributions

The particle size distributions of the fly ash were analysed using the laser particle size analyser (brand: CILAS 1190). However, for the soil, it was obtained using dry sieving and hydrometer test due to its larger particle sizes as compared to the fly ash. The test was performed in accordance to BS-1377-2 (1990).

Scanning Electron Microscope (SEM)

The morphology of the soil-fly ash geopolymer was studied using ZEISS SUPRA 40 VP SEM. A layer of gold was coated on the sample prior to the micrograph analysis.

Results and discussion

Effect of additional water content on compressive strength of geopolymer

Fig. 4 shows the effect of additional water content on compressive strength of soil-fly ash geopolymer using different ratios of alkali activator/ash and Na_2SiO_3/NaOH(KOH). The results show that the reduction of additional water content intensively increases the compressive strength of sample. Samples with the ratio of alkali activator/ash of 0.5 to 0.7 exhibit the highest compressive strength at additional water content of 10%, after which it gradually decreases with the increase of additional water content. It may be due to the reduction of alkalinity in the mixture, which will be discussed here-in-after. Mixture with further increase of additional water appears to be very liquid, particularly at additional water content of 40 %. These mixtures were directly cast into the mould with dimensions of 50 mm × 50 mm × 50 mm as denoted by L in **Fig. 4**.

Geopolymer made of alkali activator/ash = 0.4 shows different trend in strength. The optimum compressive strength was obtained at additional water of 20 to 30 %. It is most probably because the mixture at additional water of 10 % is very dry. The sample appeared to be easily broken when minimal load was applied on it. As the additional water increases, it acts as lubricant to improve the formation of rigid structure and hence, it leads to higher strength capability.

The workability of these mixtures is depicted in **Fig. 5**. It shows similar trend of workability as fly ash-based geopolymer as reported by Leong et al. (2016a). The workability increases when the additional water content and alkali activators increase. From the workability point of view, it may be beneficial to brick making industry using extrusion method. It is important to mention that geopolymer with additional water content of 0% was unable to produce. It is because that the sample at this mixture ratio was very dry and it couldn't form into shape. Hence, the comparison between the sample made with and without additional water content was not available.

Samples made using the press method appear to be more rigid in comparison to those made without using the press method. It is because through pressing the air bubbles/voids within the sample escape into the atmosphere when load is applied to the samples. Hence, entrapped air within the sample is squeezed out from the void spaces thus making the particles closely packed together. It is important to note that the press method is somewhat different from the consolidation process where water content is removed from the sample. Furthermore, the alkali activators within the sample may be further diluted by the excessive additional water content thus reducing the strength capability. The results show that the compressive strength is nearly negligible when the ratio of alkali activator/ash and additional water increase (i.e. when additional water is 40% and the ratio of alkali activator/ash ranges from 0.4 to 0.7). This observation provides a significant insight into the effect of water on compressive strength and the optimum water content for making soil-fly ash geopolymer.

Fig. 6 depicts the morphology images of the soil-fly ash geopolymer at different ratios of additional water content but having same ratios of alkali activators/ash, Na_2SiO_3/NaOH and fly ash/soil (i.e. SFG11). Geopolymer at these ratios were selected for morphology studies in terms of good compressive strength and the common use of NaOH and Na_2SiO_3 as alkali activators. **Fig. 6a** shows the SEM image of soil-fly ash geopolymer with additional water content of 10 %. The structure was observed to be very dense and rigid. The geopolymer gel was formed surrounding the soil particles, indicating better geopolymerisation. At optimum water content, it reduces the distance between soil and fly ash particles. Thus, it leads to higher compressive strength (Sukmak et al. 2013). However, the geopolymer structure became looser and cracks were visible within the samples when the additional water content increased (see **Fig. 6b**). Layer of alkali activators in excess seems present in the structure as shown in **Fig. 6c**. It is most probably due to the high water content in the sample, which reduces the contact points amongst fly ash particles and alkali activators for further reaction. At high temperature exposure, the water content within the sample evaporates thus making the alkali activators, which have not used in the geopolymerisation, remain in the structure. Some tiny pores were observed within the sample due to the evaporation of water content. It can be seen that the unreacted fly ash particles were embedded within the sample. This phenomenon is evidently shown in **Fig. 6d**. The large voids that remained were caused by the unreacted fly ash particles. As the concentration of alkali activator was further reduced by higher additional water content, the formation of geopolymer gel was lesser and therefore more unreacted fly ash particles were presented within the sample. As the bonding of the structure is weaker, these unreacted fly ash particles could be easily broken.

As discussed earlier, the alkalinity of the alkali activator could be reduced by the addition of water subsequently, resulting in reduction of geopolymer strength. The pOH value increased as the additional water increased subsequently reducing the pH value. In high pH environment, the soil particles are expected to be dispersed while the soil particles are flocculated when pH value is low (Mitchell and Soga 2005). As NaOH (or KOH) is categorised as strong base whereas Na_2SiO_3 is a weak base, the decrease in strength is governed by the variation of alkalinity in NaOH. Moreover, Na_2SiO_3 requires dissociation of water to form OH^-. The evidence of reduction in pH values in NaOH as the additional water content increases is shown in **Fig. 7**. It is noted that the pH values are greater than 14 as shown in **Fig. 7**. Commonly, it is in the range of 1 to 14. It can be attributed to the high initial molarity of alkali activator in this study (i.e. 8M NaOH solution). The concentration of NaOH in the sample also decreases as the water content increases as presented in **Fig. 8**. Hence, less fly ash particles are dissolved due to the lower concentration of alkali activators. The decline of geopolymer strength was reported as a result of less geopolymerisation. It is consistent with the observation in **Fig. 6** that unreacted fly ash particles increase when the water content increases. The example of evaluation of molarity and pH value in NaOH is shown in appendices.

Soil and water particles are not chemically or biologically inert. Other than the absorbed water in soil particles, there are some interactions amongst soil particles, dissolved ions and water molecules. The possible mechanisms that occur between water and soil particles are identified as hydrogen bonding, ion hydration, attraction by osmosis and dipole attraction (Mitchell and Soga 2005). As water molecules have dipolar character, its positive poles are attracted to the negatively charged soil surface particularly in clay particles. The bonds between water molecules and soil particles thus creating an interface layer. It reflects that soil particles are further apart from interacting the fly ash particles or the geopolymer gel formed (due to the reaction amongst fly ash and alkali activators) by the interface layer in close proximity. For the coarser fraction in soil, it has lower specific surface area as compared to the clay particles, causing greater thickness of water layer between soil particles. It indicates that the surface interaction effect is relatively much lower. More water is available and mobilised as the additional water content increases. Therefore, the alkalinity of the alkali activator as mentioned previously could be possibly reduced. It is worth mentioning that soil studied in this study may have positive surface charge. However, the cation exchange capability in soil could be much greater than the anion exchange capability due to the high pH environment (Hendershot et al. 2007) in soil-fly ash geopolymer system.

Effect of Na_2SiO_3/NaOH(KOH) on compressive strength

The effect of Na_2SiO_3/NaOH(KOH) on compressive strength of soil-fly ash geopolymer was also studied as shown in **Fig. 4**. Both NaOH- and KOH-based soil-fly ash geopolymer demonstrate the highest compressive strength at the ratios of alkali activator/ash and Na_2SiO_3/NaOH at 0.6 and 0.5 respectively. The NaOH-based geopolymer exhibits lower compressive strength than the KOH-based geopolymer. It could be due to more geopolymer precursors that exist in the geopolymer system when KOH solution is used, hence demonstrating higher strength capability (Xu and Deventer 2000). These results show similar findings as those reported in the previous study when fly ash-based geopolymer was studied (Leong et al. 2016a).

It is suspected that the alkali hydroxide may be more important for strength development than alkali silicate at the optimum additional water content in order to obtain the maximum compressive strength. It is known that alkali hydroxide plays a role of leaching the Si and Al content from the reacting fly ash whereas alkali silicate aids in increasing the Si content in the system for geopolymerisation (Xu and Deventer 2000). Sukmak et al. (2013a) reported that partial alkali hydroxide might be absorbed for soil cation exchange and therefore more alkali hydroxide was required than alkali silicate. However, the effect of Na_2SiO_3/KOH(or NaOH) on compressive strength was further investigated as shown in **Fig. 9**. The results show that the compressive strength increases when Na_2SiO_3/KOH (or NaOH) is increased. However, it decreases with further increase of Na_2SiO_3/KOH(or NaOH). It could be due to an excessive amount of alkali hydroxide within the sample as the ratio increases. It may be presented as salt precipitates which hinder the geopolymerisation thus resulting in strength reduction. Hence, it is suggested that an optimum amount of alkali hydroxide and alkali silicate could possibly obtain the maximum compressive strength. This condition is attainable when Na_2SiO_3/KOH(or NaOH) is 0.5.

Effect of curing condition and curing temperature on compressive strength

Soil-fly ash geopolymer at the ratios of alkali activator/ash of 0.6 and Na_2SiO_3/KOH(or NaOH) of 0.5 (i.e. the sample exhibits the highest compressive strength) was further studied at different types of curing condition and curing temperature. As shown in **Fig. 10**, the compressive strength gradually increases as the curing temperature increases with the exception of sample cured directly in oven for 1 day. Diop et al. (2014) explained that the strength gain with the increase of curing temperature was most probably attributed to the dehydroxylation, disintegration and polycondensation of aluminosilicate polymer between the soil particles and alkali activators. In this study, it shows that the loss of moisture increases as the curing temperature increases. It is thought that the sample which was initially dried at room temperature for 2 days could aid in removing the water content within the sample thus enhancing the geopolymerisation between fly ash and alkali activators subsequently leading to higher compressive strength. However, on the contrary, the moisture loss at this type of curing condition shows similarity to the other types of curing condition. It shows that room temperature curing only aids in removing the moisture on sample surface. For moisture within the sample, it requires oven heating and thus it explains moisture loss due to oven curing is similar.

Comparing the geopolymer samples cured in oven for 1 day and 2 days, strength gain over longer curing duration was observed in sample cured at 60 °C only. It is most likely due to the increase of moisture loss. Samples cured at low temperature might need longer duration of oven curing to build up the strength (Sukmak et al. 2013b). However, having the same curing duration at 100°C and 200°C, strength reduction was observed. It could be due to high temperature exposure and more cracks develop in the sample. The loss of moisture from 1-day oven curing to 2-day oven curing is minimal. This implies that most of the moisture had been evaporated within first 24 hours. It also demonstrated that longer duration of oven curing does not necessarily lead to higher compressive strength but resulting in strength reduction in particular to the sample cured at high temperature.

The highest compressive strength is obtained when the samples were cured directly in oven for 1 day. It intensively increased from 60°C to 100°C and decreased from 100°C to 200°C. This suggested that sample cured in oven plays an important role in strength development for soil-fly ash geopolymer. Additionally, it is postulated that sample cured at this type of curing condition (i.e. directly cured in oven for 1 day at 100°C) achieved the initial maximum strength. As mentioned earlier, moisture within the sample might not able to evaporate at low curing temperature. High temperature exposure may result in crack development subsequently reducing the strength capabilities. An adequate curing temperature (i.e. 100 °C in this case) facilitates the moisture evaporation and geopolymerisation for forming a rigid structure within first 24 hours. Therefore, this condition may be adequate for making soil-fly ash geopolymer as it required short curing duration, moderate curing temperature but it exhibits the highest strength capability.

Fig. 11a-c presents the morphologies of the geopolymer samples cured directly in oven for 1 day at different curing temperatures. At 60°C, agglomeration of particles was observed. The geopolymer structure appeared to be non-homogenous and consisted coagulation of fly ash particles and alkali activators around the soil particles. The geopolymer gel formed was distributed in scatter within the sample. Moreover, some unreacted or partially dissolved fly ash particles were also present as marked in the figure. This observation shows that the geopolymerisation process is incomplete. The geopolymer sample depicted in **Fig. 11b** exhibits more homogenity and a more compact microstructure. Furthermore, the phenomenon described in **Fig. 11a** did not occur. It implied that geopolymer cured at 100°C enhances the geopolymerisation for soil-fly ash geopolymer. When the curing temperature increases to 200°C, different structure was observed as illustrated in **Fig. 11c**. The soil particles and geopolymer gel seem to have fused together due to high temperature exposure. However, the sample showed less dense structure and cracks occurred as marked. Evaporation of the water content at high temperature increased the porosity within the sample thus causing the strength to decrease.

Effect of fly ash/soil on compressive strength

The effect of the ratio of fly ash/soil on compressive strength was studied and illustrated in **Fig. 12**. The compressive strength gradually increased when the ratio of fly ash/soil increased. It is most likely due to the increase of fly ash content, which enhances the geopolymerisation within the sample. It is evident that the geopolymer strength increased as the amount of alkali activators increased regardless of the types of alkali activator. The amorphous phase of SiO_2 and Al_2O_3 contents could be leached out from the fly ash. Hence, more geopolymer could be sufficiently formed to bind the soil particles together thus increasing the compressive strength. Although soil contains high SiO_2 and Al_2O_3 contents, it is mostly presented in the crystalline phase (Phetchuay et al. 2014). It acts as fine aggregate (Sukmak et al. 2013a) and contribution to the formation of geopolymer gel is unlikely. It is also noted that Na_2SiO_3 content is lower than NaOH content in geopolymer. As reported in previous study, Na_2SiO_3 provides more Si content to the geopolymer system whereas NaOH dissolves alumina and silica from the fly ash particles (Leong et al. 2016a). However, increase of Na_2SiO_3 may obstruct NaOH to dissolve the essential elements for geopolymerisation. Hence, an adequate amount of Na_2SiO_3 and NaOH should be adopted for good strength result. The SEM images in **Fig. 13** show that more geopolymer gel was formed as the ratio of fly ash/soil increased. The strength results obtained in this study had shown well agreement to the microscopy observations.

More unreacted fly ash particles were observed at low ratio of fly ash/soil. The structure of the sample becomes more rigid and less undissolved fly ash particles were observed as the ratio of fly ash/soil increased. Samples made using 100% fly ash exhibited the most homogenous structure, however, cracks were obviously seen in the sample due to high temperature exposure. Fly ash particles were mostly unreacted in samples cured at room temperature regardless of the ratio of fly ash/soil as shown in **Fig. 14**. Moreover, no obvious changes of the microstructure were observed over the increase of the ratio of fly ash/soil. This observation was in agreement to the strength results and it explained the reason behind the insignificant strength gain. Although low compressive strength was obtained in samples cured at room temperature, the SEM images proved that geopolymer gel could be formed at room temperature. However, it might require longer duration to achieve the desired strength.

The strength results of the samples made using 100% soil and 100% fly ash demonstrated that the trend of the strength development in terms of the ratio of fly ash/soil is principally caused by the geopolymerisation. Sample made using 100% soil exhibited very low compressive strength when curing at room temperature. As no aluminosilicate gel was formed, it showed good evidences that the geopolymerisation gel could effectively increase the geopolymer strength when fly ash and alkali activators were added into the soil. The latter type of curing condition also showed that the strength gained (i.e. 0.18MPa) was mainly due to the press method at 10kN. Hence, the remaining strength is built up through the temperature exposure and geopolymerisation. Therefore, strength gained due to these two factors can be evaluated by data presented in **Fig. 15**. The results showed that the increase of compressive strength due to the geopolymerisation at room temperature was minimal as compared to the geopolymerisation at temperature exposure. This results show well agreement to the findings obtained in fly ash-based geopolymer as reported by Leong et al. (2016a). These observations showed that soil-fly ash geopolymer behaved similar geopolymerisation as in fly ash-based geopolymer. Curing temperature plays an important role in strength development regardless of the types of raw material.

In **Fig. 12** and **Fig. 15**, the mixing sequence of raw materials were investigated and denoted as M1 and M2. M1 represents the sample premixed with soil and fly ash prior to the addition of liquid content whereas M2 represents premixing fly ash with the liquid content followed by the addition of soil. It is thought that the formation of aluminosilicate gel in M2 could effectively bind the soil particles thus leading to higher strength capability. However, the results reflected that samples prepared from M1 obtain higher strength gain than sample prepared from M2 as tabulated in **Table 3**. The possible reasons are schematized in **Fig. 16**.

It is postulated that the fly ash particles are packed closely between the soil particles during the premixing process in M1 as the former particles show much smaller particle sizes as compared to the latter as evidenced in **Fig. 2**. When alkali activators were added into the mixture, it dissolved the fly ash particles surrounding the soil particles. Hence, the aluminosilicate gel was formed around the soil particles. Moreover, the negatively charged surface of soil particle held some of the cations from the alkali activators, resulting in high concentration of absorbed cations near the surface of soil particles. It implied that the anions such as OH^- and SiO_3^{2-} from the alkali activators are adjacent to the fly ash particles, which are the essential ions for dissolution of fly ash particles and the geopolymerisation process. Combining these two factors, a strong interaction and reaction amongst soil particles, fly ash particles and alkali activators are developed, forming a rigid structure for better strength capability.

For samples prepared from M2, the formation of aluminosilicate gel due the reaction of fly ash particles and alkali activators may not sufficient to bind the soil particles completely. In this case, the binding effect only occurred in limited region of the sample. Therefore, the structure formed may not be as rigid and homogenous as achieved in M1.

Conclusion

The effect of the ratio of fly ash/soil, the ratio of alkali activator/ash, the ratio of Na_2SiO_3/KOH (or NaOH), additional water content, curing condition and curing temperature on compressive strength of soil-fly ash geopolymer had been successfully studied. The following conclusions can be made:

1. Soil-fly ash geopolymer obtains the highest compressive strength when the ratio of alkali activator/ash of 0.6, the ratio of Na_2SiO_3/KOH(or NaOH) of 0.5 and additional water of 10 %. The effect of additional water on compressive strength shows similar pattern regardless of the types of alkali activators.
2. Water is essential in shaping and forming soil-fly ash geopolymer. However, excessive water and alkali activators were not suitable for press method although it shows high workability. The increase in additional water content decreases the alkalinity and molarity of alkali activator, causing the geopolymer strength to decline.
3. More alkali activators are required for soil-fly ash geopolymer to obtain maximum compressive strength as compared to fly ash-based geopolymer. It organic matter in soil may behave as absorbent for alkali activators.
4. The compressive strength increases when the curing temperature increases. However, high curing temperature and long curing duration do not lead to higher compressive strength. Loss of moisture was reported during the curing process. Sample directly cured in oven for 1 day at 100 °C exhibits the highest compressive strength.
5. The compressive strength increases as the ratio of fly ash/soil increases. The increase of fly ash content is associated with more alkali activators that increases the formation of geopolymerisation gel thus resulting in binding of the soil particles.
6. Different mixing sequences of the raw materials used were also studied. Premixed fly ash and soil before adding the liquid contents shows better formation of geopolymer gel within the sample, thus resulting more significant strength capability.

