

EFFECT OF CHEMICAL COMPOSITION ON BASIC ENGINEERING PROPERTIES OF INORGANIC POLYMERIC BINDER BASED ON NATURAL POZZOLAN

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Previous experimental results have proved the potential of aluminosilicate materials from natural resources, i.e. natural pozzolans, for being utilized as raw material in synthesis and production of inorganic polymeric material. In this research work, basic engineering properties of an inorganic polymeric binder based on pumice-type natural pozzolan including initial and final setting times, 28-day compressive strength, and paste workability were studied by changing chemical composition, i.e. $\text{SiO}_2/\text{Na}_2\text{O}$ molar ratio of activator and total molar ratios of $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$, and $\text{H}_2\text{O}/\text{Al}_2\text{O}_3$. The results obtained show that the maximum 28-day compressive strengths up to 50 MPa can be achieved at $\text{SiO}_2/\text{Na}_2\text{O}$, $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$, and $\text{H}_2\text{O}/\text{Al}_2\text{O}_3$ molar ratios of 0.75, 0.92, and 7.50, respectively. Most of the studied systems exhibit acceptable setting time and paste workability. X-ray diffractometry, Fourier transform infrared spectroscopy, and scanning electron microscopy techniques were utilized for characterizing a number of systems and studying the effects of chemical composition on molecular and microstructure of the material.

INTRODUCTION

The need for new environmentally friendly construction materials matching today's durability requirements has provoked increasing interest into the study of alkali activated materials over the past decades. Alkali activated binder refers to any system that uses an alkali activator to initiate a reaction or a series of reactions that will produce a material possessing cementitious properties. Alkali activated slag, alkali activated fly ash, and inorganic polymeric binders, i.e. geopolymers, based on metakaolin and natural pozzolan [1-4] are all considered to be alkali activated materials exhibiting cementitious properties. The molecular structures of these materials however are vastly different depending on the compositions and mechanistic paths of chemical reactions [5,6].

It is well known that calcium silicate hydrate (CSH) is the major binding phase in Portland cement. However, the binding property of inorganic polymeric binders is generally assumed to be the result of the formation of one, two, and three-dimensional amorphous aluminosilicate network molecular structures. Davidovits [3,7] proposed that geopolymers are formed by the polymerization of individual aluminate and silicate species, which are dissolved from their original sources at high pH in the presence of alkali metals. The resultant products are reported to have the general formula $\text{Mn} \cdot [(-\text{SiO}_2)_z - \text{AlO}]_n \cdot w\text{H}_2\text{O}$, where M is the alkali metal,

z is 1, 2, 3 or more and n is the degree of polymerization. Davidovits [7] described three basic units for polymerization corresponding to $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio: $(-\text{Si}-\text{O}-\text{Al}-\text{O}-)$, polysialate (PS), $\text{SiO}_2/\text{Al}_2\text{O}_3 = 2$; $(-\text{Si}-\text{O}-\text{Al}-\text{O}-\text{Si}-\text{O}-)$, polysialatesiloxo (PSS), $\text{SiO}_2/\text{Al}_2\text{O}_3 = 4$; $(-\text{Si}-\text{O}-\text{Al}-\text{O}-\text{Si}-\text{O}-\text{Si}-\text{O}-)$, polysialatedisiloxo (PSDS), $\text{SiO}_2/\text{Al}_2\text{O}_3 = 6$.

The molecular structure and hence properties of inorganic polymeric binders depend on some parameters including chemical and mineralogical compositions of raw material and its dissolution properties, composition and dosage of alkali-activator, and curing conditions. Among which the chemical composition of both raw material and alkali-activator is very important in determining the molecular structure of the product. The chemical composition of such cementitious systems can be studied by considering molar ratios of $\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{SiO}_2/\text{Na}_2\text{O}$, $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$, and $\text{H}_2\text{O}/\text{Al}_2\text{O}_3$ [5-9].

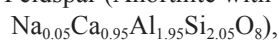
In this research work, basic engineering properties of an inorganic polymeric binder based on natural pozzolan including initial and final setting times, 28-day compressive strength, and paste workability were studied by changing parameters of chemical composition, i.e. molar ratios of $\text{SiO}_2/\text{Na}_2\text{O}$, $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$, and $\text{H}_2\text{O}/\text{Al}_2\text{O}_3$. X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) techniques were utilized for characterizing a number of systems and studying the effects of chemical composition on molecular and microstructure of the material.

EXPERIMENTAL

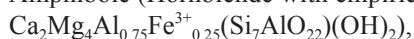
Raw Materials

Natural pozzolan used in this work was pumice-type obtained from Taftan mountain, located at the south east of Iran. The obtained pozzolan was firstly characterized for its chemical and mineralogical compositions and also its pozzolanic activity. The results of chemical analysis determined according to ASTM standard C311 are shown in Table 1. As seen, this natural pozzolan is a relatively high siliceous one. Figures 1 and 2 show the X-ray diffraction pattern and FTIR spectrum of the used pozzolan, respectively. As Figure 1 shows, the crystalline mineral phases present in Taftan pozzolan include:

Feldspar (Anorthite with empirical formula;



Amphibole (Hornblende with empirical formula;



Mica (Biotite with empirical formula;



As seen in Figure 2, the FTIR spectrum of the pozzolan shows two strong peaks. One at wavenumber about 460 cm^{-1} and the other a broad peak at wavenumbers in the range between 1007 to 1050 cm^{-1} which are both attributed to asymmetric stretching of Al–O and Si–O bonds of aluminosilicate structure.

The pozzolanic activity of Taftan pozzolan was also evaluated by determining its strength activity index with Portland cement at 7 and 28 days in accordance with ASTM C311. The results obtained, i.e. 83.2 and 86.8 percent of control respectively for 7 and 28 days, show a relatively good pozzolanic activity in accordance with ASTM standard C618. The prepared sample of po-

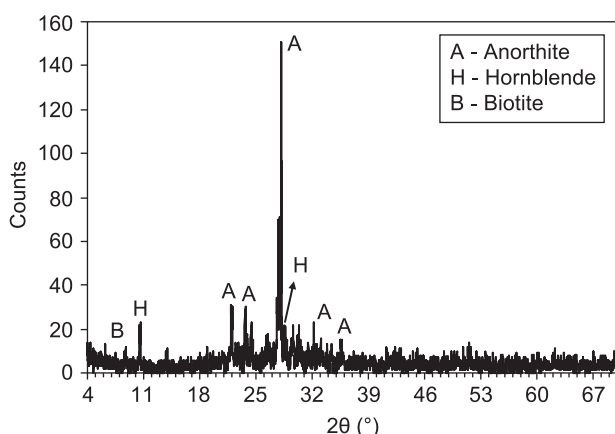


Figure 1. X-ray diffraction pattern of pozzolan.

