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Geopolymerization reaction to consolidate incoherent pozzolanic soil

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Abstract Pozzolanic material-based geopolymer has been proposed as a solving methodology to the geohazards, due to pozzolanic collapsible soils widely present in the South Italy. The geopolymer was synthesized from pozzolana material under activation of NaOH 10 M or slurry of $NaAlO_2$ in NaOH 10 M solution. The specimens were cured at 25 °C and 100% RH for different ageing times. The effect of the two activation methods on the properties of the geopolymer was investigated by means of X-ray diffraction, scanning electron microscopy (SEM), FTIR spectroscopy, nuclear magnetic resonance (^{27}Al and ^{29}Si NMR) and uniaxial compression tests. XRD, NMR and IR analysis indicate the geopolymer is generated by the dissolution of the silico-aluminate phases present in the pozzolana and the successive re-organization in amorphous and crystalline neo-formed phases. The spectroscopic evidences confirm that the 4-coordinated Al atoms present in the neat pozzolana and in the $NaAlO_2$ change their coordination state splitting between 6- and 4-coordinated atoms, modifying the traditional chemistry of polysialate formation. SEM results show the synthesized geo-polymer maintained the granular morphology of the pozzolana and the geo-polymeric reactions occurred mainly at the surface of pozzolana particulates. Furthermore, uniaxial strength data increase gradually upon the curing time, until 40 MPa for the specimens activated with the slurry system.

Introduction

Collapsible soils are one among the most significant geohazards in the world, and are a major geotechnical concern for a significant percentage of the world's population.

It is noted that the subsoil of the town of Naples is made of a thick layer of pyroclastic cohesionless silty sand, known as pozzolana, overlaying a pyroclastic soft rock known as neapolitan yellow tuff. Both these materials, extensively investigated in situ and in laboratory [1] can be affected by geotechnical problems, such as landslides and rockslides. Therefore, the improvement of their mechanical properties is often requested.

Pozzolana sand has the peculiar characteristic of being able to react with calcium hydroxide solution, hardening because of the formation of binding insoluble materials. This chemical activity was already well known to the Romans, who largely used pozzolana to prepare mortar. Since then, all soils showing such a property are generically defined as pozzolanic, regardless of their geographical origin. The peculiar behaviour is due to the presence of amorphous silica and alumina both reactive with the calcium hydroxide in alkaline ambient [2, 3].

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Geopolymerization, is a fairly new technique based on a very old principle, which has emerged during the last years, as a possible solution to solve different environmental problems. At the basis of geopolymerization lies the chemistry of alkali-activated inorganic binders, which represent a group of cement-like materials that are formed by reacting silica-rich and alumina-rich solids with a solution of alkali salts, resulting in a mixture of gels and crystalline compounds that eventually harden into a new strong matrix.

Geopolymers belong to the some silico-alluminates family as zeolites but have a significant difference from them: they are essentially amorphous polymers. They consist of tetrahedral AlO_4 and SiO_4 units polycondensed at room (or high) temperature under highly alkaline conditions into three-dimensional structure with charge stabilization provided by alkaline earth ions [4, 5].

The mechanism of geopolymer formation includes an initial dissolution step, where the alkali solution not only hydrolyzes the surface of mineral particles, but also dissolves a small amount of Al and Si species. These dissolved species react with already dissolved silicate ions forming a gel that is transformed into the final structure trough crystallization or another dissolution process [6].

Typical geopolymer compositional range proposed by Davitovits is generally expressed as $nM_2O{*}Al_2O_3{*}xSiO_2{*}yH_2O$ (where n: 1–1.6; $x > 2$; y: 3–7; and M: Na, K) with a characteristic initial pH (alkaline) value greater than 10 [7]. In particular, three classes of geopolymers exist, which depend on the Si/Al ratio, and which are based on the following three different monomer: (–Si–O–Al–O–) polysialate (PS), $SiO_2/Al_2O_3 = 2$; (–Si–O–Al–O–Si–O–) polysialatesiloxo (PSS), $SiO_2/Al_2O_3 = 4$ (–Si–O–Al–O–Si–O–Si–O–) polysialatedisiloxo (PSDS), $SiO_2/Al_2O_3 = 6$ [8].