7. In this study, the compressive strength of soil-fly ash geopolymer ranges from 0.88 MPa to 32.05 MPa. It is thus evidenced that fly ash and residual soil can be potentially used to produce soil-fly ash geopolymer, an alternative to traditional clay fired brick.

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Appendices

Evaluation of molarity and pH value in NaOH

$NaOH <-> Na^{+} + OH^{-}$

Assume: 8M NaOH = 106.7 g
Water = 50 g

Consider 1g/mL,

□ Molarity, $M_{NaOH\ (8M)}$ = 106.7 g
Volume, $V_{NaOH\ (8M)}$ =106.7 mL

Number of mol, $n_{NaOH} = (106.7\ mL \times 10^{-3}) \times 8M$
$= 0.853$ mol

Volume of solution = $(106.7 + 50) \times 10^{-3}$

$= 0.157\ \text{L}$

Molarity of $OH^- = \frac{0.853\ mol}{0.157\ L}$

$= 5.45\ \text{M}$

$\text{p}(OH^-) = -\log_{10}(OH^-)$

$= -\log_{10}(5.45)$

$= -\ 0.74$

$\text{pH} = 14 - (-0.74)$

$= 14.74$

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Table 1. Chemical Composition of Fly Ash and Residual Soil

Elements (%)	**Sarawak Fly Ash**	**Residual Soil**
SiO_2	43.8	32.71
Al_2O_3	18.1	25.33
Fe_2O_3	7.7	21.29
CaO	3.9	0.04
MgO	0.5	0.22
MnO	22.8	-
K_2O	2.0	0.03
Na_2O	0.3	0.07
SO_3	0.1	0.01
TiO_2	0.6	-
P_2O_5	0.1	-
LOI	0.5	17.18

Table 2. Designations of soil-fly ash geopolymers

Fly ash/ soil	**Alkali activator/ ash**	**NaOH or KOH**	**Na_2SiO_3/ NaOH (or KOH)**	**Water (%)**	**Curing temperature (°C)**	**Curing time**	**Mixing sequence**	**Designation**
0.8	0.4	KOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG1
0.8	0.5	KOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG2
0.8	0.6	KOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG3
0.8	0.7	KOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG4
0.8	0.4	KOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG5
0.8	0.5	KOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG6
0.8	0.6	KOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG7
0.8	0.7	KOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG8
0.8	0.4	NaOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG9
0.8	0.5	NaOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG10
0.8	0.6	NaOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG11
0.8	0.7	NaOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG12
0.8	0.4	NaOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG13
0.8	0.5	NaOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG14
0.8	0.6	NaOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG15
0.8	0.7	NaOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG16

0.8	0.6	KOH	0.1, 0.3, 0.5, 1	10	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG17
0.8	0.6	NaOH	0.1, 0.3, 0.5, 1	10	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG18
0.8	0.6	KOH	0.5	10	60, 100, 200	Dried at room temperature for 2 days then cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG19
0.8	0.6	KOH	0.5	10	60, 100, 200	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG20
0.8	0.6	KOH	0.5	10	60, 100, 200	Directly cured in oven for 2 days	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG21
0.8	0.6	NaOH	0.5	10	60, 100, 200	Dried at room temperature for 2 days then cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG22
0.8	0.6	NaOH	0.5	10	60, 100, 200	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG23
0.8	0.6	NaOH	0.5	10	60, 100, 200	Directly cured in oven for 2 days	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG24
100% soil, 0.3, 0.6, 0.8, 0.9, 100% fly ash	0.6	NaOH	0.5	10	Room temperature	Directly cured at room temperature for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG25
100% soil, 0.3, 0.6, 0.8, 0.9, 100% fly ash	0.6	NaOH	0.5	10	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG26
100% soil, 0.3, 0.6, 0.8, 0.9, 100% fly ash	0.6	NaOH	0.5	10	100	Directly cured in oven for 1 day	Fly ash and the liquid content were premixed followed by the addition of soil (M2)	SFG27

Table 3. Strength increment due to sequence of mixing

Ratio of fly ash/soil	**M1 (%)**	**M2 (%)**
0.3	45.08	66.95
0.6	86.22	78.25
0.8	92.30	80.29
0.9	90.81	77.53

Table 1. Chemical Composition of Fly Ash and Residual Soil

Elements (%)	Sarawak Fly Ash	Residual Soil
SiO_2	43.8	32.71
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MnO	22.8	-
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Na_2O	0.3	0.07
SO_3	0.1	0.01
TiO_2	0.6	-
P_2O_5	0.1	-
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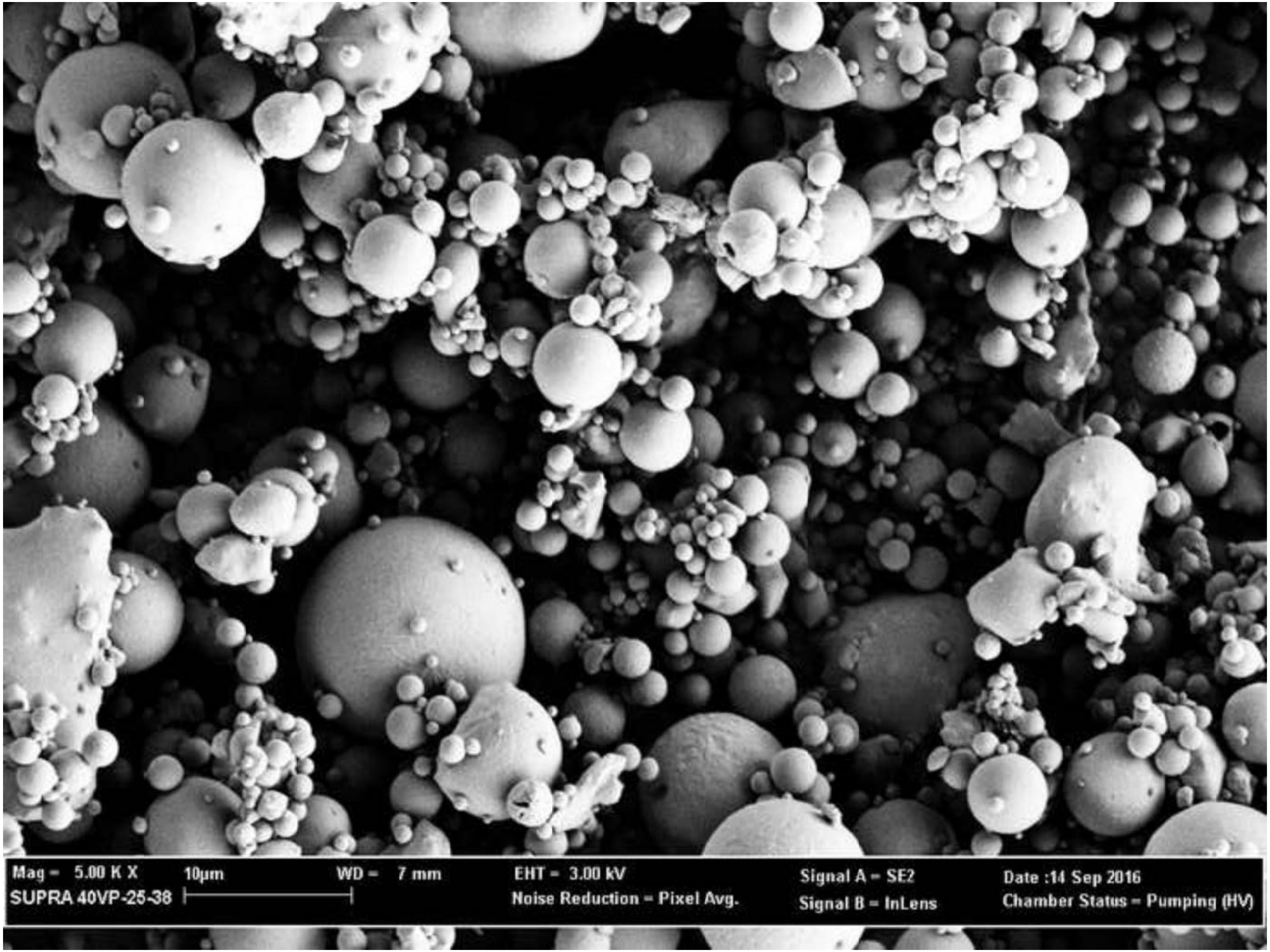
Fly ash/ soil	**Alkali activator/ ash**	**NaOH or KOH**	**Na_2SiO_3/ NaOH (or KOH)**	**Water (%)**	**Curing temperature (°C)**	**Curing time**	**Mixing sequence**	**Designation**
0.8	0.4	KOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG1
0.8	0.5	KOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG2
0.8	0.6	KOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG3
0.8	0.7	KOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG4
0.8	0.4	KOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG5
0.8	0.5	KOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG6
0.8	0.6	KOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG7
0.8	0.7	KOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG8
0.8	0.4	NaOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG9
0.8	0.5	NaOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG10
0.8	0.6	NaOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG11
0.8	0.7	NaOH	0.5	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG12
0.8	0.4	NaOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG13
0.8	0.5	NaOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG14
0.8	0.6	NaOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG15
0.8	0.7	NaOH	1	10, 20, 30, 40	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG16

0.8	0.6	KOH	0.1, 0.3, 0.5, 1	10	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG17
0.8	0.6	NaOH	0.1, 0.3, 0.5, 1	10	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG18
0.8	0.6	KOH	0.5	10	60, 100, 200	Dried at room temperature for 2 days then cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG19
0.8	0.6	KOH	0.5	10	60, 100, 200	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG20
0.8	0.6	KOH	0.5	10	60, 100, 200	Directly cured in oven for 2 days	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG21
0.8	0.6	NaOH	0.5	10	60, 100, 200	Dried at room temperature for 2 days then cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG22
0.8	0.6	NaOH	0.5	10	60, 100, 200	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG23
0.8	0.6	NaOH	0.5	10	60, 100, 200	Directly cured in oven for 2 days	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG24
100% soil, 0.3, 0.6, 0.8, 0.9, 100% fly ash	0.6	NaOH	0.5	10	Room temperature	Directly cured at room temperature for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG25
100% soil, 0.3, 0.6, 0.8, 0.9, 100% fly ash	0.6	NaOH	0.5	10	100	Directly cured in oven for 1 day	Soil and fly ash were premixed prior to the addition of liquid content (M1)	SFG26
100% soil, 0.3, 0.6, 0.8, 0.9, 100% fly ash	0.6	NaOH	0.5	10	100	Directly cured in oven for 1 day	Fly ash and the liquid content were premixed followed by the addition of soil (M2)	SFG27

Table 3. Strength increment due to sequence of mixing

Ratio of fly ash/soil	M1 (%)	M2 (%)
0.3	45.08	66.95
0.6	86.22	78.25
0.8	92.30	80.29
0.9	90.81	77.53

Figure 1a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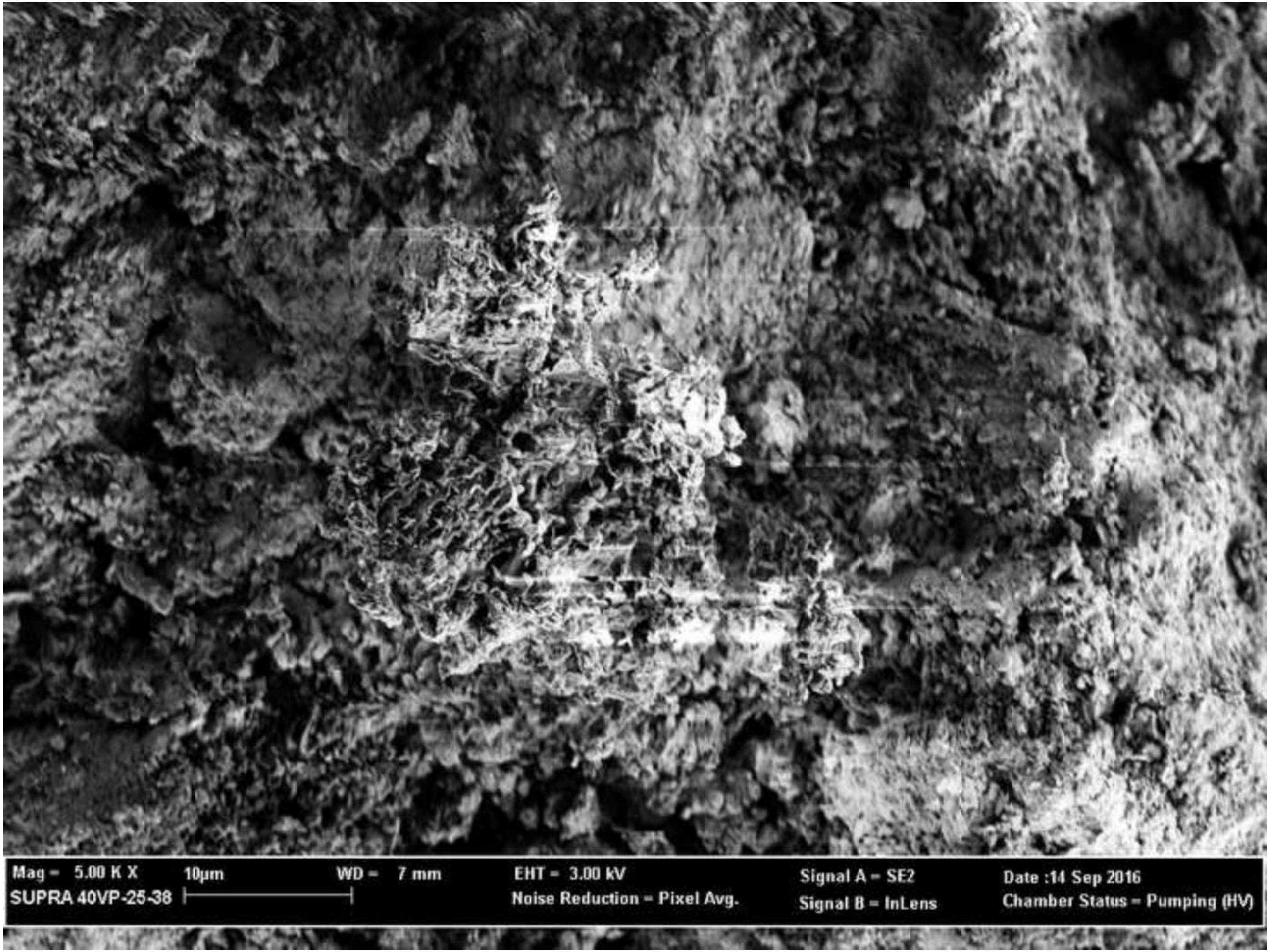
Signal B = InLens
Chamber Status = Pumping (HV)

Figure 1b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SUPRA 40VP-25-38
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Figure 2

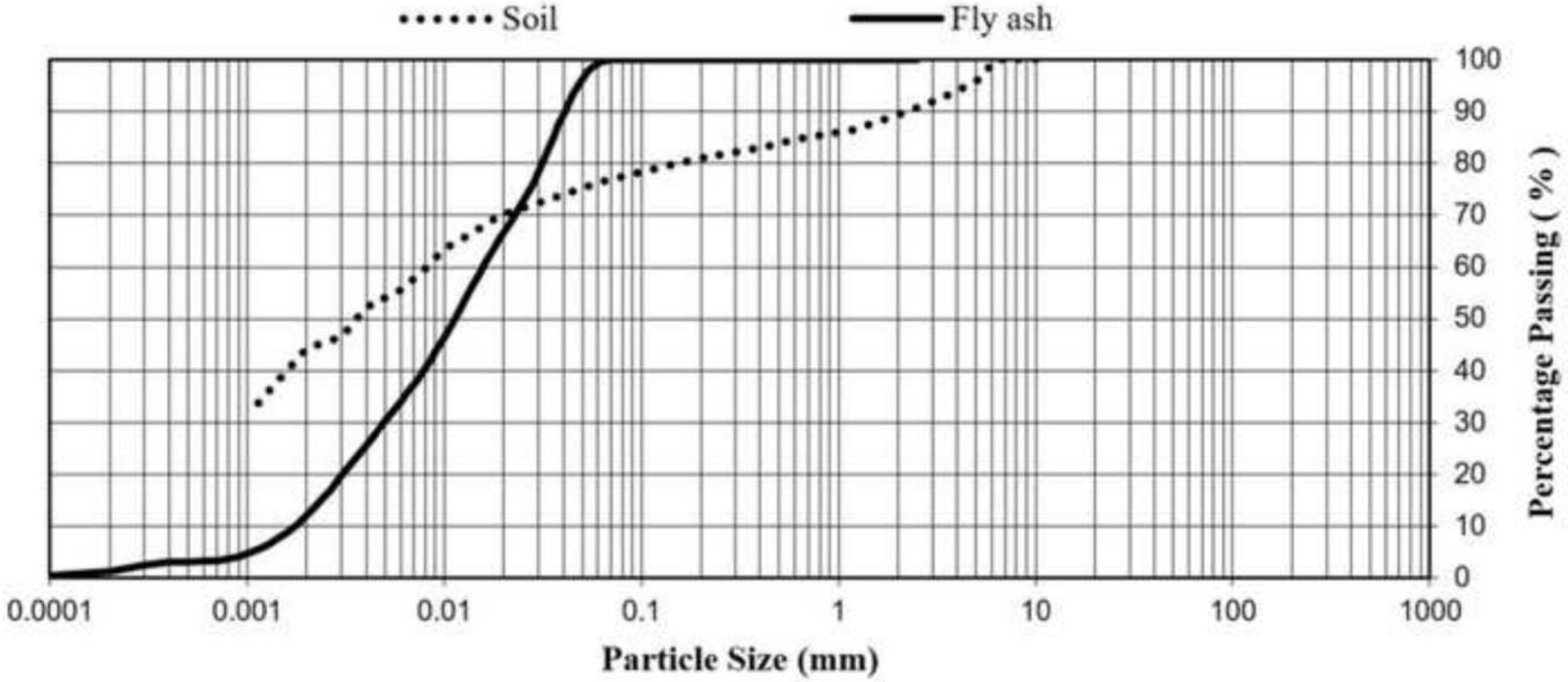

Soil
Fly ash
100
90
80
70
60
50
40
30
20
10
0
Percentage Passing (%)
0.0001
0.001
0.01
0.1
1
10
100
1000
Particle Size (mm)