Table 1. Chemical composition of pozzolan (wt.%).

Composition	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	K ₂ O	Na ₂ O	Cl ⁻	LOI
wt %	61.57	18.00	4.93	6.69	2.63	0.10	1.95	1.65	0.04	2.15

zzolan, previously ground in an industrial closed mill to attain a Blaine specific surface area of $305\text{ m}^2/\text{kg}$, was a relatively highly fine powder. The particle size distribution of which was determined by a laser particle size analyzer (Sympatec, GmbH, HDD) and the corresponding curve is presented in Figure 3. The mean particle size of the ground natural pozzolan was $22.63\text{ }\mu\text{m}$. Industrial sodium silicate solution (weight ratio of $\text{SiO}_2/\text{Na}_2\text{O} = 0.92$ and $\text{SiO}_2 = 31.36\text{ wt \%}$) and industrial-grade NaOH (99% purity) were used throughout all experiments.

Specimens Preparation

A number of systems were prepared in accordance with molar ratios given in Table 2. Chemical composition of the systems has been varied by changing $\text{SiO}_2/\text{Na}_2\text{O}$ (Si/Na) molar ratio of activator and $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ (Na/Al) total molar ratio. Enough sodium hydroxide was added to sodium silicate solution and the dosage of activator was so adjusted to prepare cementitious systems (dry binder and activator) having molar ratios of Si/Na and Na/Al adjusted at the values given in Table 2. The corresponding calculated values for total $\text{SiO}_2/\text{Al}_2\text{O}_3$ (Si/Al) molar ratio are also given in Table 2.

Table 2. Chemical composition of cementitious systems (at a constant total H/Al molar ratio of 8.50).

System name	Activator Si/Na molar ratio (adjusted)	Total Na/Al molar ratio (adjusted)	Total Si/Al molar ratio (calculated)
P1	0.3	0.77	5.58
P2	0.45	0.77	5.66
P3	0.6	0.77	5.78
P4	0.75	0.77	5.92
P5	0.9	0.77	6.10
P6	0.3	0.92	5.60
P7	0.45	0.92	5.70
P8	0.6	0.92	5.84
P9	0.75	0.92	6.00
P10	0.9	0.92	6.22
P11	0.3	1.08	5.62
P12	0.45	1.08	5.76
P13	0.6	1.08	5.90
P14	0.75	1.08	6.10
P15	0.9	1.08	6.36
P16	0.3	1.23	5.66
P17	0.45	1.23	5.80
P18	0.6	1.23	5.98
P19	0.75	1.23	6.20
P20	0.9	1.23	6.48

Test Procedure

The above systems were all prepared and studied for their paste workability, setting times, and 28-day compressive strength at a constant total H_2O/Al_2O_3 (H/Al) molar ratio of 8.50. To determine the 28-day compressive strength, the prepared pastes were cast into $2 \times 2 \times 2$ cm moulds. The moulds were held at an ambient of nearly 95% relative humidity for preventing drying and giving enough time (24 hr) to the pastes to set and harden at ambient temperature, i.e. 25 °C. After demoulding, the specimens were cured in an atmosphere of 95% relative humidity at 25°C until the testing time. For investigating the effect of total H/Al molar ratio (depending on water-to-dry binder ratio and water content of both sodium silicate and sodium hydroxide) on basic engineering properties of the material, four systems exhibiting the highest 28-day compressive strength including systems P4, P9, P13, and P18 were selected and their basic engineering properties were studied at five different total H/Al molar ratios of 7.5, 8.0, 8.5, 9.0, and 9.5.

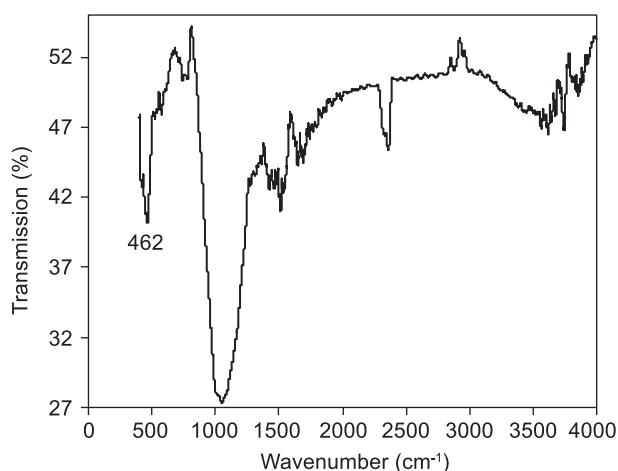


Figure 2. FTIR spectrum of pozzolan.

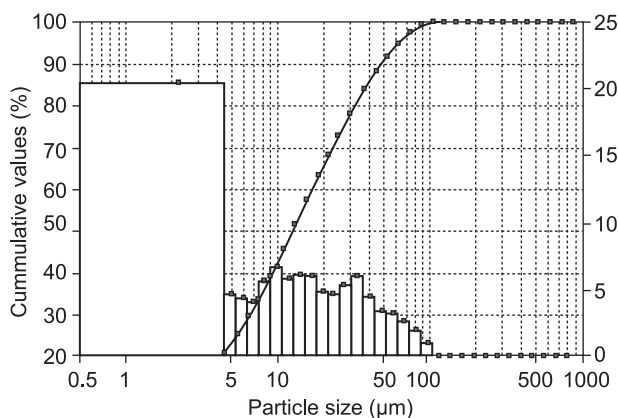


Figure 3. Particle size distribution of ground pozzolan.

To evaluate paste workability, spread diameter was measured according to ASTM standard C230. For measurement of setting times, Vicat needle was used in accordance with ASTM standard C191-82. From each system, three specimens were used for determining 28-day compressive strength. Systems exhibiting the highest 28-day compressive strengths were characterized by laboratory techniques of Fourier transform infrared spectroscopy (FTIR; Nicolet 740), X-ray diffractometry (XRD; Philips Expert System, Cu $K\alpha$ -radiation and Ni-filter), and scanning electron microscopy (SEM; CamScan MV 2300, EDS; Oxford 7538). For SEM studies, a number of specimens were cut into halves to expose internal regions. Suitable halves were then impregnated with epoxy resin, polished and coated with carbon.