The goal of this research was to obtain a polysialatesiloxo with the following formula 1,5 (Na_2O–K_2O) Al_2O_3 $4SiO_2$, utilizing pozzolanic soil, as a source of reactive silica and alumina. NaOH solutions and NaOH–$NaAlO_2$ slurries were tested as activators to trigger the dissolution of silico-aluminate structures present in the pozzolana soil and consequently to promote the formation of new amorphous and crystalline phases.

The choice to synthesize the geopolymer from pozzolana using aluminate activator was made because it is well known that for high pH values in the range 12–14, the Al atom in tetrahedral coordination with four hydroxyl groups $[Al\ (OH)_4]^-$ is more capable of attracting negatively charged OH groups from other species. It is observed that the positive partial charge of Al atom is always higher than that of Si atom under conditions with the same pH value.

In this condition the Al atom displays the potential to expand its coordination number with greater ease and condensation reactions involving aluminate species that appear to occur, more readily [9].

This research represents a preliminary study to understand, whether the geopolymerization widely studied in the construction material field could be adopted as a methodology to consolidate incoherent pozzolana soils.

However, owing to the high viscosity of the alkaline activators, there is no way to inject them in pozzolana soil by simple permeation. Therefore an alternative application may be proposed, for instance, by using the so called “deep mixing” technique, which improves soil properties by remoulding it on site via a flight auger, and adding the desired grout at low pressure from small nozzles placed on the auger.

Experimental

Materials and methods

Pozzolanic material was obtained from Campi Flegrei sites. Analytical grade NaOH and $NaAlO_2$ as received from Aldrich were used.

Pozzolana was subjected to chemical characterization by dissolving the material in acid solution with a digesting apparatus and analysing the solution by ICP (Induced Coupled Plasma) spectroscopy. The XRD analysis was performed on the pozzolana powder.

Cylindrical specimens of 5.7 cm diameter and 13.5 cm height with a solid/liquid weight ratio equal to 2.5, were prepared by remoulding the pozzolana soil with the activators.

Two different activators were used:

(1) NaOH 10 M solution;
(2) slurry consisting of $NaAlO_2$ solid partly dissolved in NaOH 10 M. The weight ratio NaOH 10 M/$NaAlO_2$ solid was equal to 3.5.

The specimens were cured at 100% RH and 25 °C for different times ranging between 7 days and 1 year. The pozzolana specimens treated with the NaOH 10 M activator solution showed, since their preparation, the segregation of a viscous phase, which evolved into gel upon curing period.

The samples were chemically and physically characterized by Fourier Transform Infrared Spectroscopy (FTIR), Diffraction of X ray (XRD), Electron Scansion Microscopy (SEM) and solid-state MAS Nuclear Magnetic Resonance (^{27}Al, ^{29}Si-MAS NMR). At the same time they were mechanically analysed by uniaxial compression strength test to verify the efficiency of the mechanical improvement treatment. FTIR and XRD were performed on powder by using a Perkin Elmer and a Philips devices respectively. The FTIR spectra were collected in absorbance mode on transparent pellet obtained dispersing the sample powders 1% wt/wt in KBr. NMR spectra were acquired using a 600Avance Bruker spectrometer under magic-angle spinning conditions. ^{27}Al spectra were obtained at 156.33 MHz with a single 15° excitation pulse by co-adding 256 transient with a recycle time of 3 s. During the acquisition the sample was spun at 14 KHz around the magic angle. Silicon spectra were acquired by a single pulse at the resonance frequency of 119.19 MHz co-adding 1,024 transients with a recycle time of 60 s to avoid signal saturation. In this case the sample was spun at 10 KHz around the magic angle. Microscopy analysis was performed by using a Leica scanning electronic microscopy, coupled with an energy dispersive spectrometer (EDS). All samples were observed on the fractured surfaces coated with carbon before the analysis. The mechanical strength of all samples was tested at various ageing times using an Instron apparatus. Three cylindrical specimens were tested for each sample and an average result was obtained.

The compositions of the several specimens prepared in this research along with the labels used to indicate them are reported in Table 1.

Results and discussion

Pozzolana soil characterization

Table 2 reports the chemical composition of pozzolana soil along with its physical properties.

The X ray diffraction analysis showed that the material is mainly composed of an amorphous phase and no diffractive peaks due to crystalline domains could be observed.