Figure 3a

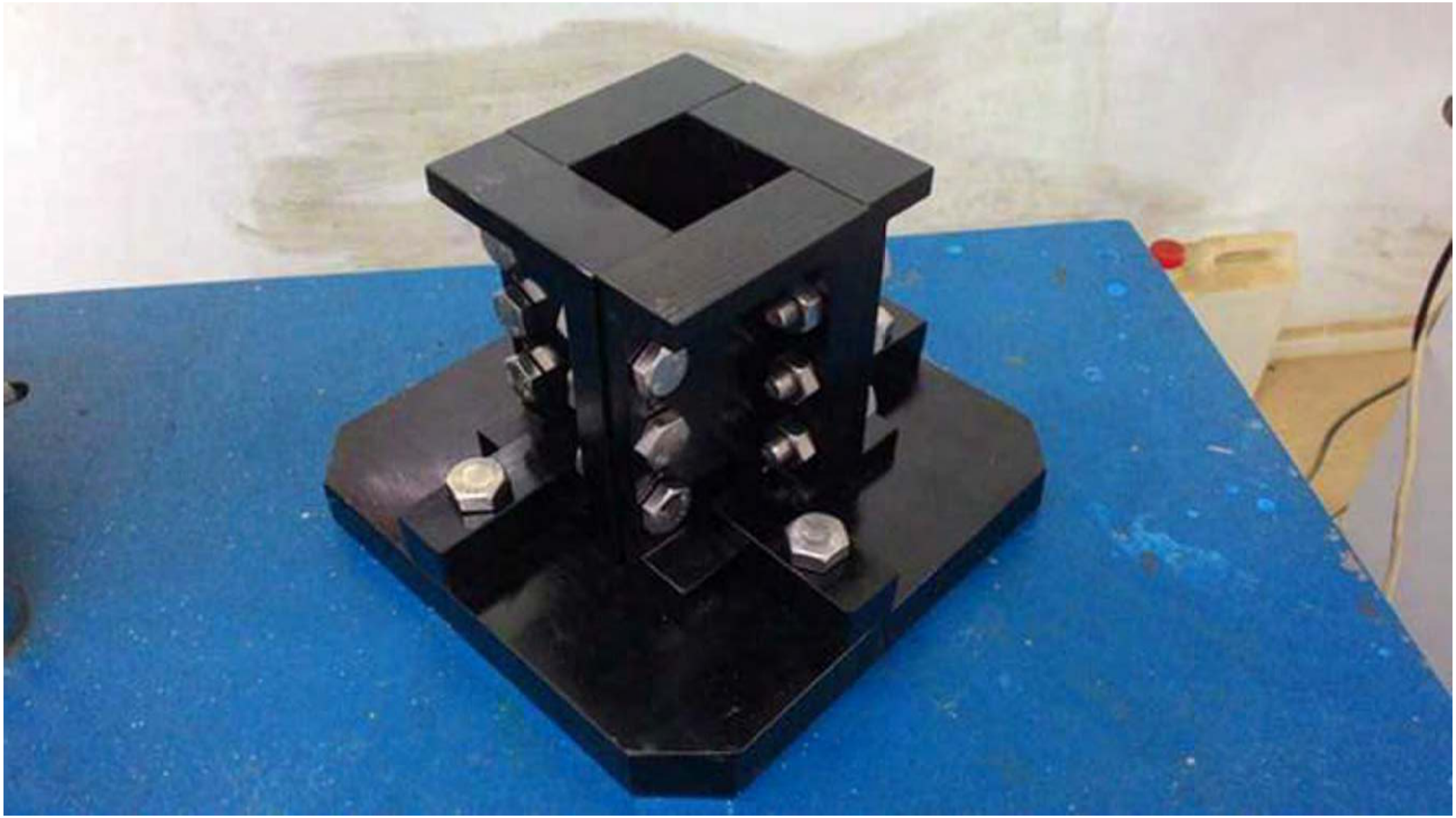


Figure 3b

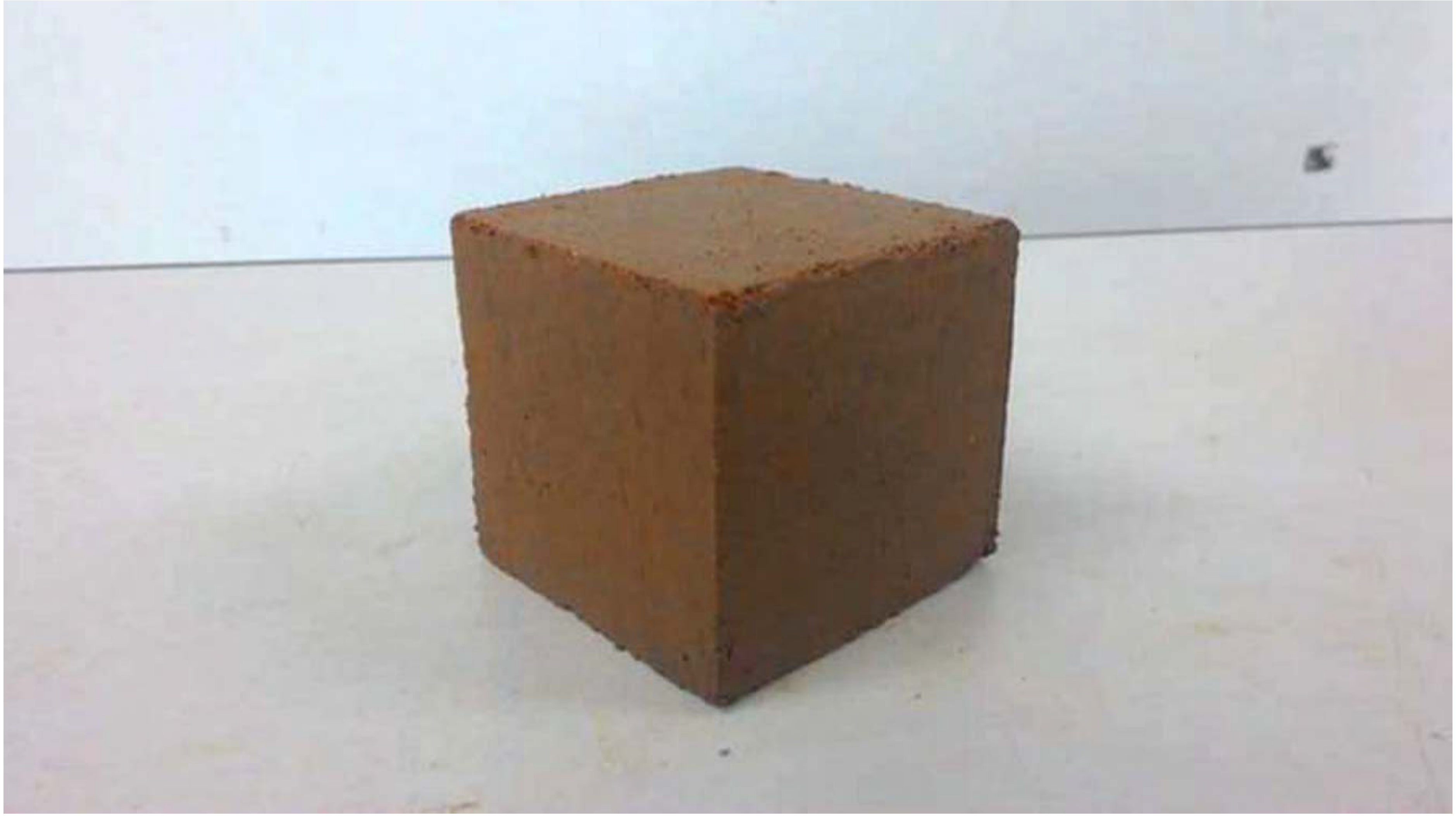


Figure 3c

Figure 4a

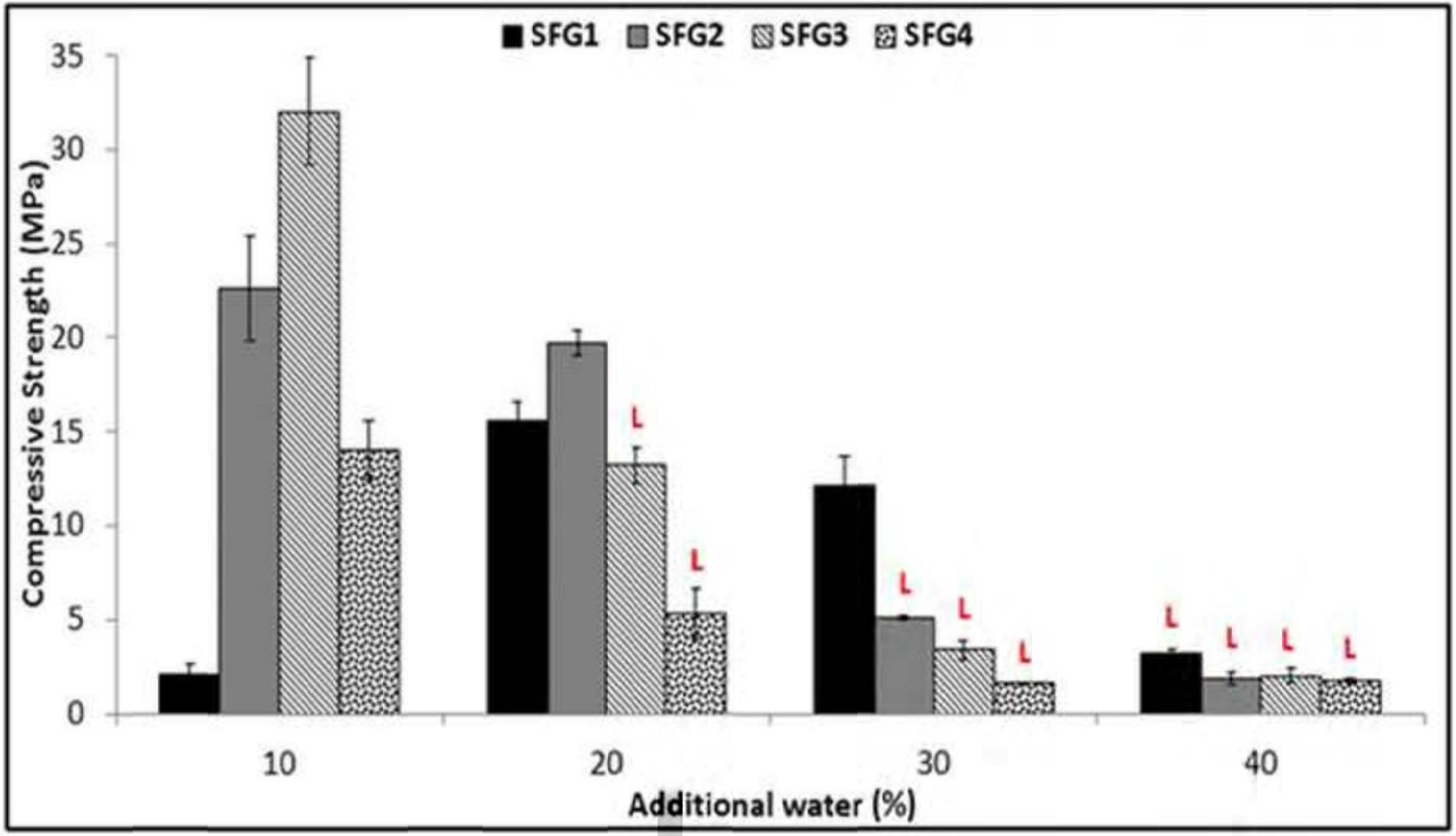

■ SFG1
▨ SFG2
▨ SFG3
▨ SFG4
Compressive Strength (MPa)
35
30
25
20
15
10
5
0
10
20
30
40
Additional water (%)
L
L
L
L
L
L
L
L
L

Figure 4b

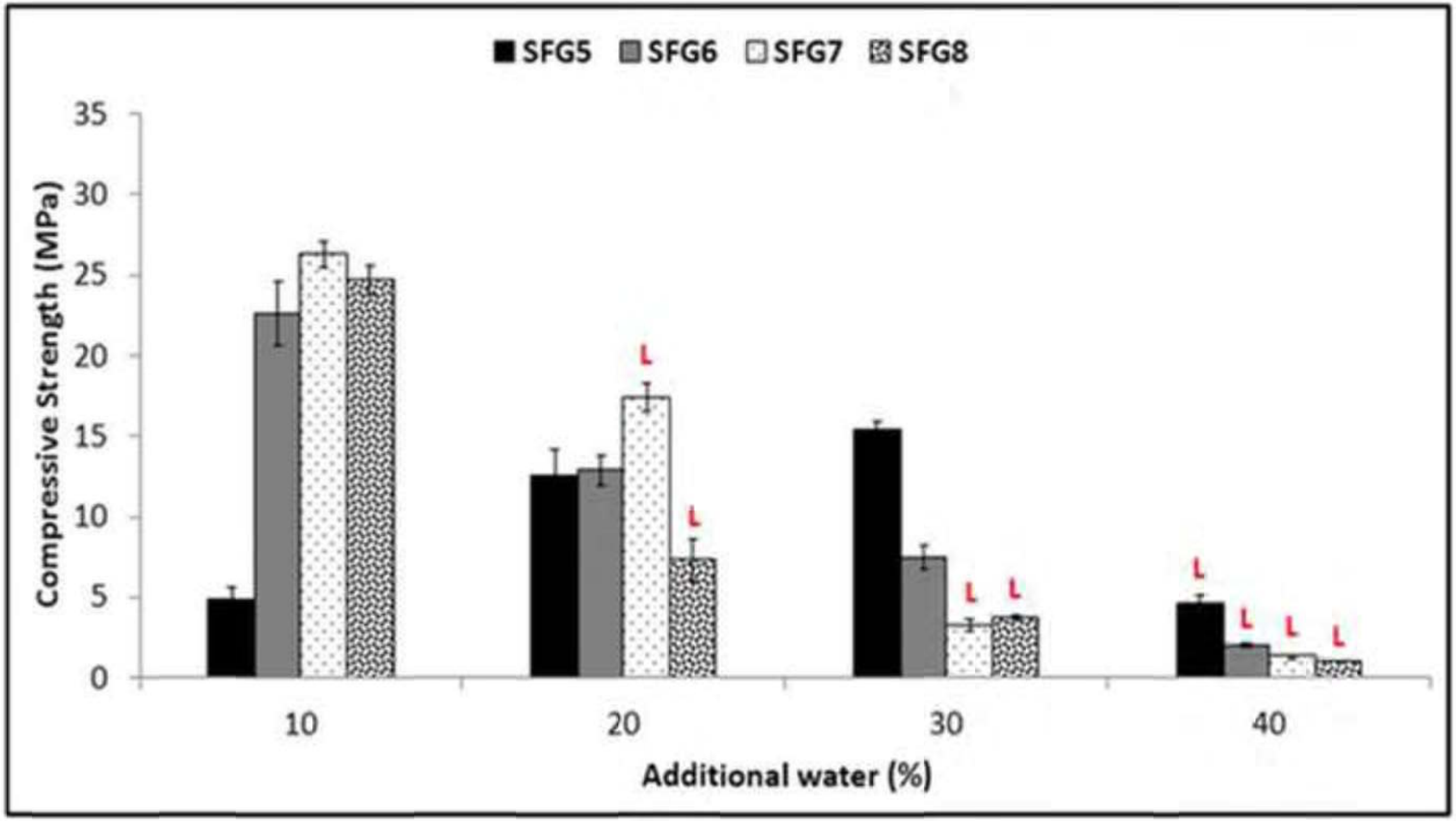

■ SFG5
▨ SFG6
☐ SFG7
▩ SFG8
Compressive Strength (MPa)
35
30
25
20
15
10
5
0
10
20
30
40
Additional water (%)
L
L
L
L
L
L
L
L

Figure 4c

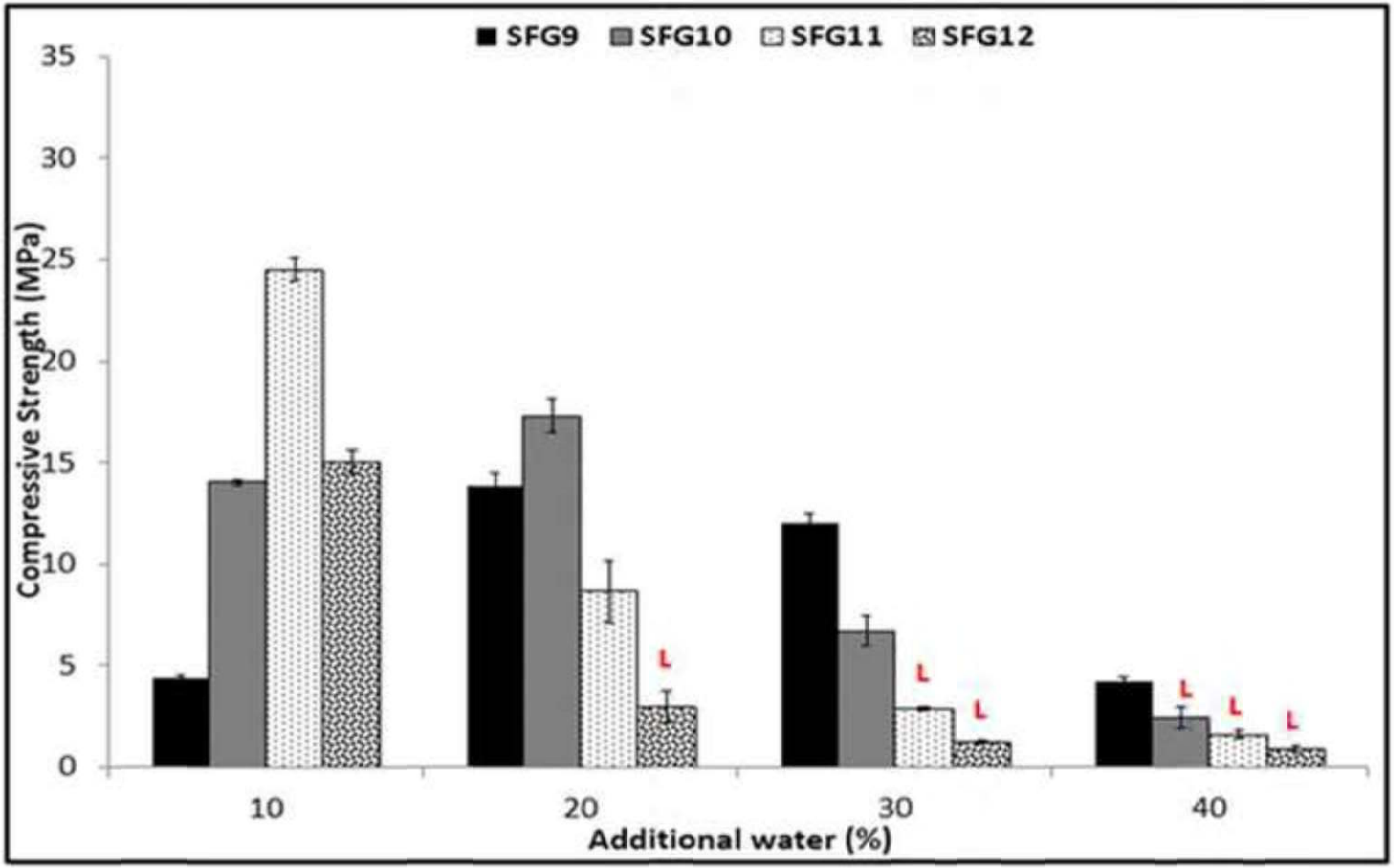

■ SFG9
▨ SFG10
☐ SFG11
▨ SFG12
Compressive Strength (MPa)
35
30
25
20
15
10
5
0
L
L
L
L
L
L
10
20
30
40
Additional water (%)