RESULTS AND DISCUSSION

Effects of Si/Na molar ratio of activator and total Na/Al molar ratio

Workability

It is well known that the amount of water added to the dry binder or the total molar ratio of H/Al is the main factor significantly influencing the paste workability. Experimental results, however, prove that at a given amount of water added to the dry binder or at a constant molar ratio of H/Al, variations in Na_2O and SiO_2 content of the material can also result in changes in paste workability. Figure 4 shows variations of spread diameter as a measure of paste workability at constant molar ratio of H/Al = 8.50. As seen, the spread diameter of the freshly prepared paste depends on both Si/Na molar ratio of activator and total Na/Al molar ratio. The higher both the Si/Na and Na/Al molar ratios, the higher the spread diameter or paste workability.

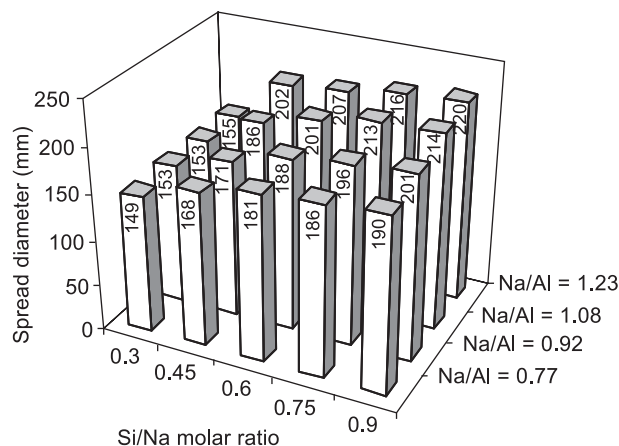


Figure 4. Relative paste workabilities at constant total H/Al molar ratio of 8.50.

Setting Times

Figures 5 and 6 show the effects of Si/Na molar ratio of activator and total Na/Al molar ratio on initial and final setting times of systems at constant total molar ratio of H/Al = 8.50. As seen, both initial and final setting times sharply decrease as the Si/Na molar ratio increases from 0.3 to 0.6, especially for lower molar ratios of Na/Al. At all the four Na/Al molar ratios, the minimum setting times occur at Si/Na = 0.6. Both initial and final setting times show gradual increase when Si/Na molar ratio is increased from 0.6 to 0.9. It is also seen that at Si/Na molar ratios lower than 0.6, both setting times sharply decreases as the Na/Al molar ratio increases from 0.77 to 1.23, whereas for Si/Na molar ratios higher than 0.6, increases in Na/Al molar ratio from 0.77 to 1.23 result in gradually longer setting times. The maximum initial and final setting times occurring at the lowest values of both Si/Na and Na/Al molar ratios are 225 and 280 min respectively which are practically acceptable compared to standard values given for Portland cement. System prepared at Si/Na = 0.6 and Na/Al = 0.77 and

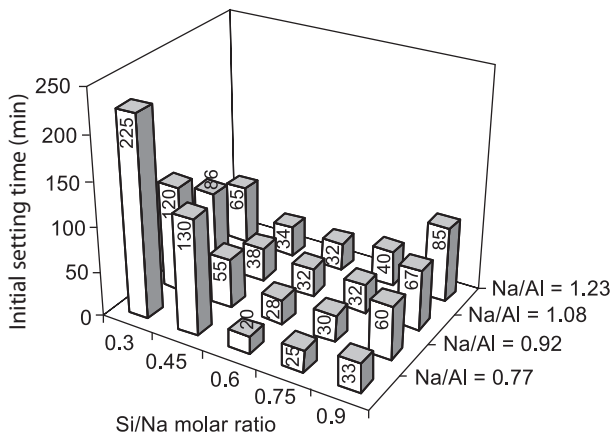


Figure 5. Results obtained for initial setting time.

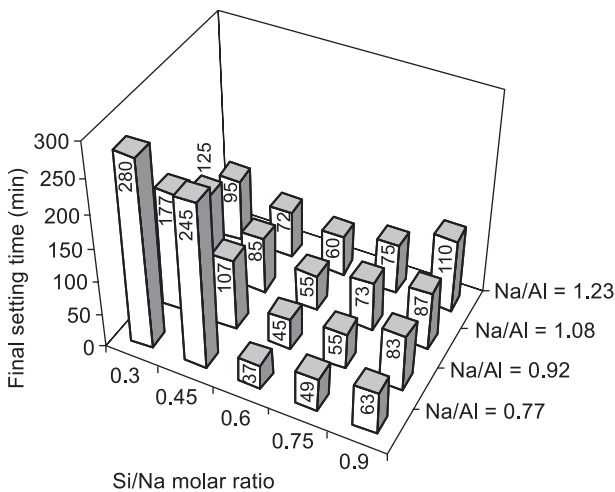


Figure 6. Results obtained for final setting time.

exhibiting the shortest setting times, i.e. 20 and 37 min respectively, behaves as a fast set cement compared to Portland cement. The time of setting could be considered as an indication of the kinetics of the very first reactions of geopolymerization which leads to polycondensation and hardening of the produced gel.

Compressive Strength

Before measuring the 28-day compressive strength, the specimens were observed visually for any possible macro-crack. They were quite sound and no crack was observed visually. Figure 7 shows the effects of Si/Na and Na/Al molar ratios on 28-day compressive strength. As seen in Figure 7, the molar ratio of SiO₂/Na₂O of activator plays an important role in the compressive strength development. Si/Na molar ratio shows a positive effect on compressive strength up to 0.6 for the systems

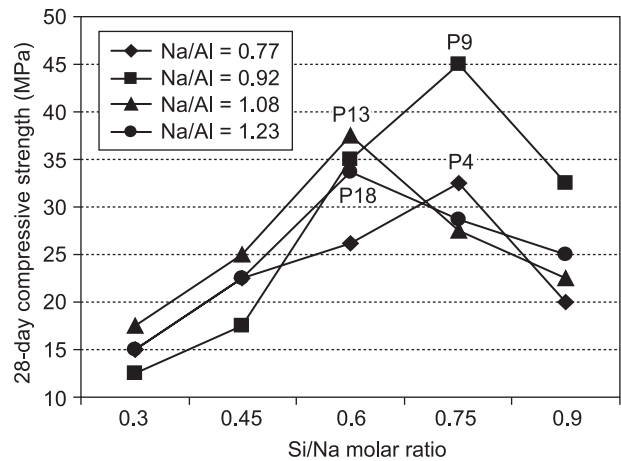


Figure 7. 28-day compressive strength versus Si/Na molar ratio of activator.