Infrared characterization of the geopolymers

Table 2 Chemical composition and physical properties of pozzolana

Chemical composition (% wt/wt)	
SiO_2	59.5
Al_2O_3	19
CaO	4
Na_2O–K_2O	6
Fe_2O_3	6.5
MgO	4.25
Physical properties	
Unit weight γ_s (kN/m^3)	22–25
Mean particle size (d_{20} μm)	20
Mean particle size (d_{50} μm)	70
Mean particle size (d_{80} μm)	200
Void index e_o	1.2–1.5

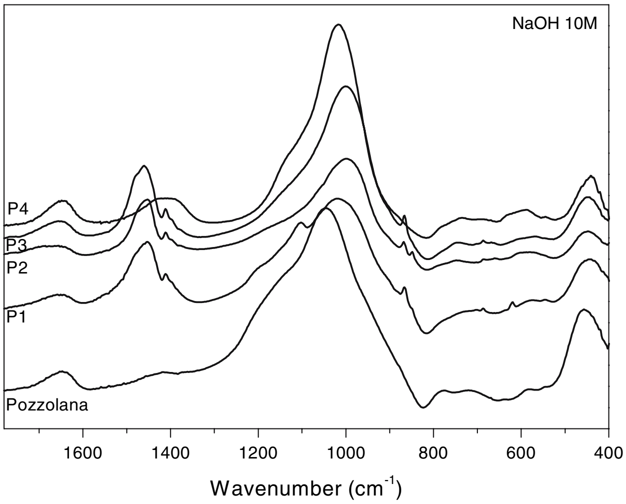

Fig. 1 FTIR spectra of neat pozzolana and geopolymer materials obtained by activation with NaOH 10 M solutions at different curing time

Figures 1 and 2 show the IR spectra of neat pozzolana in comparison with those related to pozzolana activated by NaOH 10 M solution and pozzolana activated by the NaOH–$NaAlO_2$ slurry, respectively. The latter have been collected at different curing time. The comparison of IR spectra represents a viable method to investigate and

Table 1 Composition of specimens prepared

Specimens	Pozzolana (g)	NaOH (mL)	$NaAlO_2$ (g)	T (°C)	Curing time
P1	150	60	0	25	7 days
PA1	150	60	17.14	25	7 days
P2	150	60	0	25	30 days
PA2	150	60	17.14	25	30 days
P3	150	60	0	25	150 days
PA3	150	60	17.14	25	150 days
P4	150	60	0	25	1 year
PA4	150	60	17.14	25	1 year

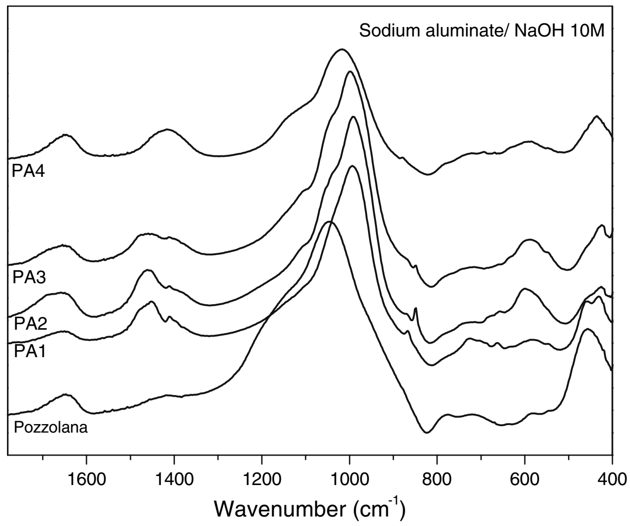

Fig. 2 FTIR spectra of neat pozzolana and geopolymer materials obtained by activation with NaOH 10 M and $NaAlO_2$ at different curing time

monitor the chemical modification of the silico–alluminate phases, involved during the geopolymer reactions.

In Table 3 are listed the assignments of the several absorbance bands observed in the spectra [10].