Figure 4d

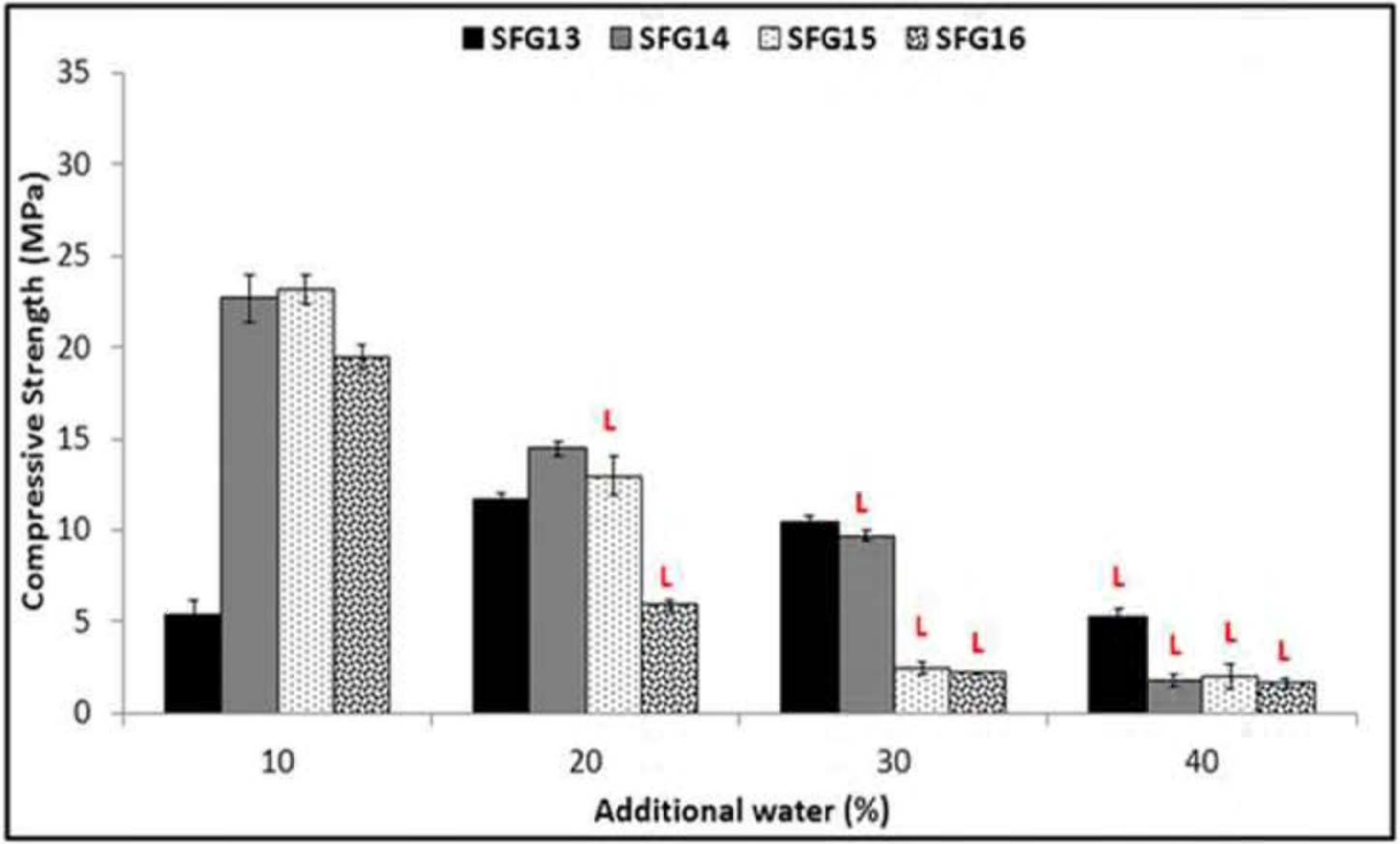

■ SFG13
▨ SFG14
☐ SFG15
▩ SFG16
Compressive Strength (MPa)
35
30
25
20
15
10
5
0
L
L
L
L
L
L
L
L
L
10
20
30
40
Additional water (%)

Figure 5a

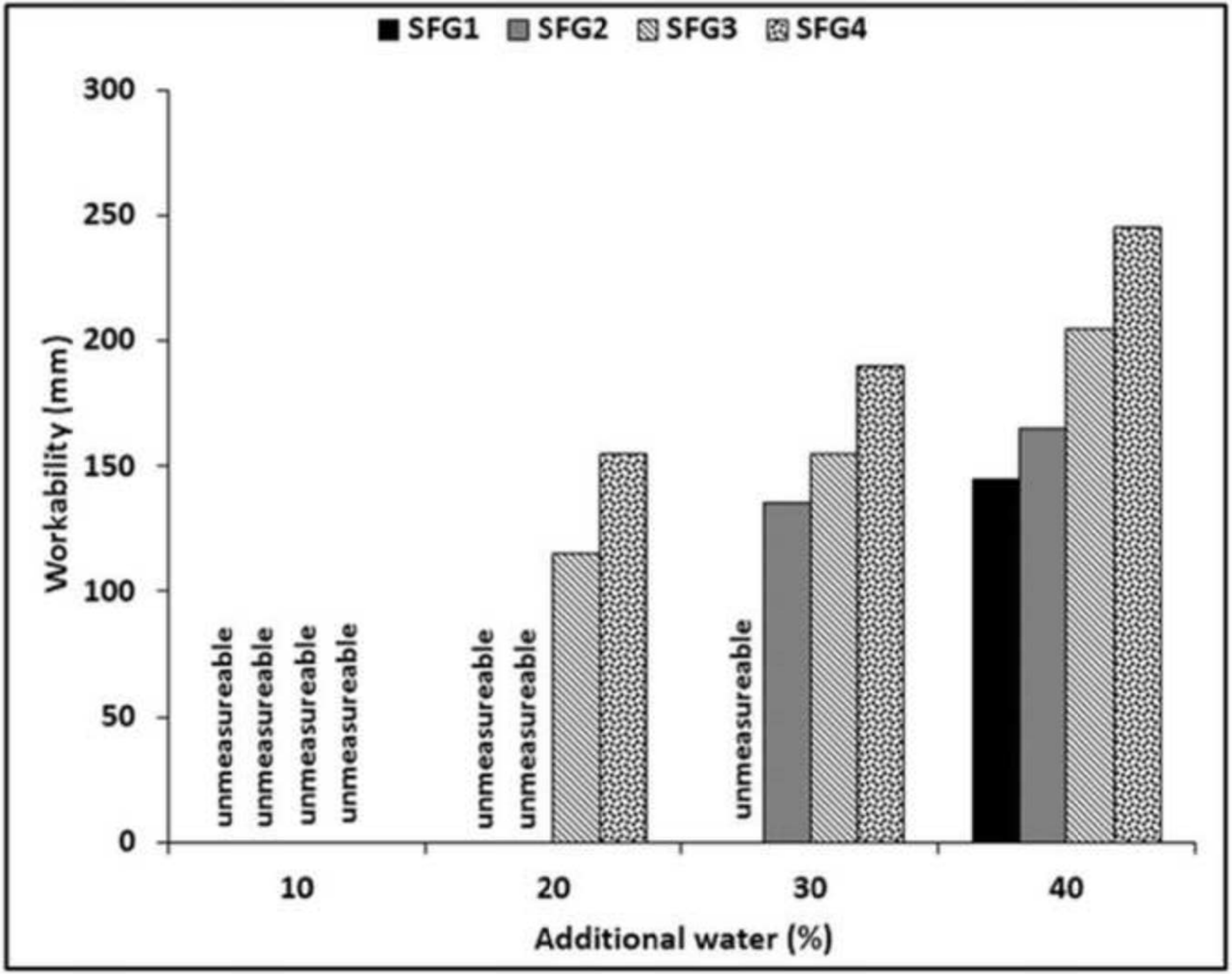

■ SFG1
▨ SFG2
▧ SFG3
▩ SFG4
Workability (mm)
300
250
200
150
100
50
0
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
10
20
30
40
Additional water (%)

Figure 5b

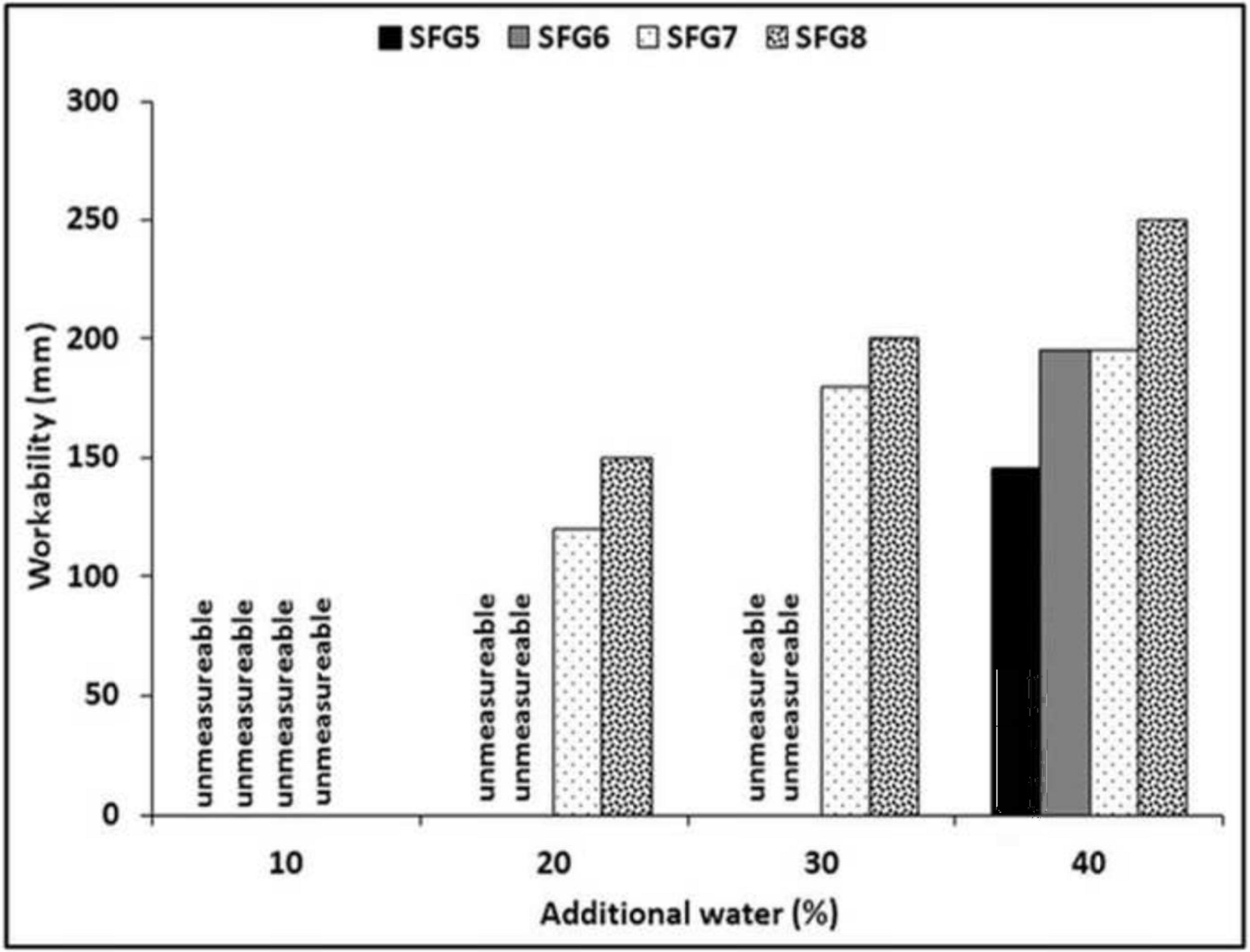

■ SFG5
▩ SFG6
☐ SFG7
▨ SFG8
Workability (mm)
300
250
200
150
100
50
0
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
10
20
30
40
Additional water (%)

Figure 5c

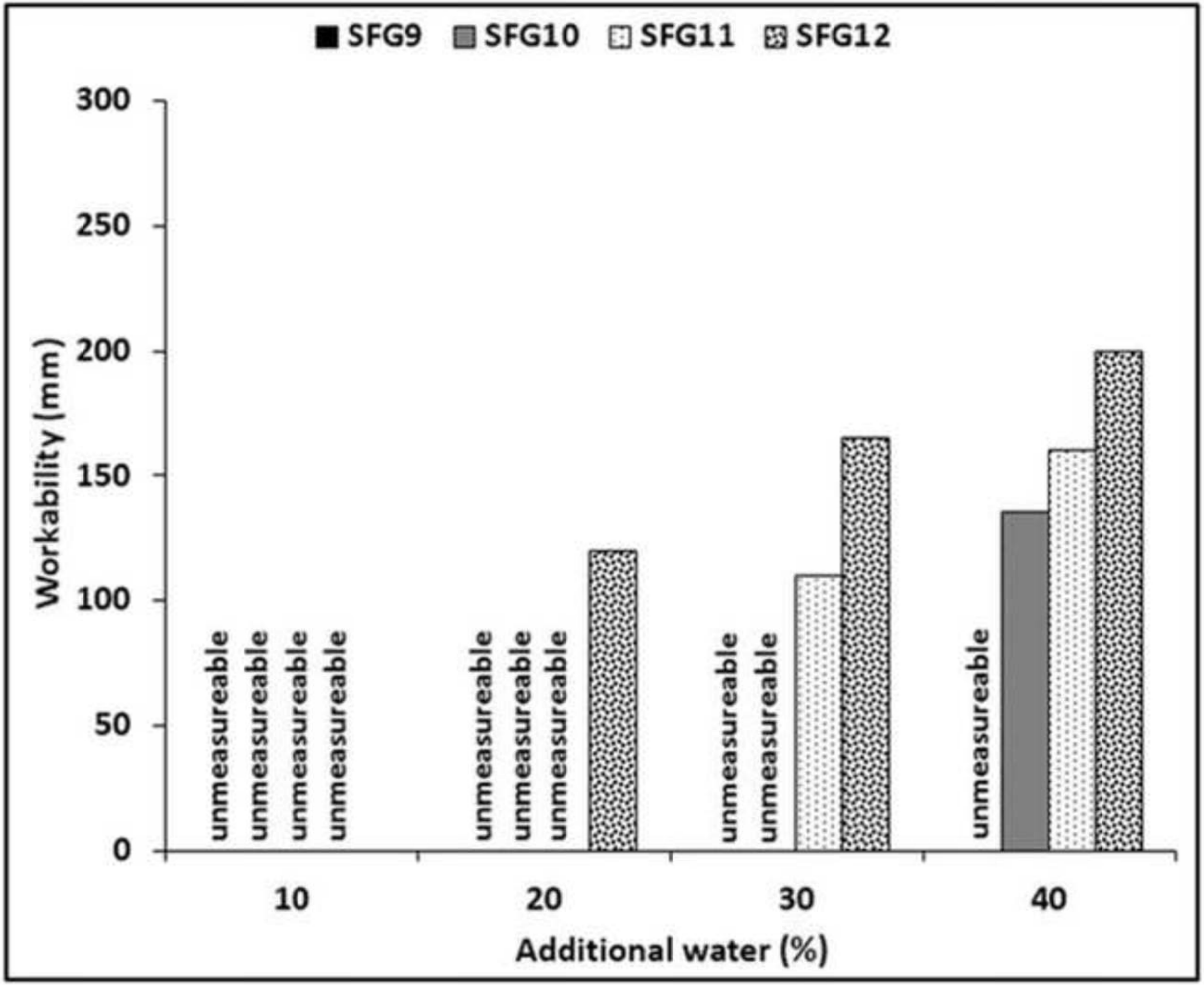

■ SFG9
▩ SFG10
⬚ SFG11
▨ SFG12
300
250
200
150
100
50
0
Workability (mm)
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
10
20
30
40
Additional water (%)