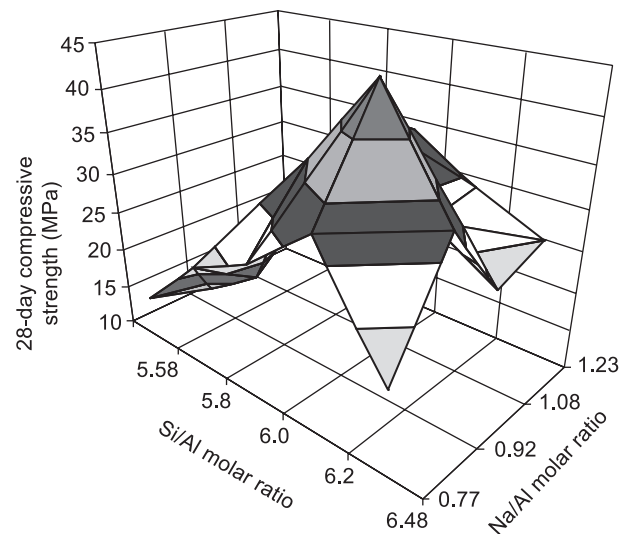


Figure 8. 28-day compressive strength versus Si/Al and Na/Al total molar ratios.

with Na/Al molar ratios of 1.08 and 1.23 and up to 0.75 for the systems with Na/Al molar ratios of 0.77 and 0.92. After that, any increase in Si/Na molar ratio of activator resulting from either a decrease in the concentration of sodium oxide or an increase in the concentration of silica causes a significant decrease in 28-day compressive strength. In other words, for the two higher values of Na/Al molar ratios (1.08 and 1.23), the Si/Na molar ratio providing the maximum 28-day compressive strength is 0.6 where as at the two lower values of Na/Al molar ratios (0.77 and 0.92), a relatively higher Si/Na molar ratio, i.e. 0.75, provides the maximum 28-day compressive strength.

Figure 8 shows the effects of Si/Al and Na/Al total molar ratios on 28-day compressive strength development. As seen in Figure 8, for all systems the calculated amounts of total Si/Al molar ratios show an optimum value of about 6 in which the maximum compressive strength is observed. By increase in the amount of total Si/Al molar ratio up to approximately 6 for systems with Na/Al molar ratios of 0.92 and 1.08, the compressive strength increases. After that, any increase in total Si/Al molar ratio causes a significant decrease in 28-day compressive strength.

Since the composition of dry binder, i.e. natural pozzolan, is constant, all the changes brought about in Si/Na, Si/Al, and Na/Al molar ratios are due to changes made in sodium hydroxide and sodium silicate contents of the activator. Both sodium hydroxide and sodium silicate play important roles in geopolymerization reactions. Sodium hydroxide provides both hydroxide anion (OH^-) which is very important for dissolution of the aluminosilicates in the first stage and sodium cation (Na^+) which is important for charge balance of the aluminosilicate network formed in the last stage. Solubility of aluminosilicate increases with increasing OH^- concentration. Utilization of too much sodium hydroxide in preparation of alkali-activator, however, is not beneficial. Excess OH^- could cause the polycondensation reactions to occur not only

faster, but also too soon and therefore hindering dissolution of aluminosilicates which needs enough time to proceed. Such a condition leads to formation of a material with quite a short setting time due to very soon polycondensation reactions and relatively lower compressive strength due to not a quite matured molecular structure caused by incomplete dissolution of aluminosilicates [2,10,11]. Excess Na^+ remaining unreacted in the geopolymer matrix could be simply leached out or results in the formation of efflorescence due to accumulation of carbonated sodium oxide on the surface of the material.

Sodium silicate also provides good interparticle bonding and therefore mechanical strength of the material by synthesizing aluminosilicate gel. In addition, it hinders water evaporation and provides suitable conditions for structure formation [10]. The properties of the geopolymer material therefore strongly depend on its chemical composition and to develop a sound geopolymer cement exhibiting acceptable set and strength behavior, it is necessary to determine the optimum chemical composition.

Effect of total H/Al molar ratio

Five different H/Al molar ratios, i.e. 7.5, 8.0, 8.5, 9.0, and 9.5, were used for investigating the effects of this parameter on basic engineering properties of systems P4, P9, P13, and P18 exhibiting the highest 28-day compressive strength. Pastes workability, initial and final setting times, and 28-day compressive strength of systems were measured and studied.

Figure 9 shows the effects of H/Al molar ratios on paste workability at different Na/Al molar ratios. As seen, the higher the molar ratios of Na/Al and H/Al, the higher the paste workability. The paste workability therefore is not only a function of H/Al molar ratio, but also a function of Na/Al molar ratio. Since the changes

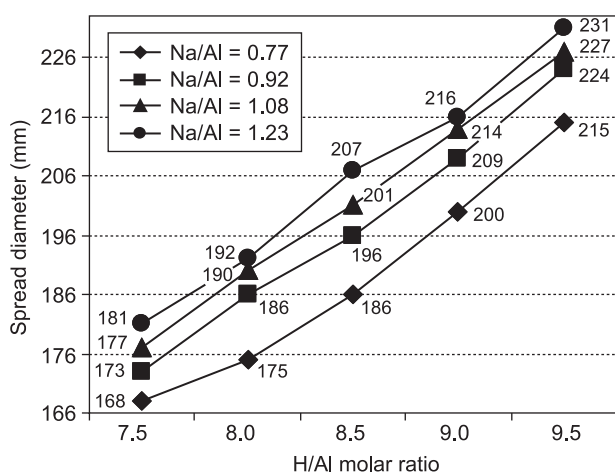


Figure 9. Relative paste workability at different total H/Al molar ratios.