The spectrum of neat pozzolana shows a broad absorbance band ranging between 700 and 1,300 cm^{-1}. As reported by several authors [11, 12], the spectral profile of this band displays a fine structure, which is due to the overlapping of single peaks attributed to the asymmetric stretching of T–O–Si (T = Si and Al) bonds present in the amorphous structure of aluminosilicate. The broadness of the observed absorbance band is furthermore connected with the variability of the bond angles and bond lengths of the tetrahedral structures around the silicon atoms. These units are shown schematically in Fig. 3 and are referred to as Q_n. The subscript n denotes the number bridging oxygen present inside the tetrahedral units. In particular the bridging oxygen atoms connect either silicon atoms or silicon and aluminium atoms of different tetrahedral units [13].

Table 3 The experimental assignment of characteristics IR absorbance bands present in neat pozzolana and pozzolana treated with alkaline activators

Wavenumber, cm^{-1}	Assignments
950–1,200 (s)	Asymmetric stretching Si–O–Si and Si–O–Al
1,165 (s)	Asymmetric stretching Si–O–Si
1,074 (s)	Asymmetric stretching Si–O–Si and Si–O–Al
882 (s)	Stretching Si–OH
798 (m)	Symmetric stretching Si–O–Si
730 (s)	Stretching Al 6-coordinated geometry
620 (sh)	Symmetric stretching Si–O–Si and Si–O–Al
561 (s)	Symmetric stretching Si–O–Al
466 (s)	Bending (Si–O–Si and Si–O–Al)

The abbreviations in parenthesis are as follows: s, strong; m, medium; sh, shoulder

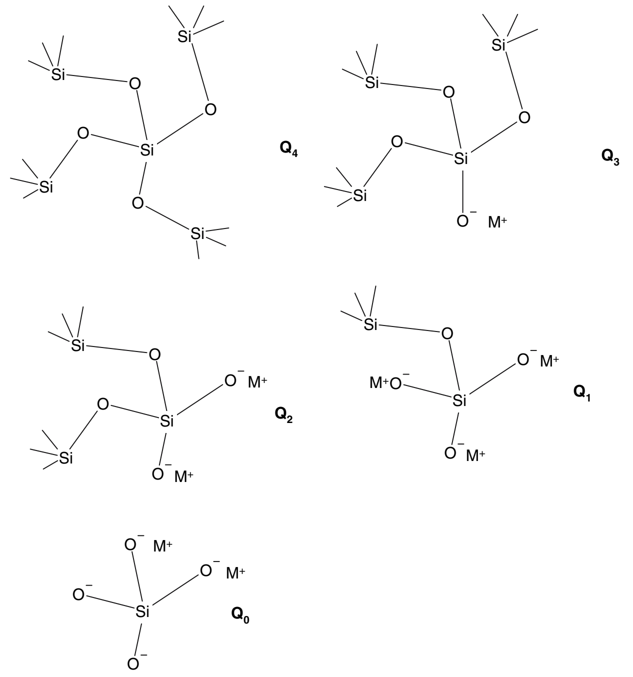

Fig. 3 Silicate structural units—schematic indicating the nature of bridging and non-bridging oxygen. M^+ represents the sodium cation

The comparison between the spectra of neat pozzolana and pozzolana activated by NaOH and NaOH–$NaAlO_2$ clearly evidences a shift of the T–O–Si stretching band towards lower wavenumbers, regardless of the curing time. Since the broad band is constituted by several single peaks, the blue shift (lower wavenumbers) could be due to changes in the relative amounts of the several species, which absorb in that spectral region. The maximum shift is obtained for the samples cured for about 30 days, regardless of type of the activation (NaOH solution or NaOH–$NaAlO_2$ slurry). At longer curing time the broad absorbance band moves towards higher wavenumbers recovering partly the previous blue shift. This spectral evidence can be attributed to the chemical modifications of the aluminosilicate structure of the pozzolana induced by the alkaline activation solutions. In fact it is well known that the alkaline solutions induce the breaking of covalent bonds of aluminate and silicate structure (present in the neat pozzolana) revealing more SiOH bonds along with Q_1 and Q_2 tetrahedral units. The increment of species characterised by these tetrahedral units induce the blue shift of the overall broad T–O–Si stretching band observed up to 30 days of curing time. Afterwards the species generated by the alkaline attack aggregate and react with each other in species characterized by a higher covalent connectivity T–O–Si (T = Si or Al) which contributes to shifting the overall broad band towards higher wavenumbers.