Figure 5d

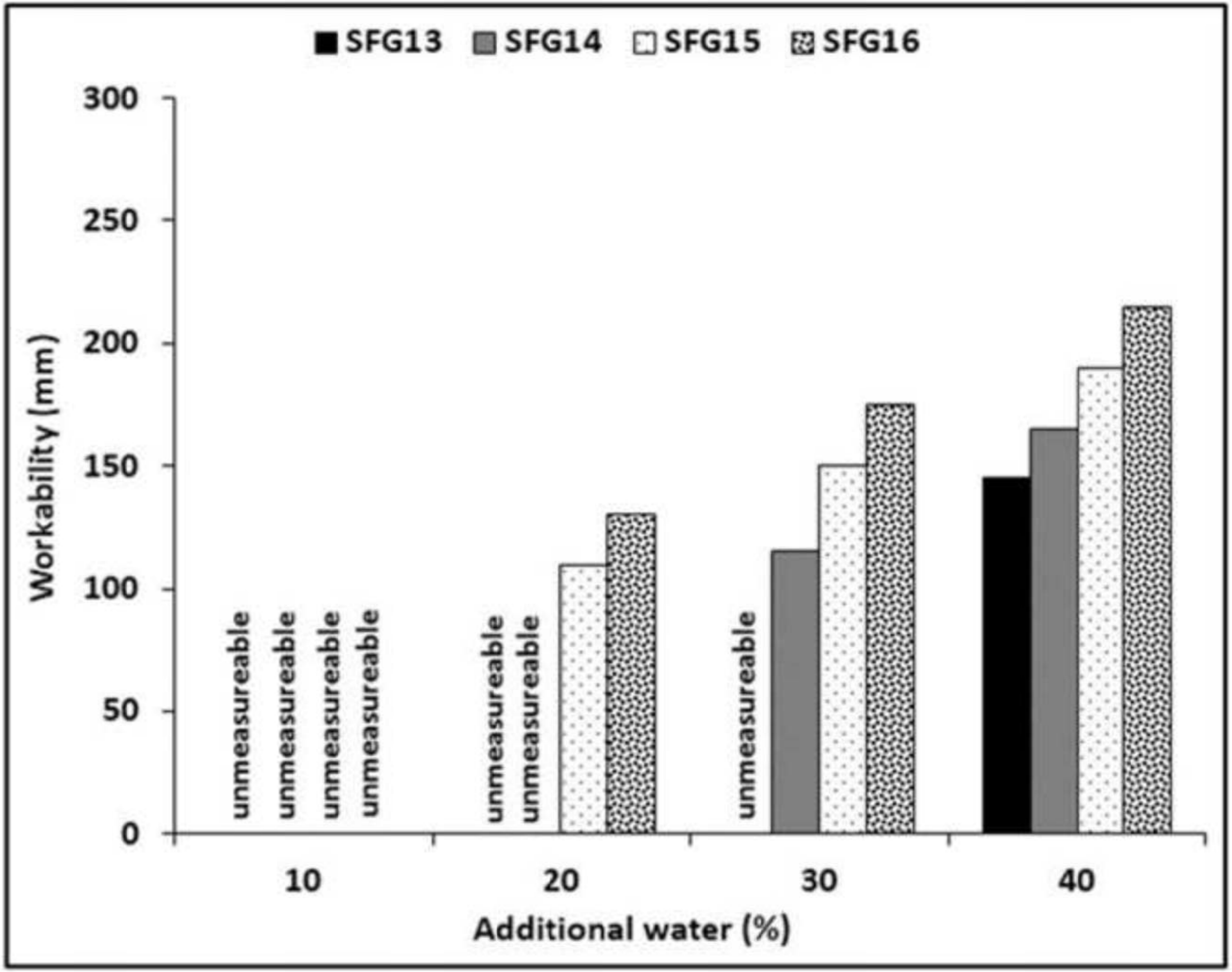

■ SFG13
▨ SFG14
☐ SFG15
▩ SFG16
Workability (mm)
300
250
200
150
100
50
0
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
unmeasureable
10
20
30
40
Additional water (%)

Figure 6a

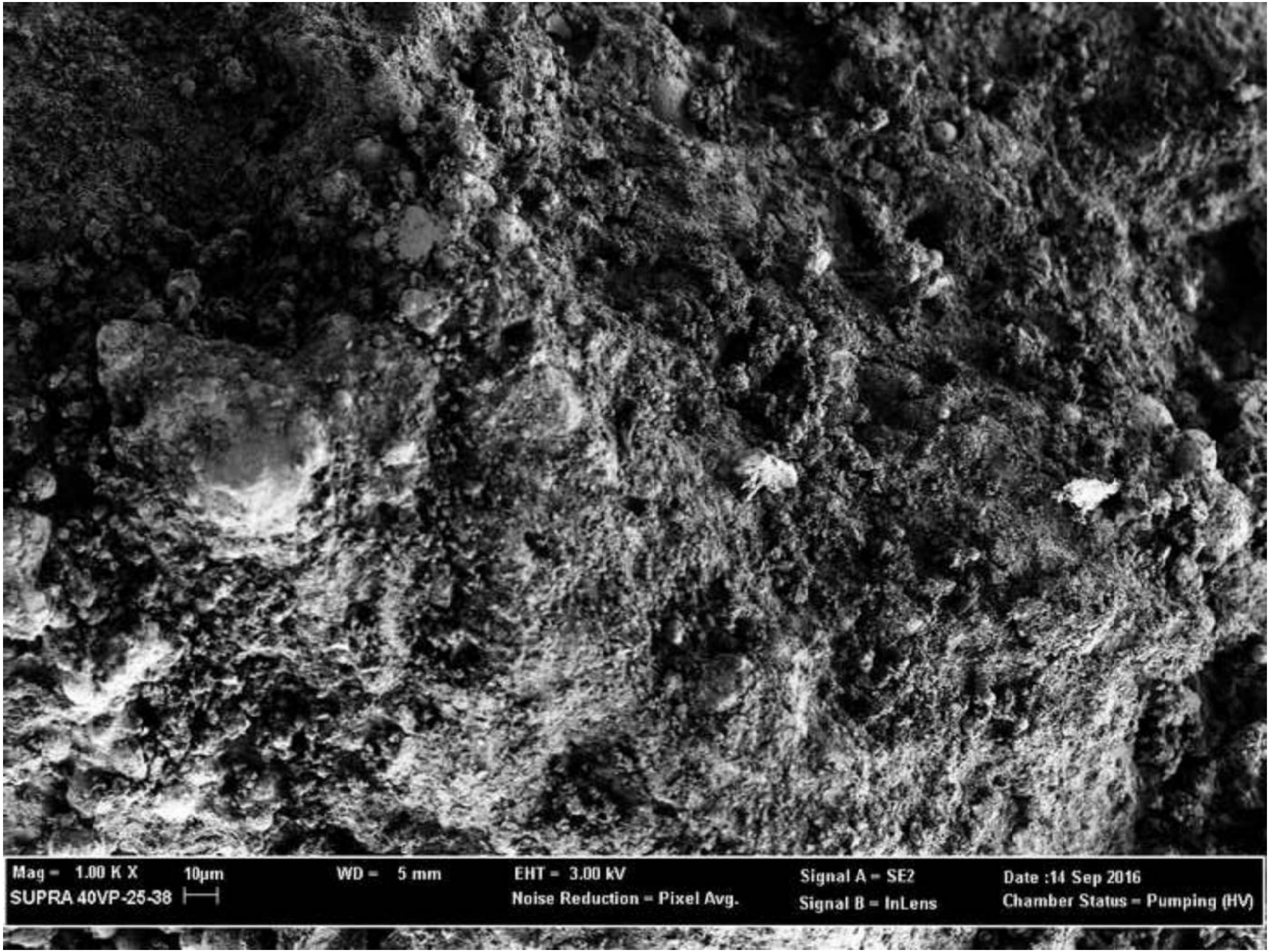

Mag = 1.00 K X
10µm
SUPRA 40VP-25-38
WD = 5 mm
EHT = 3.00 kV
Noise Reduction = Pixel Avg.
Signal A = SE2
Signal B = InLens
Date :14 Sep 2016
Chamber Status = Pumping (HV)

Figure 6b

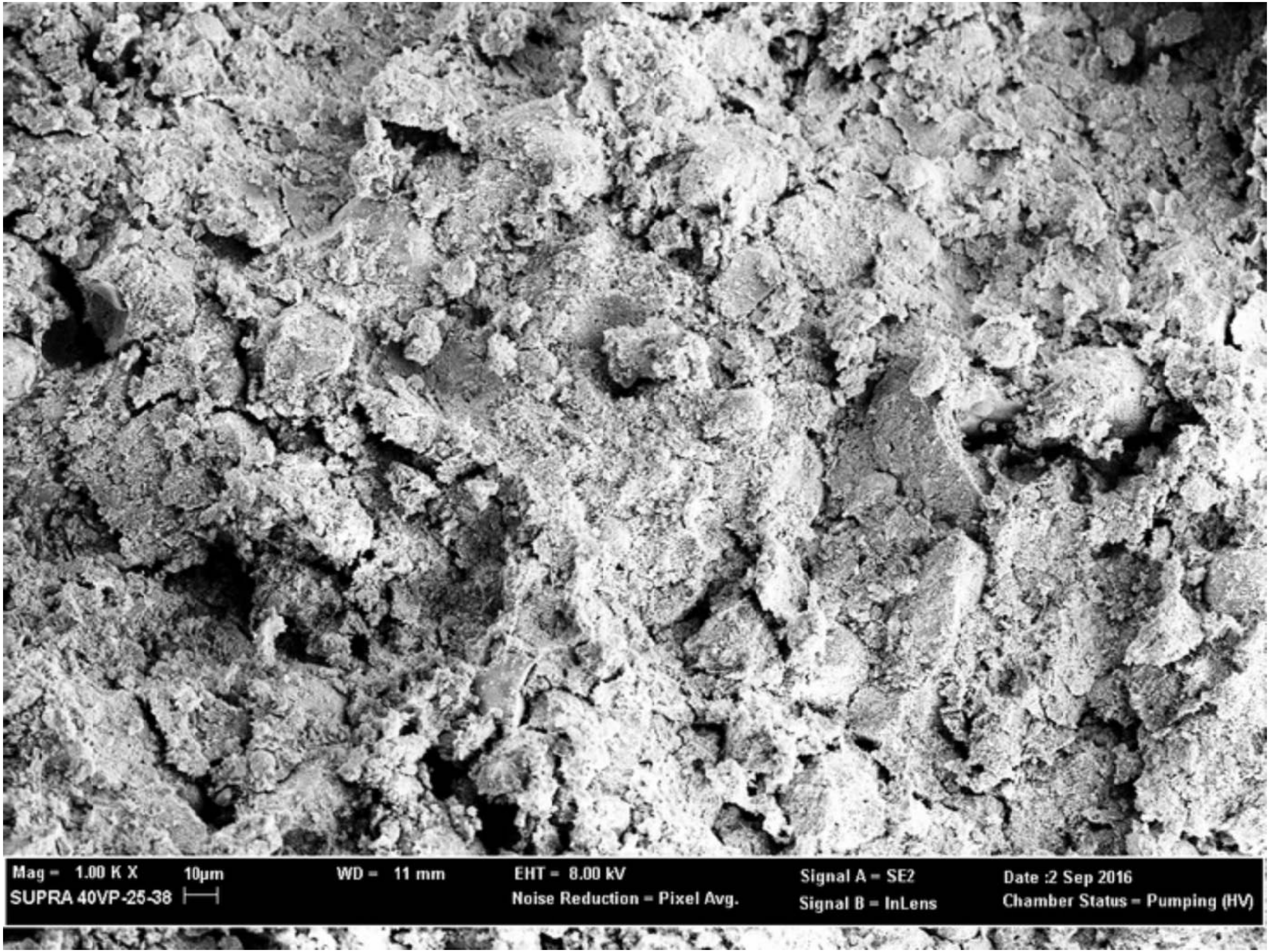

Mag = 1.00 K X
10µm
SUPRA 40VP-25-38
WD = 11 mm
EHT = 8.00 kV
Noise Reduction = Pixel Avg.
Signal A = SE2
Signal B = InLens
Date :2 Sep 2016
Chamber Status = Pumping (HV)

Figure 6c

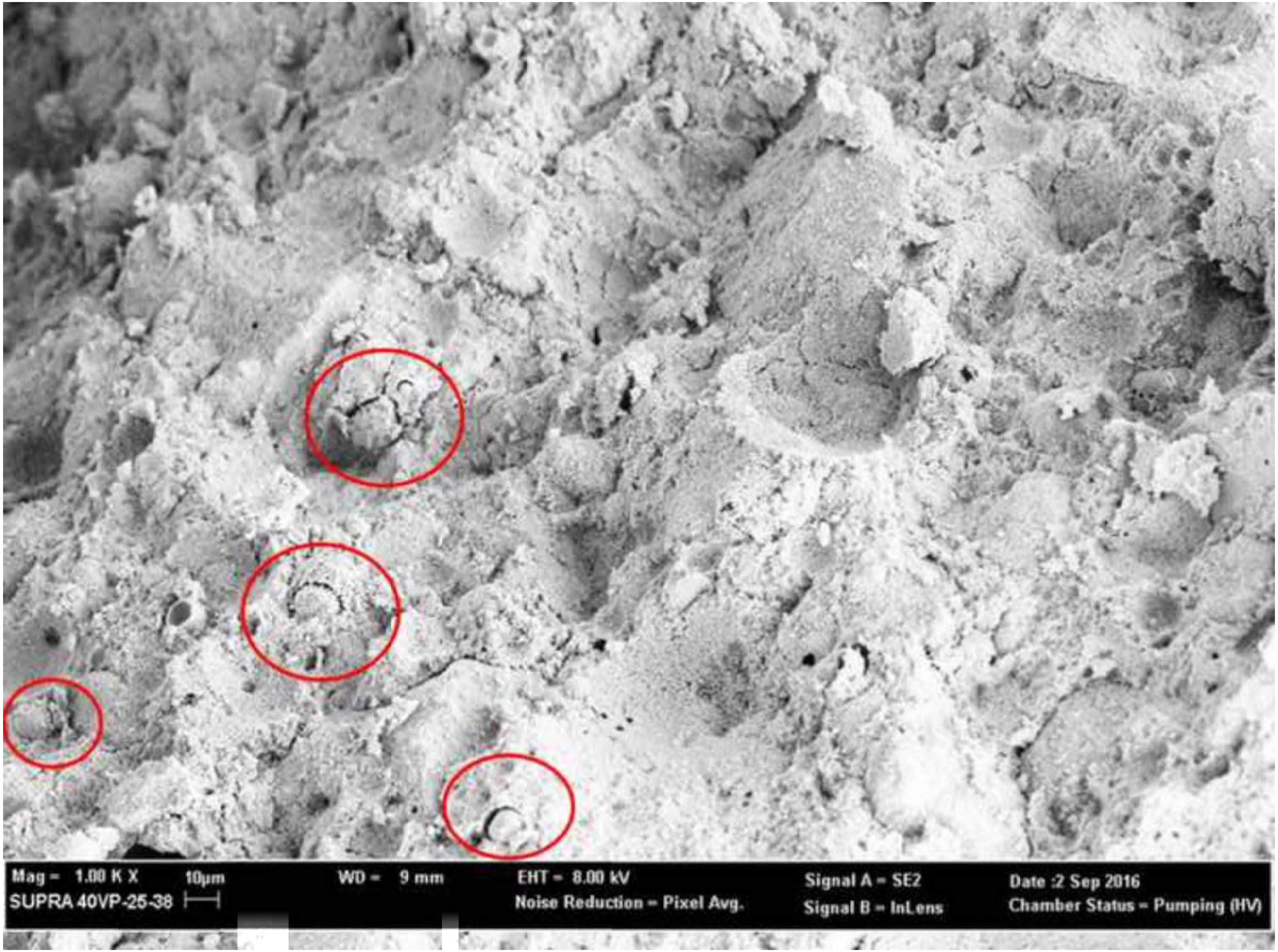

Mag = 1.00 K X
10µm
SUPRA 40VP-25-38
WD = 9 mm
EHT = 8.00 kV
Noise Reduction = Pixel Avg.
Signal A = SE2
Signal B = InLens
Date :2 Sep 2016
Chamber Status = Pumping (HV)

Figure 6d

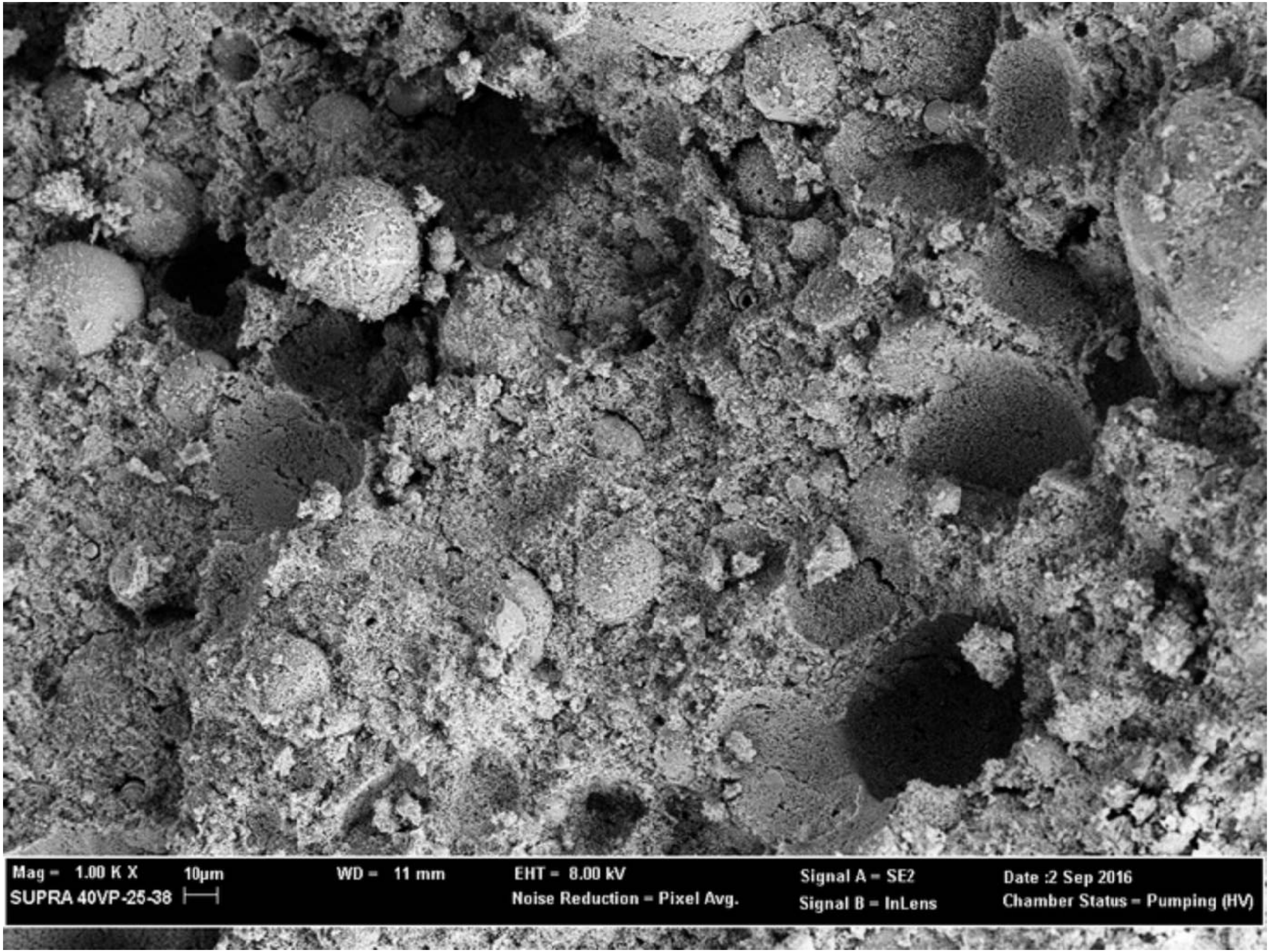

Mag = 1.00 K X
10μm
SUPRA 40VP-25-38
WD = 11 mm
EHT = 8.00 kV
Noise Reduction = Pixel Avg.
Signal A = SE2
Signal B = InLens
Date :2 Sep 2016
Chamber Status = Pumping (HV)