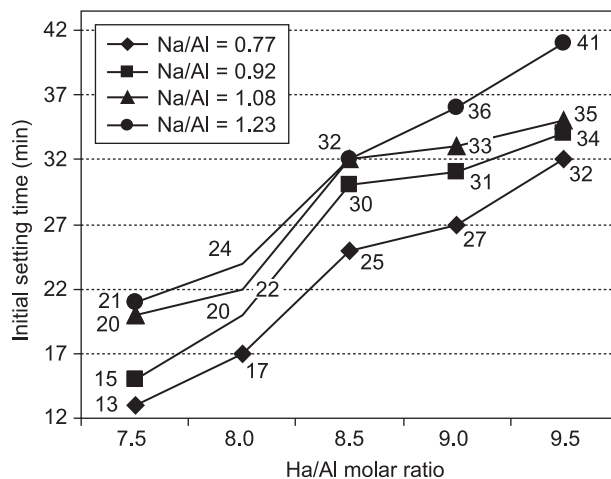


Figure 10. Results obtained for initial setting time.

brought about in H/Al and Na/Al molar ratios are due to changes made in the water content and sodium oxide content of the pastes, the sodium oxide concentration is also an important factor significantly influencing the paste workability in addition to the water content or water-to-dry binder ratio.

Figures 10 and 11 show the effects of H/Al molar ratio on initial and final setting times at different Na/Al molar ratios. As seen, both initial and final setting times increase as the H/Al molar ratio increases. The variations of both initial and final setting times due to changes made in Na/Al molar ratio, however, are not significant compared to those brought about by changes in H/Al molar ratio.

Figure 12 shows the effects of H/Al molar ratios on 28-day compressive strength at different Na/Al molar ratios. As seen, at constant Na/Al molar ratio, increasing the amount of H/Al molar ratio decreases the 28-day compressive strength. Various authors [12-14] have mentioned the importance of the H_2O/Al_2O_3 molar ratio

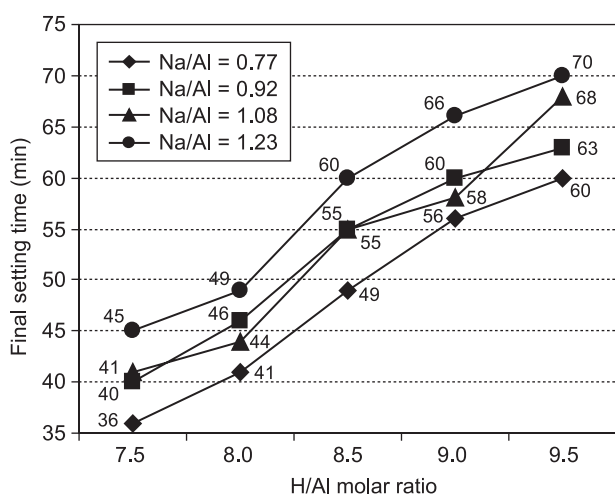


Figure 11. Results obtained for final setting time.

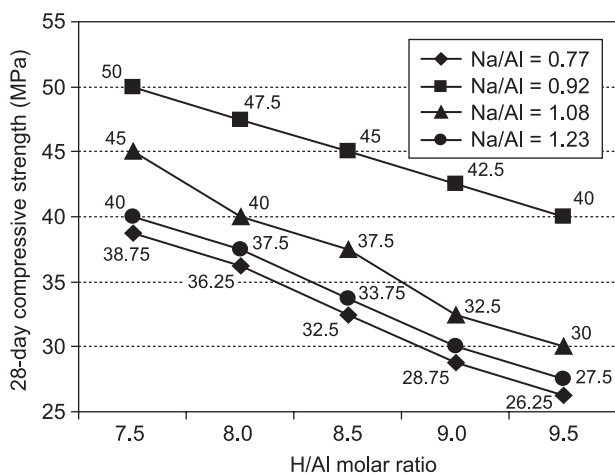


Figure 12. Results obtained for 28-day compressive strength.

in the synthesis of geopolymers as well as other aluminosilicates such as zeolites. The mineralizing and stabilizing actions of water play important roles during both dissolution and polycondensation of geopolymeric precursor species. In general, the 28-day compressive strength decreases as the H_2O/Al_2O_3 molar ratio increases.

X-Ray diffraction analysis

X-ray diffraction pattern of 28-day hardened paste of geopolymer cement system prepared at Si/Na, Na/Al, and H/Al molar ratios of 0.6, 1.08, and 8.5, respectively and cured at 95% relative humidity at 25°C is presented in Figure 13. A comparison of the patterns of pozzolan and hardened paste, Figure 1 and Figure 13 respectively, clearly shows that the diffuse halo at around 2θ-angles in the range 25 to 30 degrees has been enlarged and the intensity of the peaks has been significantly reduced in the hardened paste. The geopolymerization reactions therefore have resulted in a lower degree of crystallinity in the hardened paste of the material. According to the experiences, X-ray diffractometry is not useful in identifying the geopolymerization reactions products, since all products are almost always present in amorphous state.

FTIR Analysis

Figure 14 displays FTIR spectra of systems P4, P9, P13, and P18 (with given chemical compositions in Table 2), exhibiting the highest 28-day compressive strength at constant H/Al molar ratio of 8.5. Infrared spectra of the samples are rather similar, presenting analogous absorption bands. All show bands at 3440 and 1650 cm^{-1} , respectively, related to O-H stretching

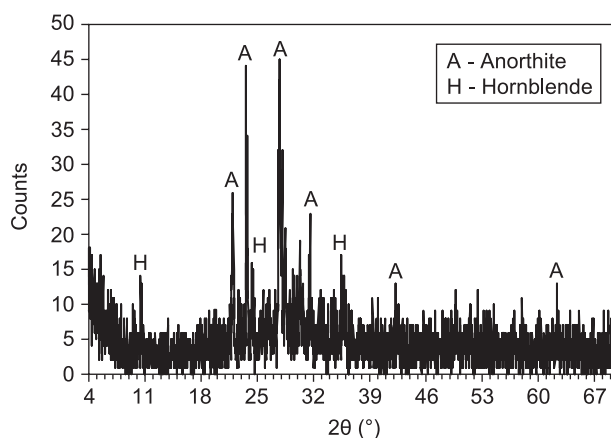


Figure 13. X-Ray diffraction pattern of 28-day hardened paste of geopolymer cement system prepared at Si/Na, Na/Al, and H/Al molar ratios of 0.6, 1.08, and 8.5, respectively.

and bending modes of molecular water. Also, the peaks near 1000 cm^{-1} and 450 cm^{-1} due to asymmetric Si–O–Al stretching vibrations and in-plane Si–O bending vibrations in SiO_4 tetrahedra, respectively.