The spectra of pozzolana sample activated with NaOH–$NaAlO_2$ slurry displays a strong increment of the absorbance peak centred at about 580 cm^{-1}, which is not evident in the spectra of neat pozzolana and pozzolana samples activated with NaOH solutions. This peak is indicative of silicate and aluminosilicate glasses which possess long-range structural order in the form of rings of tetrahedral or octahedral [14, 15]. Furthermore the absorbance peak at 730 cm^{-1} is ascribed to the stretching vibration of Al–O–Si bonds with Al 6-coordinated [16]. This last peak is particularly evident at very short curing times and its absorbance intensity decreases with the geopolymerization process.

Both systems show an absorbance around 1,460 cm^{-1} attributed to the stretching of carbonate ions in sodium carbonate.

In the light of the different experimental evidences, we can infer that both the activation procedures (NaOH solution or NaOH–$NaAlO_2$ slurry) are capable of inducing a depolymerisation and structural reorganisation of the amorphous aluminosilicate phases present in the starting pozzolana. During the curing time, the amorphous phase is replaced by a new phase, which presents less long-range structural order. As far as the pozzolana activated by alkaline sodium aluminate slurry is concerned, the formation of Al 6-coordinated is probably due to the synergic effect of NaOH solution and high amount of sodium aluminate which favours the growth of structures with Si–O–Al long range structural order as confirmed by the absorbance peak located at 580 cm^{-1}. The presence of this peculiar absorbance peak represents the most important spectral evidence which differentiates the two activation mechanism adopted in this work. As reported by Davidovits [9] sodium-aluminate and Al 6-coordinated modify the chemistry of the polysialate macromolecules during the geopolymerization process and originate new amorphous and crystalline phases, which were able to bind together to the single pozzolana particles could justify the improvement of the mechanical performances of the pozzolana samples treated with NaOH–$NaAlO_2$ slurry in contrast to the sample treated with NaOH solution (see later).

XRD characterization of the geopolymers

Figures 4 and 5 displays the XRD patterns of neat pozzolana, pozzolana activated by NaOH 10 M solution and pozzolana activated by NaOH–$NaAlO_2$ slurry after different curing time. The XRD pattern of the neat pozzolana shows some broad bands typical of the amorphous structure. At the same time the XRD patterns of the pozzolana treated show some peculiar and interesting crystalline diffraction peaks that overlap the existing amorphous humps [17]. As for the pozzolana activated by NaOH–$NaAlO_2$ slurry the XRD diffractogram exhibits a series of new peaks at *d*-spacing values around 3.25 Å (27.5°), whereas the pozzolana activated by NaOH exhibits new crystalline peaks at 2.13 Å (42°).

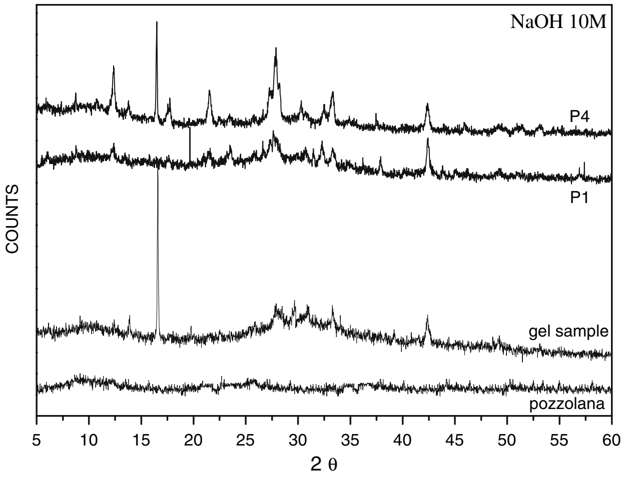

Fig. 4 XRD diffractograms of neat pozzolana, pozzolana treated with NaOH 10 M for different curing time