Figure 7

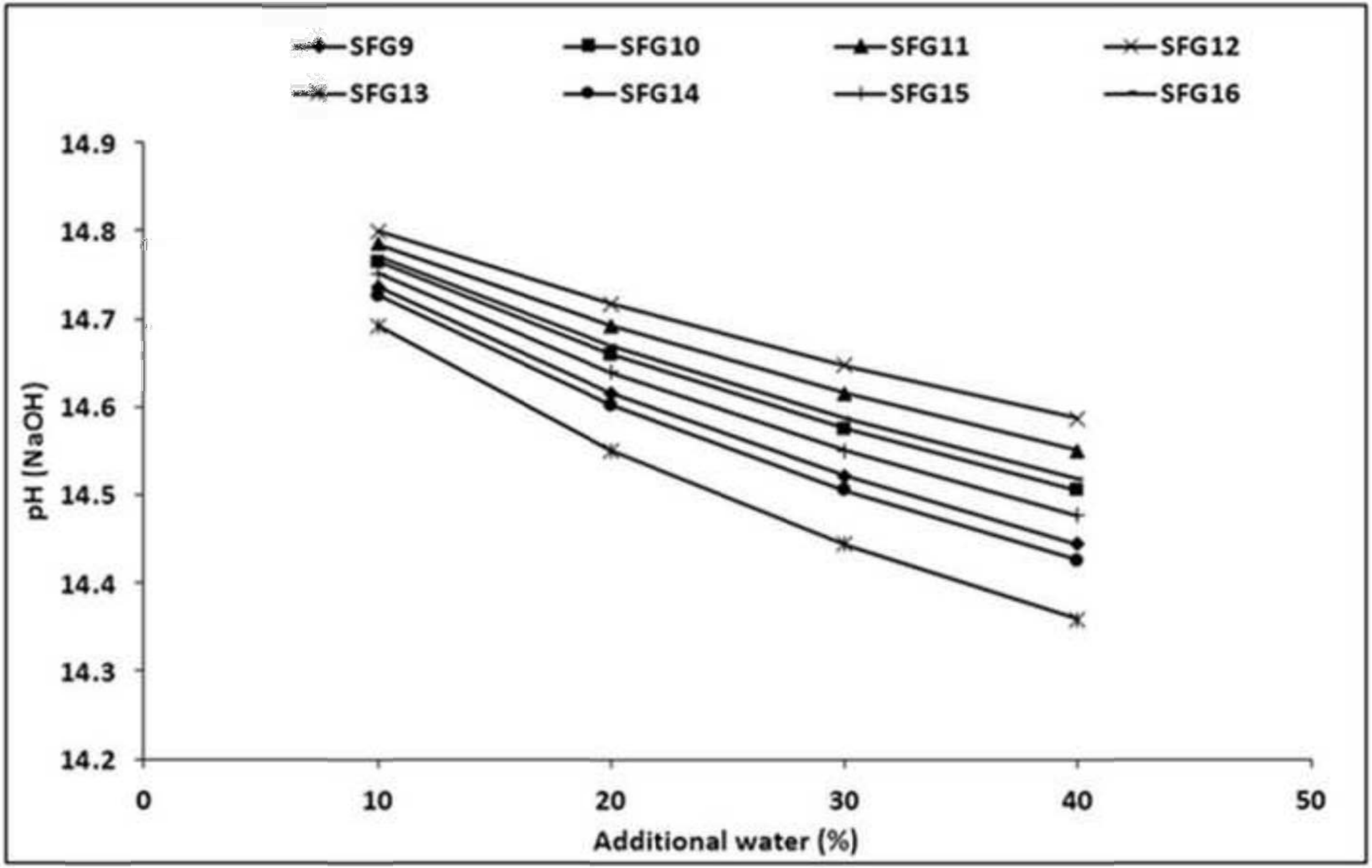

SFG9
SFG10
SFG11
SFG12
SFG13
SFG14
SFG15
SFG16
pH (NaOH)
14.9
14.8
14.7
14.6
14.5
14.4
14.3
14.2
0
10
20
30
40
50
Additional water (%)

Figure 8

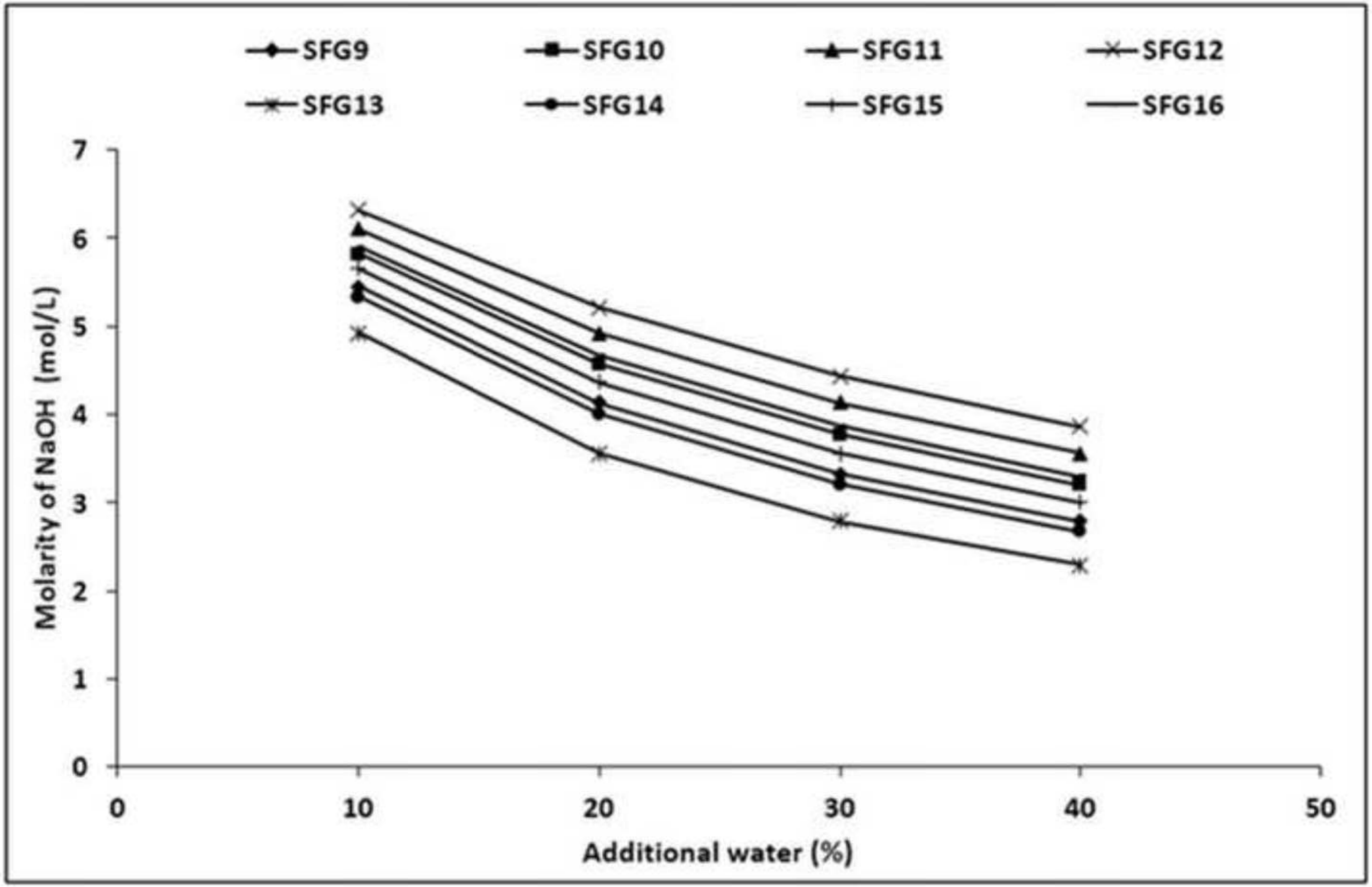

SFG9
SFG10
SFG11
SFG12
SFG13
SFG14
SFG15
SFG16
Molarity of NaOH (mol/L)
0
1
2
3
4
5
6
7
0
10
20
30
40
50
Additional water (%)

Figure 9a

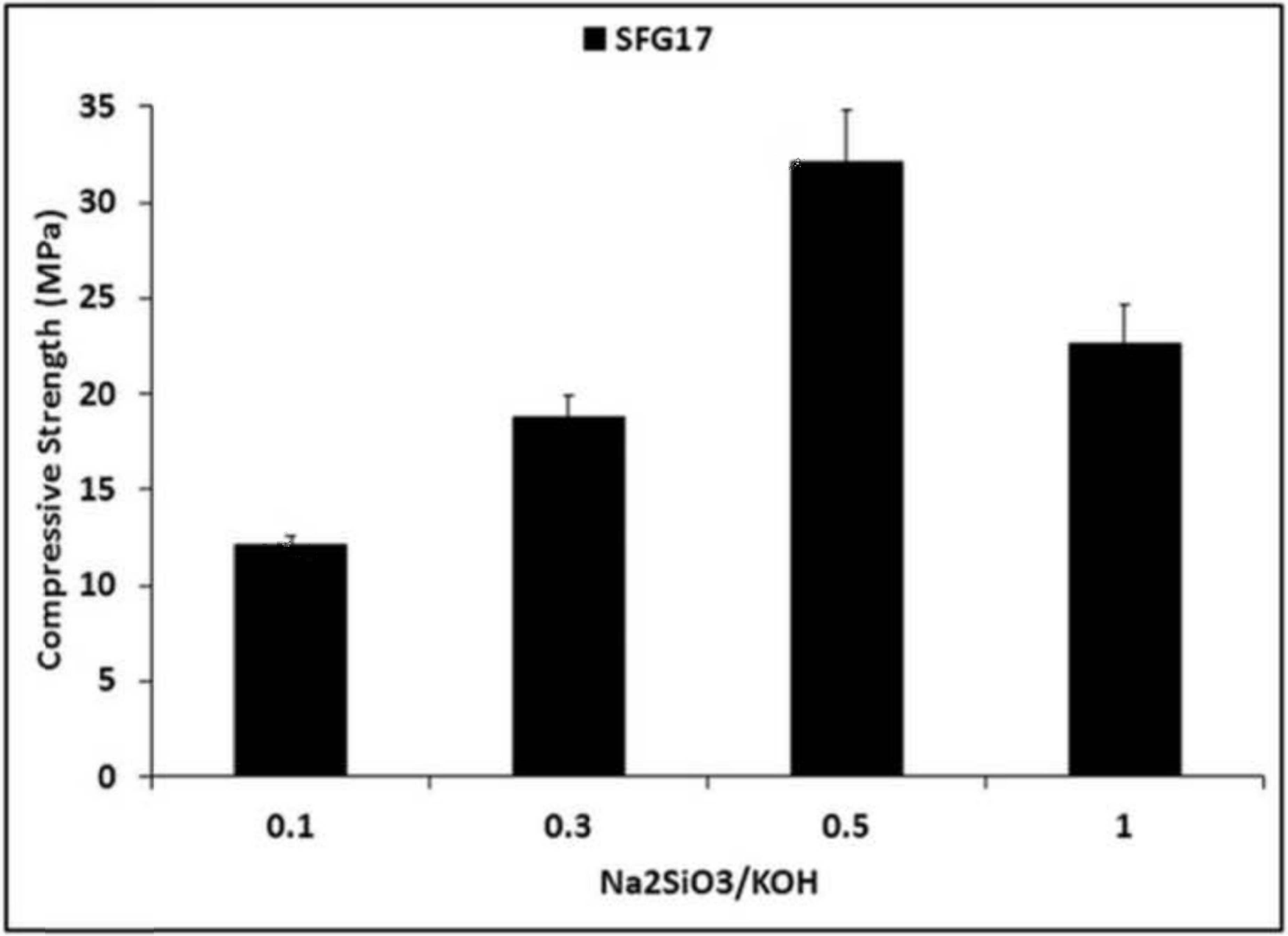

■ SFG17
Compressive Strength (MPa)
35
30
25
20
15
10
5
0
0.1
0.3
0.5
1
Na2SiO3/KOH

Figure 9b

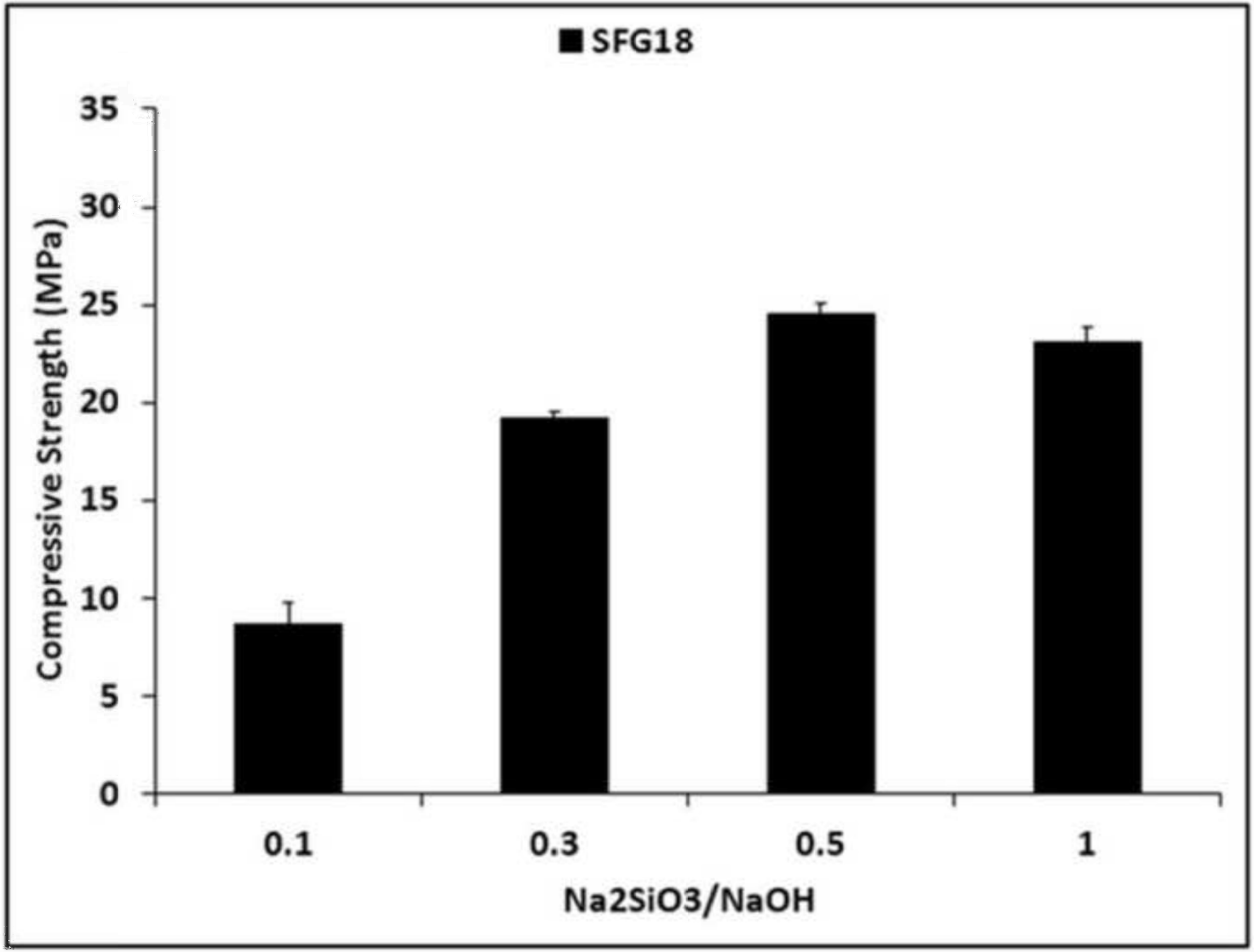

■ SFG18
Compressive Strength (MPa)
35
30
25
20
15
10
5
0
0.1
0.3
0.5
1
Na2SiO3/NaOH