As seen in all the spectra, there exist a main broad and strong absorption peak appearing at about 1000 cm^{-1} and a fairly broad and relatively strong peak at about 460 cm^{-1} . The first of these bands that is the most intensive is usually a superposition of some bands situated close to each other [15,16].

The Si–O stretching modes for the SiQ^n units show infrared absorption bands localized around 1100 , 1000 , 950 , 900 , and 850 cm^{-1} for $n = 4, 3, 2, 1$, and 0 , respectively [15]. These values shift to lower wavenumbers when the degree of silicon substitution by aluminum in the second coordination sphere increases, as a consequence of the weaker Al–O bonds [16]. The peaks at around 1000 cm^{-1} are a major fingerprint for geopolymer materials representing the fusion of both Al–O and Si–O asymmetric stretching and can indicate the extent of aluminum incorporation with a lowering in the energy of the peak [16,17]. The infrared spectra

presented in Figure 14 show some differences when compared to the spectrum of the starting natural pozzolan (Figure 2). The relatively broad peak at around 1000 cm^{-1} in natural pozzolan has changed to a concentrated one showing that the geopolymerization reactions has resulted in a more oriented molecular structure in the material. In addition, the position of the main peaks appearing around 1000 cm^{-1} has changed to lower wavenumbers confirming that the geopolymerization reactions has resulted in a higher degree of silicon substitution by aluminum in the second coordination sphere.

Figures 15 to 18 show FTIR spectra of the systems P4, P9, P13, and P18 respectively at different H/Al molar ratios of 7.5, 8.5, and 9.5. As seen in all systems, by increase in the amount of H/Al molar ratio, the main broad peak appearing at around 1000 cm^{-1} shift to a little bit higher wavenumbers. This could be due to the more oriented bands of Si–O–Al. It was mentioned previously that the nucleation mechanism involves the ordering of water molecules by the alkali metal cations present [14]. A higher water content therefore has a lower cation

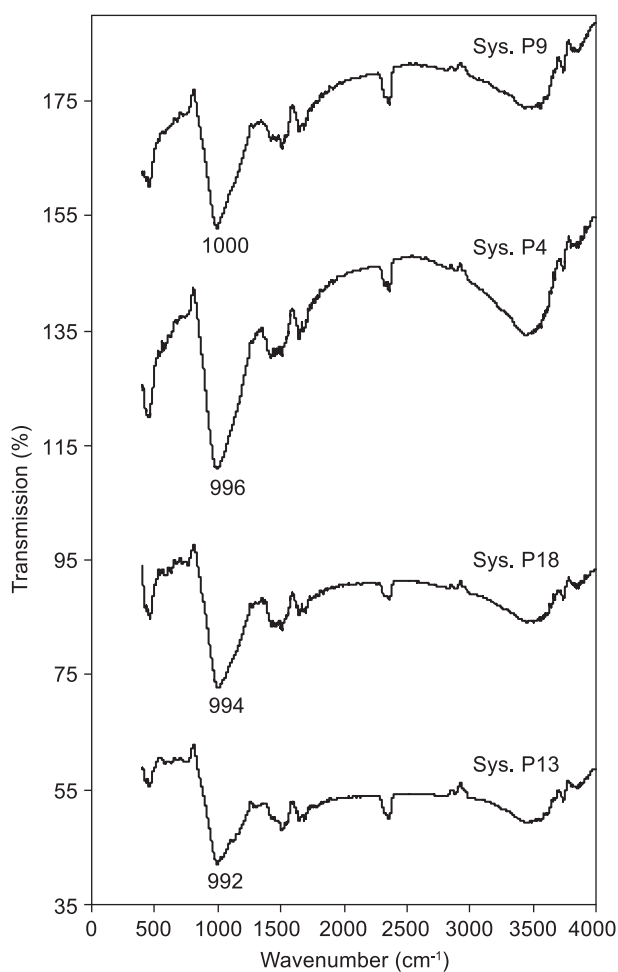


Figure 14. FTIR spectra of the systems exhibiting the highest compressive strength at constant H/Al molar ratio of 8.5.

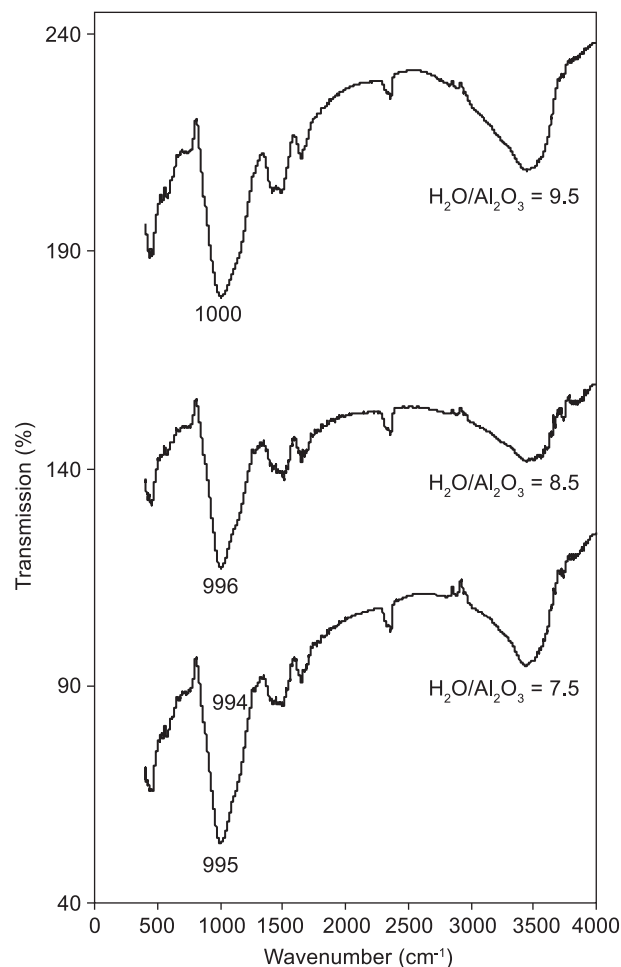


Figure 15. FTIR spectra of geopolymer cement systems prepared at Si/Na and Na/Al molar ratios of 0.75, 0.77, respectively (P4) at different H/Al molar ratios.

concentration to order it, resulting in a matrix with a higher degree of polycondensation, i.e. a more disordered system [12].