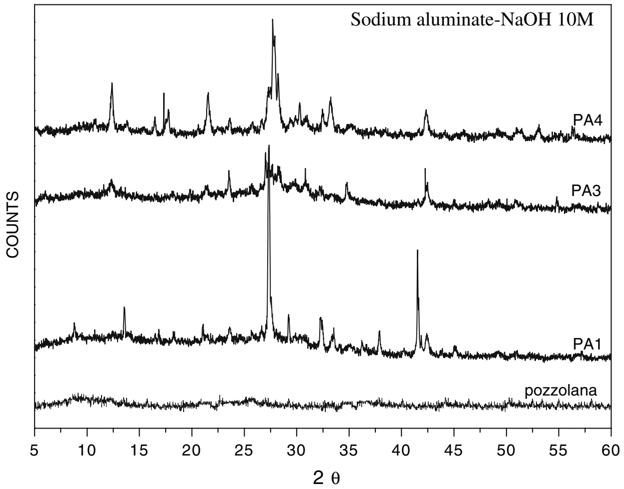

Fig. 5 XRD diffractograms of neat pozzolana, pozzolana treated with NaOH 10 M and $NaAlO_2$ for different curing time

The assignment of these crystalline peaks is not easy to perform. We can exclude for the specimens treated by NaOH 10 M the presence of sodium hydroxide crystalline diffraction peaks (because the fundamental *d*-spacing value is 2.35 Å (37.5°)) and for the pozzolana treated with NaOH–sodium aluminate solution the presence of sodium hydroxide and sodium aluminate crystalline diffraction peaks (because the fundamental *d*-spacing values are 2.35 Å and 2.30 Å (39°), respectively).

At the same time we cannot exclude the possibility of zeolite formation particularly when NaOH 10 M solution was used as activator [9, 18, 19]. In fact it is possible to observe, just in the gel phase, the presence of intense crystalline peaks attributed to the zeolitic phase (mullite). In the case of the activation by sodium aluminate–NaOH slurry we can observed, from XRD patterns, for the specimens of activated pozzolana cured at short time (PA1 in the Fig. 4) crystalline peak at 3.25 Å *d*-value spacing which was extremely intense and its intensity reduced during the curing process.

According to the FTIR spectra, which show for the same system the presence of an intense broad absorbance band at 730 cm^{-1} due to the 6-coordinate Al atoms, we could conclude that at short curing time an unstable crystalline phase precipitates where presumably the Al was 6-coordinated. This evidence is in agreement with some results presented by van Deventer [20–23] related to the effect of sodium aluminate diluted in NaOH solution during Fly-Ash based geopolymer production.

MAS NMR characterization of the geopolymers

MAS ^{27}Al NMR spectra of raw and treated pozzolana at different curing times are reported in Fig. 6. The ^{27}Al NMR MAS spectrum of neat pozzolana displays a broad peak at about 60 ppm characteristic of aluminium in a tetrahedric environment, and a barely visible peak at about 0 ppm due to aluminium 6-coordinated [24]. The treatment of pozzolana with NaOH and NaOH–NaAlO$_2$ induces a sharpening of the tetrahedral peak revealing an enhancement of the symmetry in the 4-coordinated phase after the treatment [25]. The presence of a small peak at about 5 ppm in the PA1 sample confirms that the presence of high amount of aluminate along with NaOH solution was capable of generating Al 6-coordinated at least during short curing time.

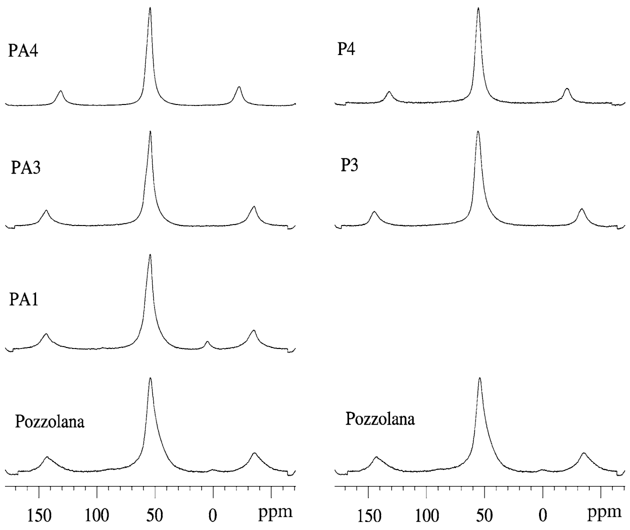

Fig. 6 ^{27}Al MAS spectra of neat pozzolana and pozzolana treated with NaOH and NaOH–NaAlO$_2$ for different curing time

The presence of Al 6-coordinated species, at short curing time, might affect the polysialate formation in terms of Al available for the polysialate relative reactions. Actually, it is important to see to what extent and in which way the presence of NaAlO$_2$ may influence the final structure of treated pozzolana after a long curing period.