Figure 10a

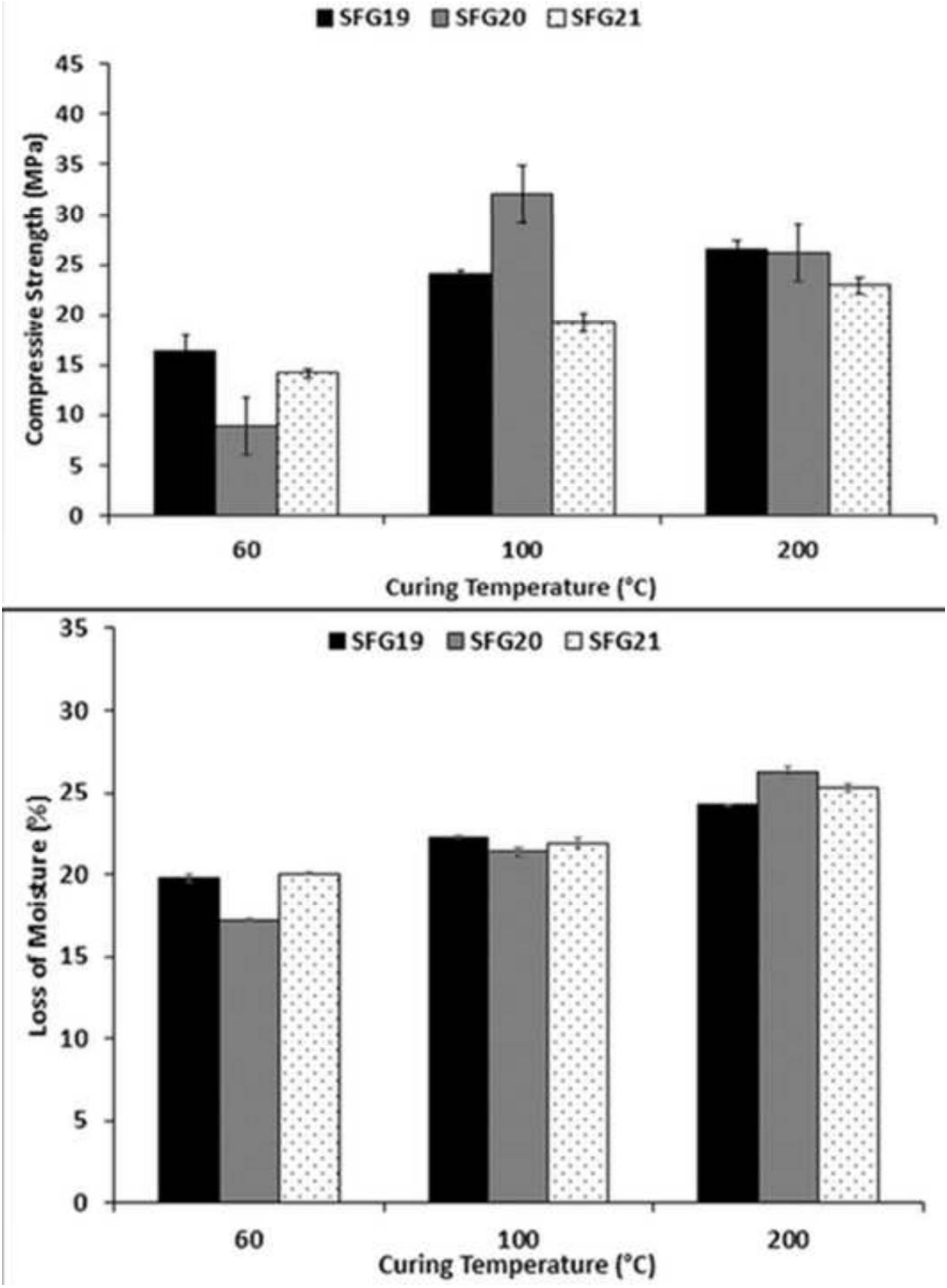

■ SFG19 ▨ SFG20 ☐ SFG21
Compressive Strength (MPa)
0
5
10
15
20
25
30
35
40
45
60
100
200
Curing Temperature (°C)
■ SFG19 ▨ SFG20 ☐ SFG21
Loss of Moisture (%)
0
5
10
15
20
25
30
35
60
100
200
Curing Temperature (°C)

Figure 10b

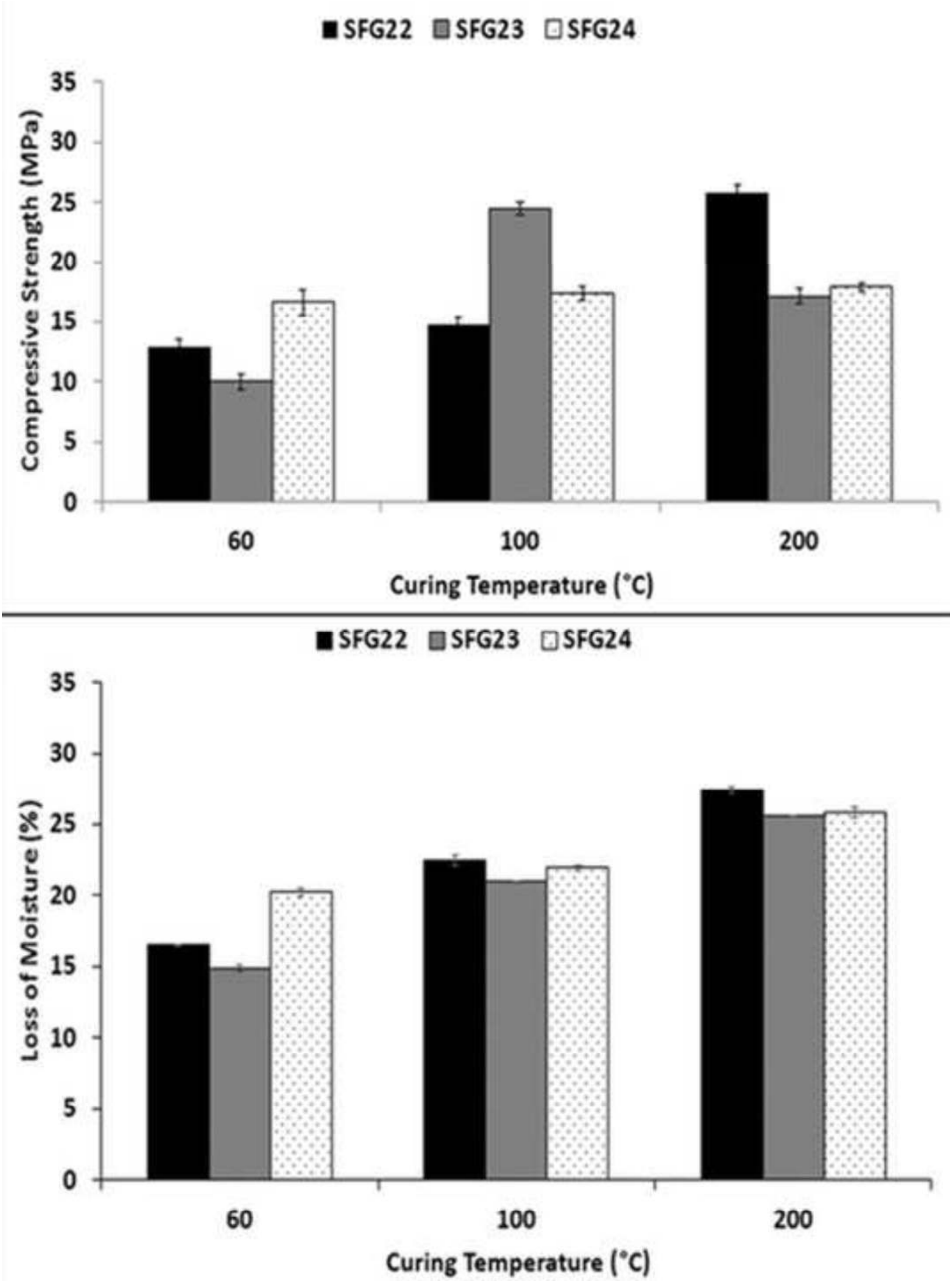

■ SFG22 ▨ SFG23 ☐ SFG24
Compressive Strength (MPa)
35
30
25
20
15
10
5
0
60
100
200
Curing Temperature (°C)
■ SFG22 ▨ SFG23 ☐ SFG24
Loss of Moisture (%)
35
30
25
20
15
10
5
0
60
100
200
Curing Temperature (°C)

Figure 11a

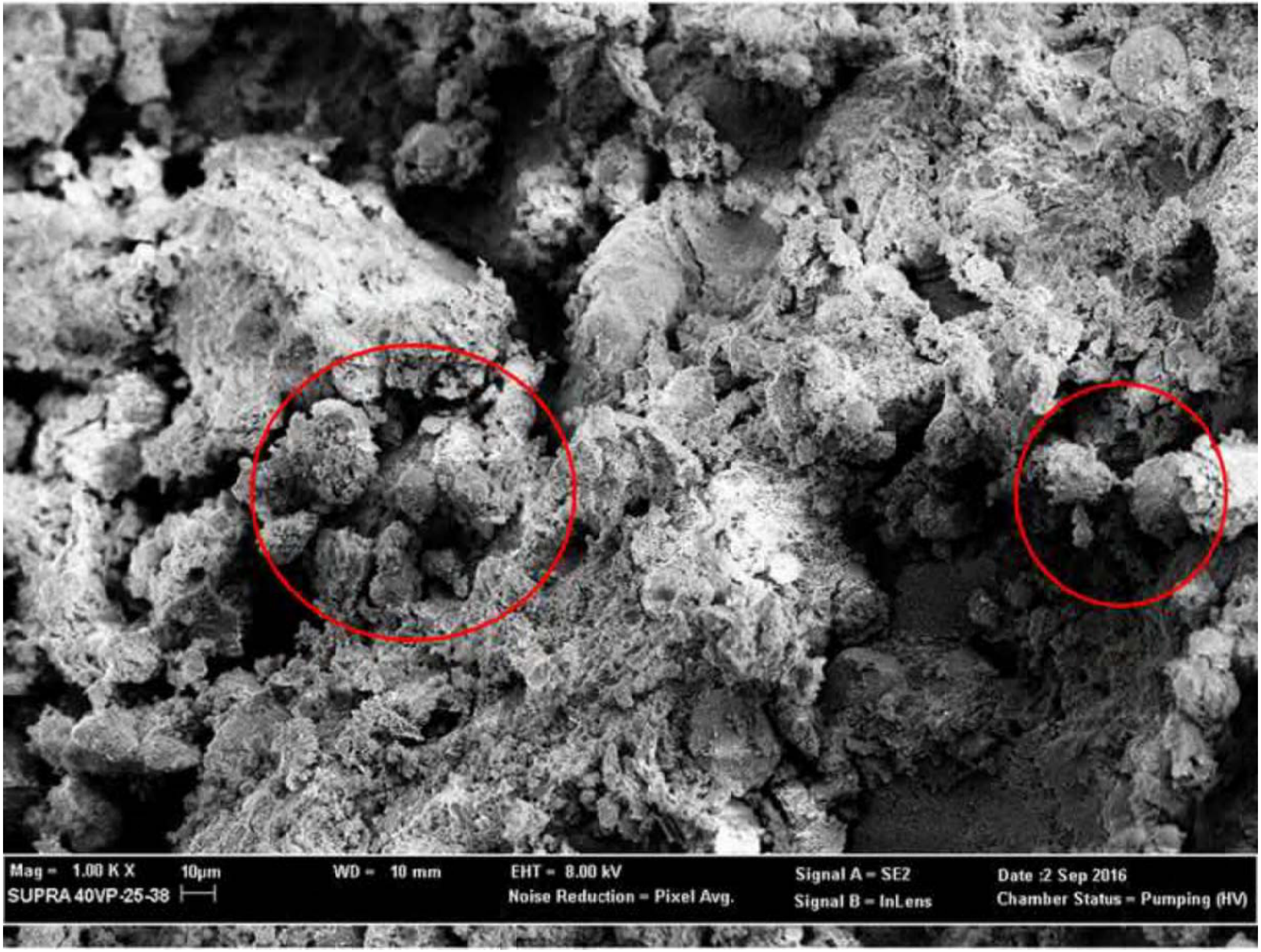

Mag = 1.00 K X
10µm
SUPRA 40VP-25-38
WD = 10 mm
EHT = 8.00 kV
Noise Reduction = Pixel Avg.
Signal A = SE2
Signal B = InLens
Date :2 Sep 2016
Chamber Status = Pumping (HV)

Figure 11b

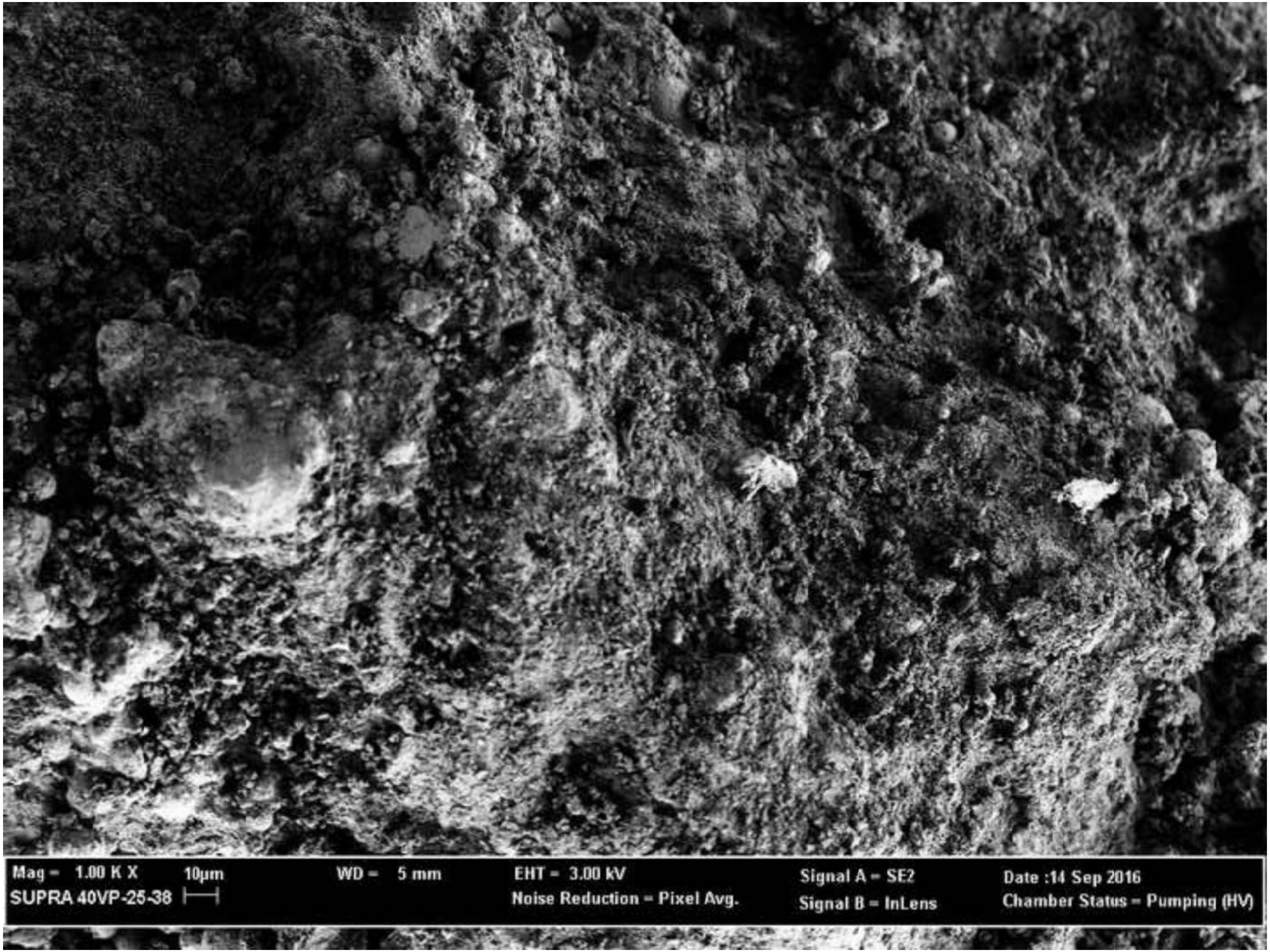

Mag = 1.00 K X
10µm
SUPRA 40VP-25-38
WD = 5 mm
EHT = 3.00 kV
Noise Reduction = Pixel Avg.
Signal A = SE2
Signal B = InLens
Date :14 Sep 2016
Chamber Status = Pumping (HV)

Figure 11c

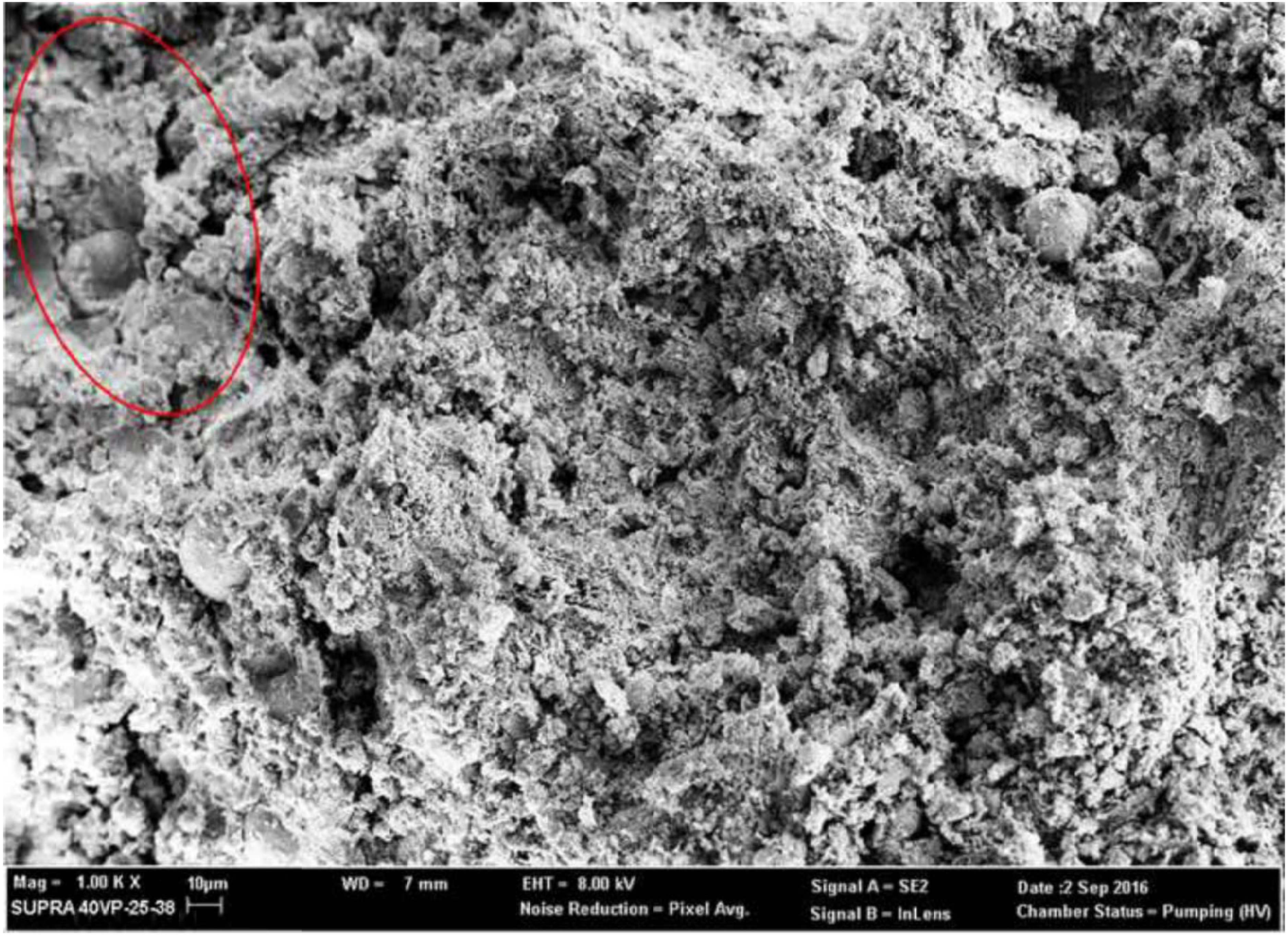

Mag = 1.00 K X
10µm
SUPRA 40VP-25-38
WD = 7 mm
EHT = 8.00 kV
Noise Reduction = Pixel Avg.
Signal A = SE2
Signal B = InLens
Date :2 Sep 2016
Chamber Status = Pumping (HV)