Scanning electron microscopy

Investigations done by scanning electron microscopy (SEM) on 28-day hardened paste of geopolymer cement prepared at Si/Na and Na/Al molar ratios of 0.6 and 1.08 respectively and cured at 95% relative humidity at 25°C clearly confirm the presence of an amorphous matrix in which particles of various shapes and sizes are embedded. Geopolymers are known to contain amounts of unreacted solid aluminosilicate source [18, 19]. This is confirmed by the embedded particles observed in the SEM micrographs in Figures 19 and 20. However, there is no definitive and accurate method for quantitatively determining the amount of unreacted material in a particular specimen. For any qualitative or semi-quantitative description of the effect of unreacted material on the strength of geopolymers, a measure of the amount of unreacted material is required.

Figures 19 and 20 show the microstructure of the hardened paste at two different regions and at the same magnification. As seen, the microstructure is relatively coarse along with a number of microcracks and a few fiber-like crystals which were quite difficult to identify.

CONCLUSIONS

1. Experimental results prove the potential application of natural pozzolans in synthesis and production of inorganic polymeric binder.
2. The microstructure and the basic engineering properties of the studied inorganic polymeric binder based on natural pozzolan depend on the chemical composition of the activator and the amount of water used.
3. At constant H_2O/Al_2O_3 total molar ratio, the spread diameter of the freshly prepared paste depends on both SiO_2/Na_2O molar ratio of activator and total Na_2O/Al_2O_3 molar ratio. In this case, both initial and final setting times sharply decrease as the SiO_2/Na_2O

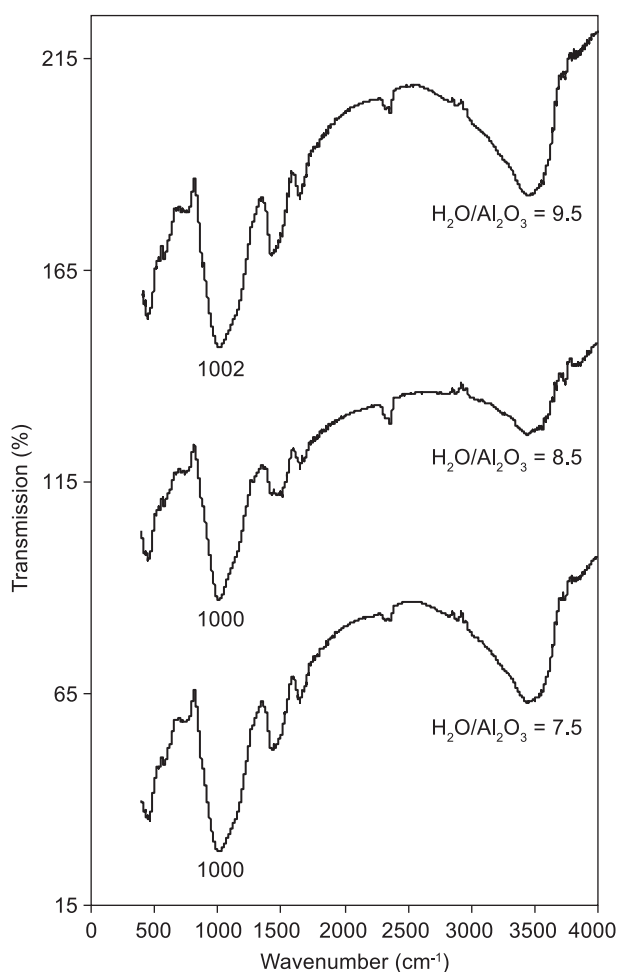


Figure 16. FTIR spectra of geopolymer cement systems prepared at Si/Na and Na/Al molar ratios of 0.75, 0.92, respectively (P9) at different H/Al molar ratios.

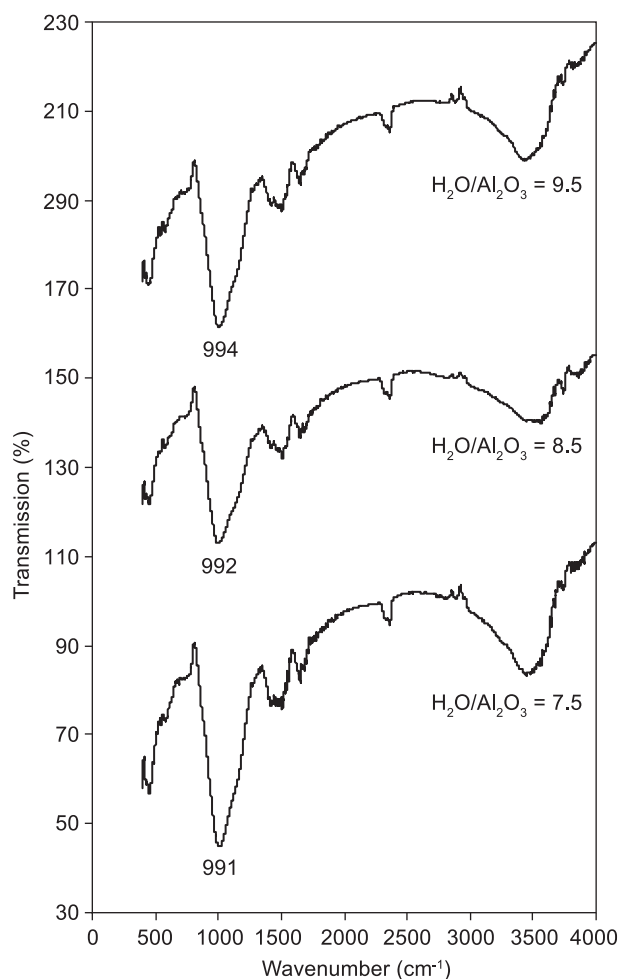


Figure 17. FTIR spectra of geopolymer cement systems prepared at Si/Na and Na/Al molar ratios of 0.6, 1.08, respectively (P13) at different H/Al molar ratios.

molar ratio increases from 0.3 to 0.6, especially for lower molar ratios of $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$. System prepared at $\text{SiO}_2/\text{Na}_2\text{O} = 0.6$ and $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3 = 0.77$ and exhibiting the shortest initial and final setting times, i.e. 20 and 37 min respectively, behaves as a fast set cement compared to Portland cement. By changing the amount of $\text{H}_2\text{O}/\text{Al}_2\text{O}_3$ total molar ratio it has been observed that the paste workability and setting times are not only a function of $\text{H}_2\text{O}/\text{Al}_2\text{O}_3$ molar ratio, but also a function of $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ molar ratio.