However, a better inside can be obtained by ^{29}Si spectroscopy [26–28].

In Fig. 7 the ^{29}Si spectra of pozzolana treated with NaOH and NaOH–NaAlO$_2$ are shown. The spectra show a single broad convoluted band between 50 and 150 ppm which can be deconvoluted into six lines assigned to

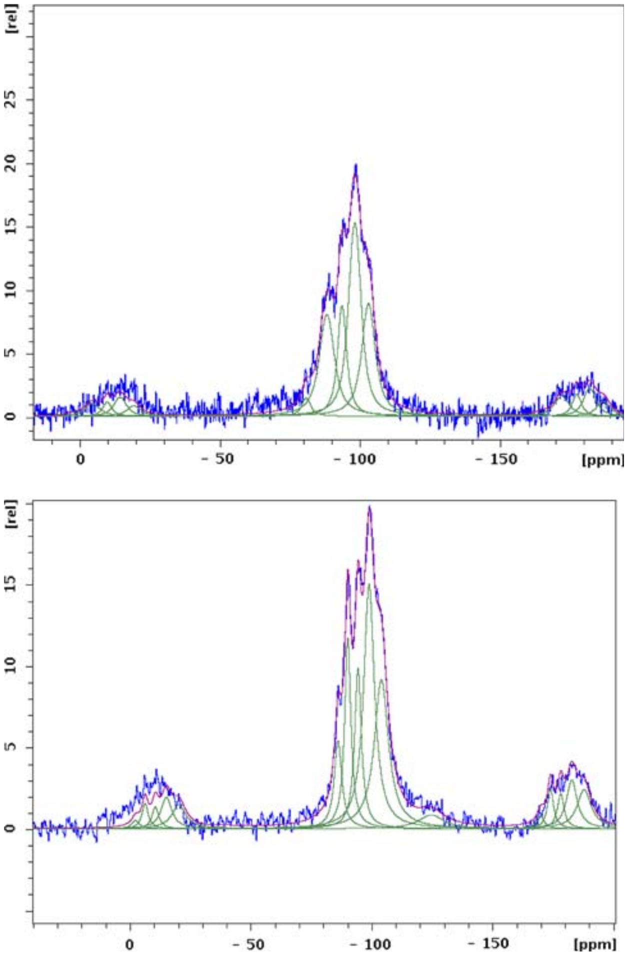

Fig. 7 ^{29}Si MAS spectra of neat pozzolana and pozzolana treated with NaOH and NaOH–NaAlO$_2$ for 1 year curing time. The deconvolution into quadrupolar lines is also reported

Table 4 The assignment of ^{29}Si NMR resonances in geopolymer

Chemical shift, ppm	Assignments
–72.9	$Si(OH)_4$
[–81,–84]	Q^4(4Al)
–88.7	Q^4(3Al)
–93.8	Q^4(2Al)
–99	Q^4(1Al)
–104.2	Q^4(0Al)
–108.6	Q^4(0Al) SiO_4

Q^4(mAl) species (m = 0,4). A summary of the line assignment is reported in Table 4.

From the areas of the deconvoluted lines the Si/Al ratio and the amount of Q^4(mAl) sites can be evaluated for the two samples. The results of these calculations are reported in Fig. 8.

As can be seen there are significant differences between the two samples. First of all the $NaAlO_2$ treated sample shows a lower Si/Al ratio confirming that the additional source of Al provided by $NaAlO_2$ actually affect the final composition of the treated pozzolana. In addition we observe a different distribution of Al atoms in the tetra coordinated Si–O–Al structures. Actually in the sample treated with only NaOH the most concentrated species is Q^4(1Al). The presence of high concentration of $NaAlO_2$ actually increments the coordination of four Al atoms to SiO_4 structures.

From the ^{29}Si spectra we effectively observe the insersion of Al atoms into the silicate network when $NaAlO_2$ is present during the polymerization reaction.