Figure 12

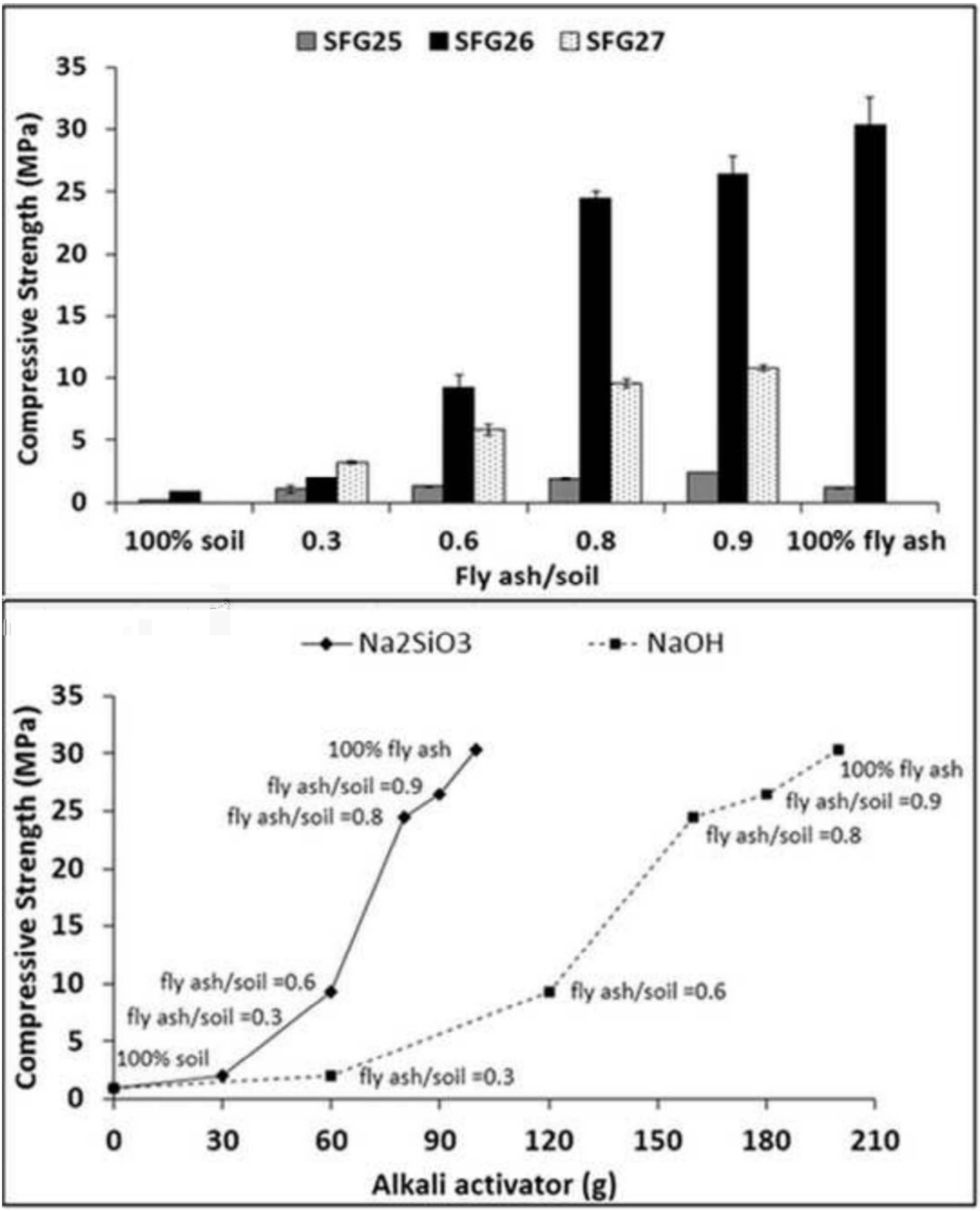

SFG25
SFG26
SFG27
Compressive Strength (MPa)
35
30
25
20
15
10
5
0
100% soil
0.3
0.6
0.8
0.9
100% fly ash
Fly ash/soil
Na2SiO3
NaOH
Compressive Strength (MPa)
100% fly ash
fly ash/soil =0.9
fly ash/soil =0.8
fly ash/soil =0.6
fly ash/soil =0.3
100% soil
100% fly ash
fly ash/soil =0.9
fly ash/soil =0.8
fly ash/soil =0.6
fly ash/soil =0.3
0
30
60
90
120
150
180
210
Alkali activator (g)

Figure 13a

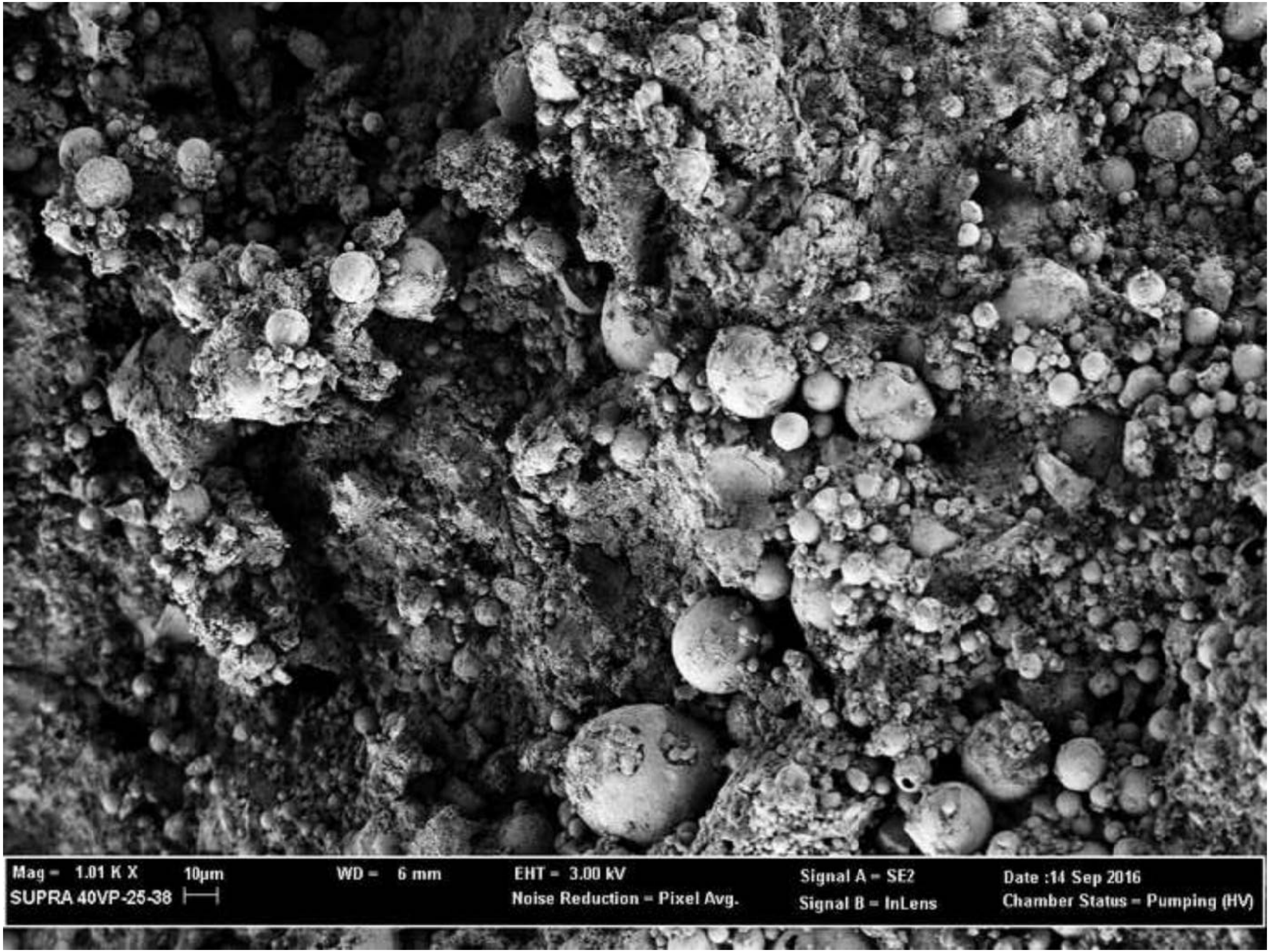

Mag = 1.01 K X
10μm
SUPRA 40VP-25-38
WD = 6 mm
EHT = 3.00 kV
Noise Reduction = Pixel Avg.
Signal A = SE2
Signal B = InLens
Date :14 Sep 2016
Chamber Status = Pumping (HV)

Figure 13b

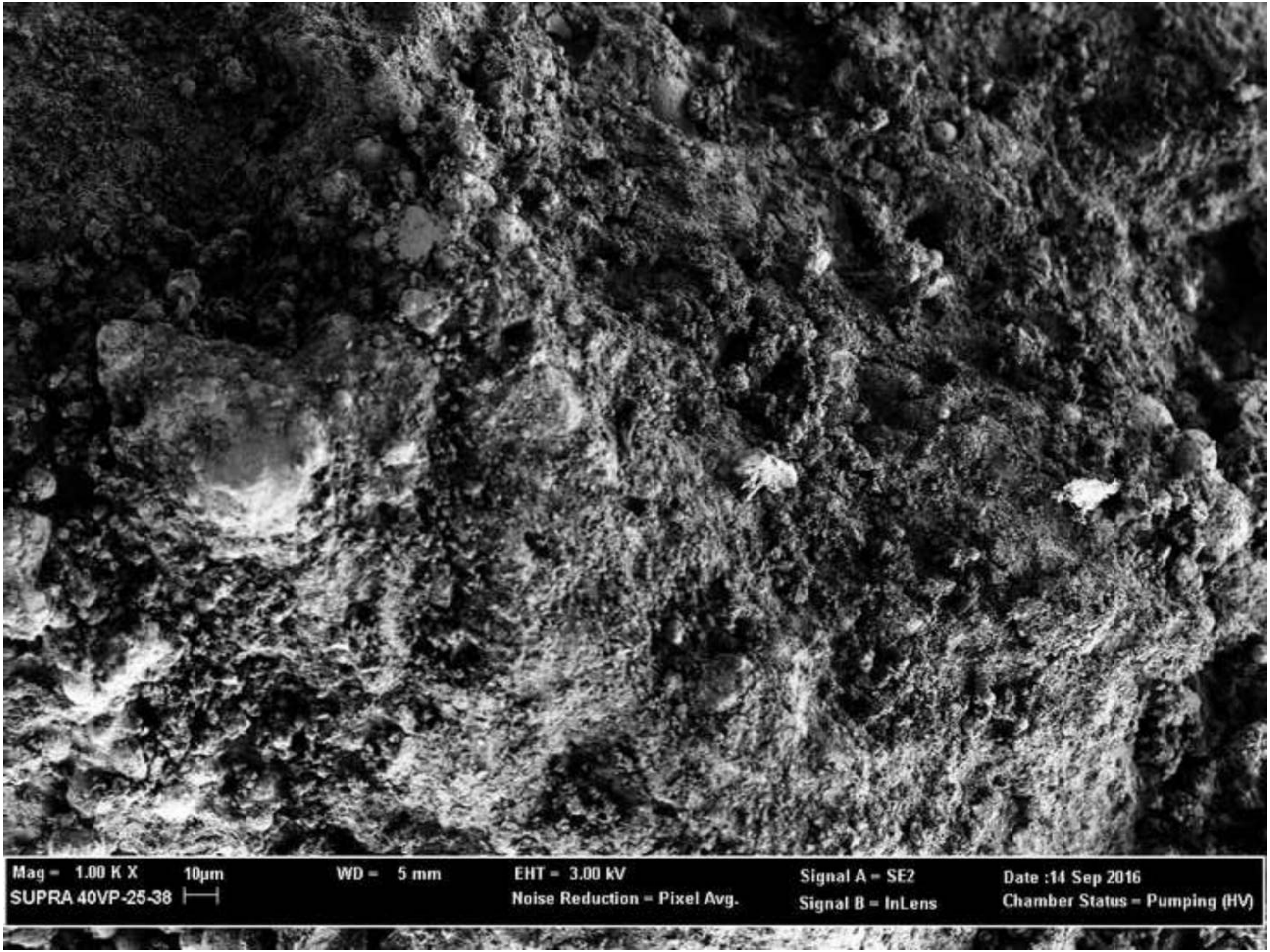
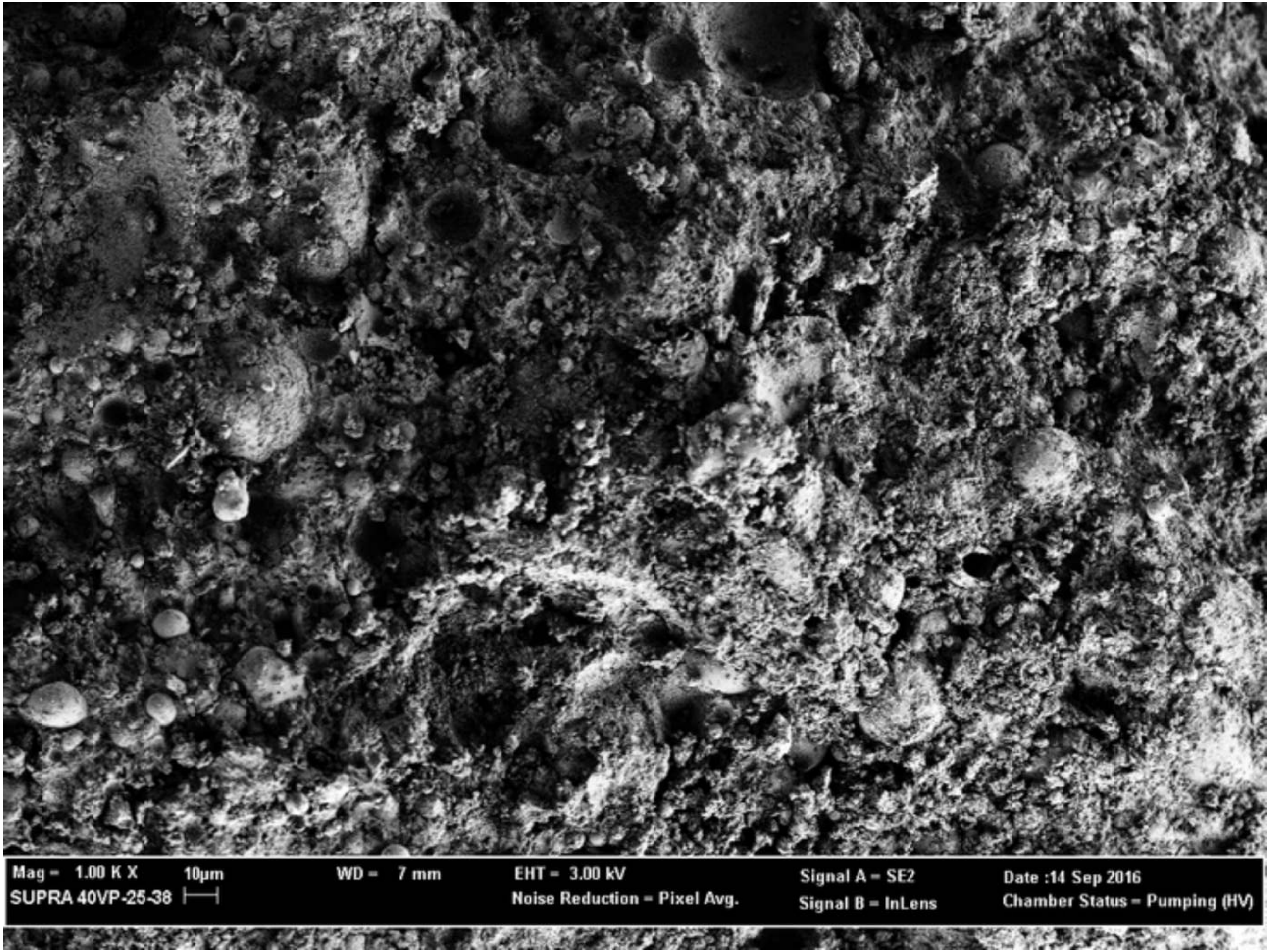

Mag = 1.00 K X
10µm
SUPRA 40VP-25-38
WD = 5 mm
EHT = 3.00 kV
Noise Reduction = Pixel Avg.
Signal A = SE2
Signal B = InLens
Date :14 Sep 2016
Chamber Status = Pumping (HV)

Figure 13c


Mag = 1.00 K X
10µm
SUPRA 40VP-25-38
WD = 7 mm
EHT = 3.00 kV
Noise Reduction = Pixel Avg.
Signal A = SE2
Signal B = InLens
Date :14 Sep 2016
Chamber Status = Pumping (HV)