4. Results obtained show that, at constant $\text{H}_2\text{O}/\text{Al}_2\text{O}_3$ total molar ratio, for the two higher values of $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ molar ratios (1.08 and 1.23), the $\text{SiO}_2/\text{Na}_2\text{O}$ molar ratio providing the maximum 28-day compressive strength is 0.6 whereas at the two lower values of $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ molar ratios (0.77 and 0.92), a relatively higher $\text{SiO}_2/\text{Na}_2\text{O}$ molar ratio, i.e. 0.75, provides the maximum 28-day compressive strength.

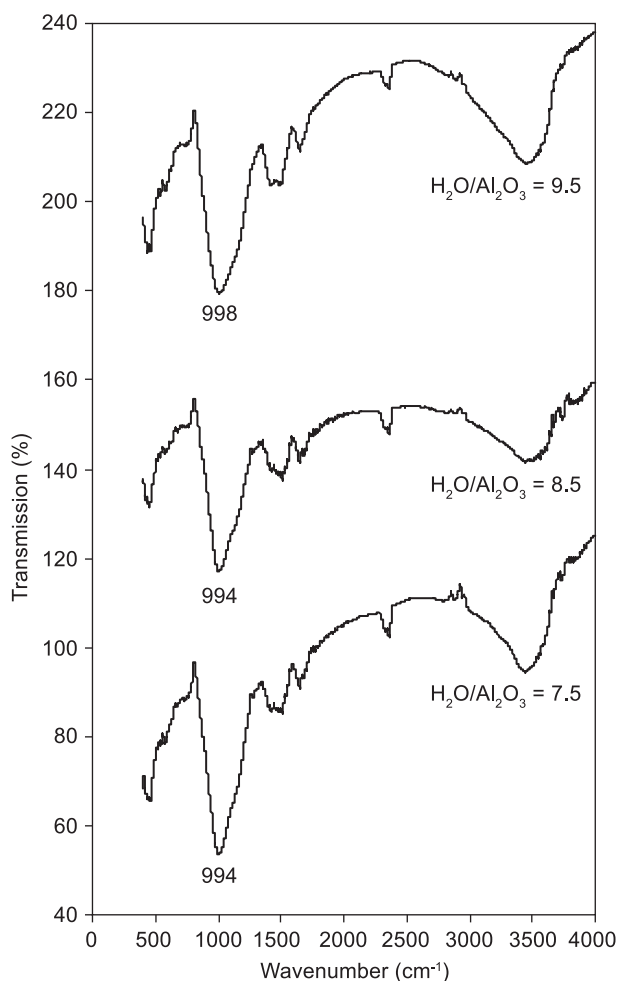


Figure 18. FTIR spectra of geopolymer cement systems prepared at Si/Na and Na/Al molar ratios of 0.6, 1.23, respectively (P18) at different H/Al molar ratios.

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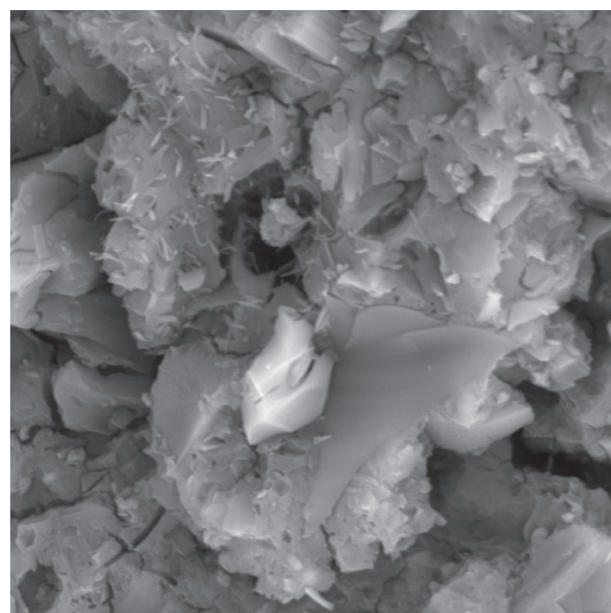


Figure 19. SEM image from microstructure of 28-day hardened paste prepared at Si/Na and Na/Al molar ratios of 0.6 and 1.08 respectively.

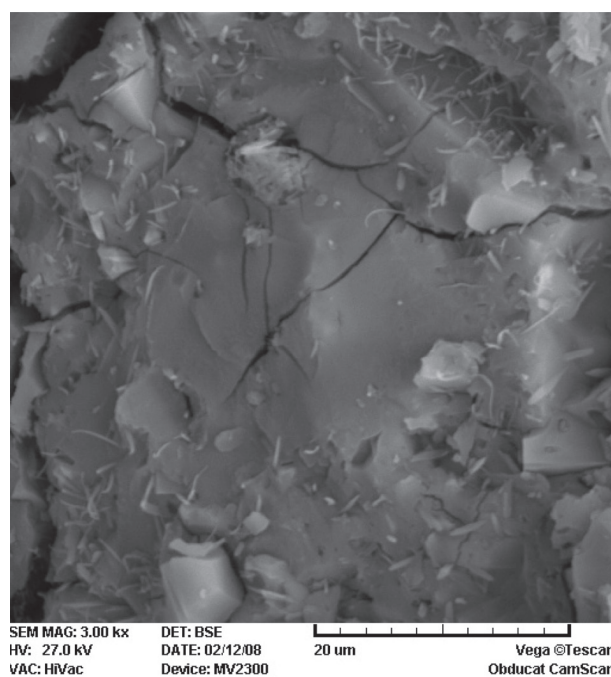


Figure 20. SEM image from microstructure of 28-day hardened paste prepared at Si/Na and Na/Al molar ratios of 0.6 and 1.08 respectively.

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