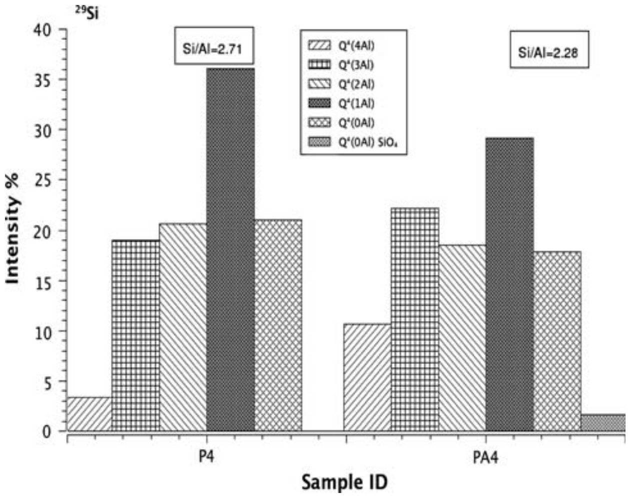

Fig. 8 Intensities of the Q^4(mAl) lines obtained from the ^{29}Si spectra of pozzolana treated with NaOH and NaOH–$NaAlO_2$ for 1 year curing time

SEM characterization and influence of the activation procedures on the microstructures of the geopolymers

The geopolymers synthesized starting from pozzolana showed a surface microstructure with the presence of peculiar morphologies. These originated from the reorganization of the amorphous phase triggered by the action of NaOH 10 M solution or $NaAlO_2$–NaOH slurry. Nevertheless, it is worth noting that observations under low magnifications displayed sample surfaces highly nonhomogeneous, as shown in Figs. 9a and 10a. Particles sized up to 20–30 μm with very smooth surface, due to the pozzolana material could be easily identified. These particles resulted clearly embedded in a matrix generated by the geopolymerization process. Observations under higher magnification of the geopolymer system obtained by NaOH solution activation showed a homogeneous matrix whose microstructure was (Fig. 10b) due to the presence of smaller "germinated morphology" particles sized up to about 1 μm. Otherwise the geopolymer system obtained by NaOH–$NaAlO_2$ slurry activation displayed a microstructure less

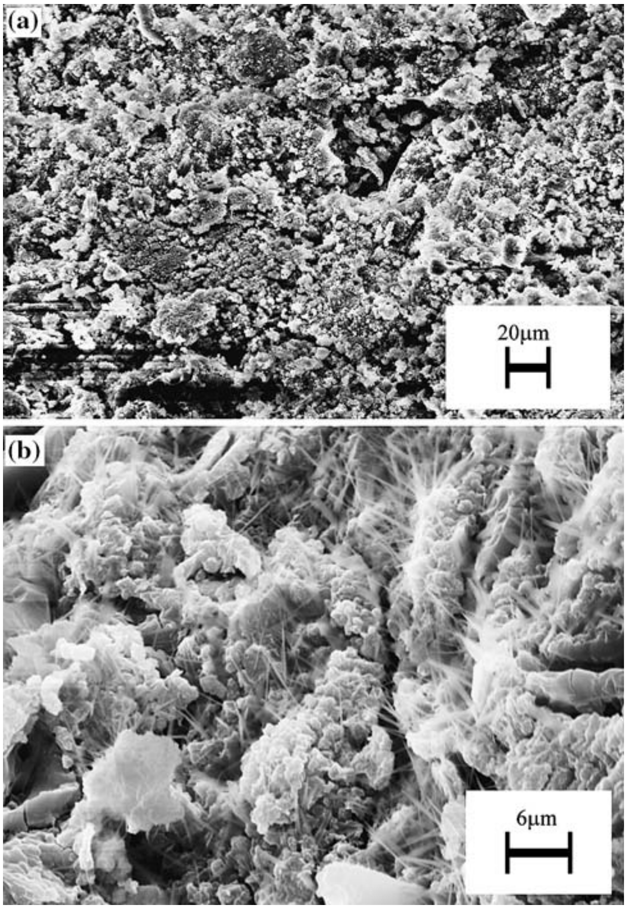

Fig. 9 SEM micrographs for selected systems; (**a**) pozzolana treated with NaOH 10 M–$NaAlO_2$ (574×); (**b**) pozzolana treated with NaOH 10 M–$NaAlO_2$ (5.24 K×)

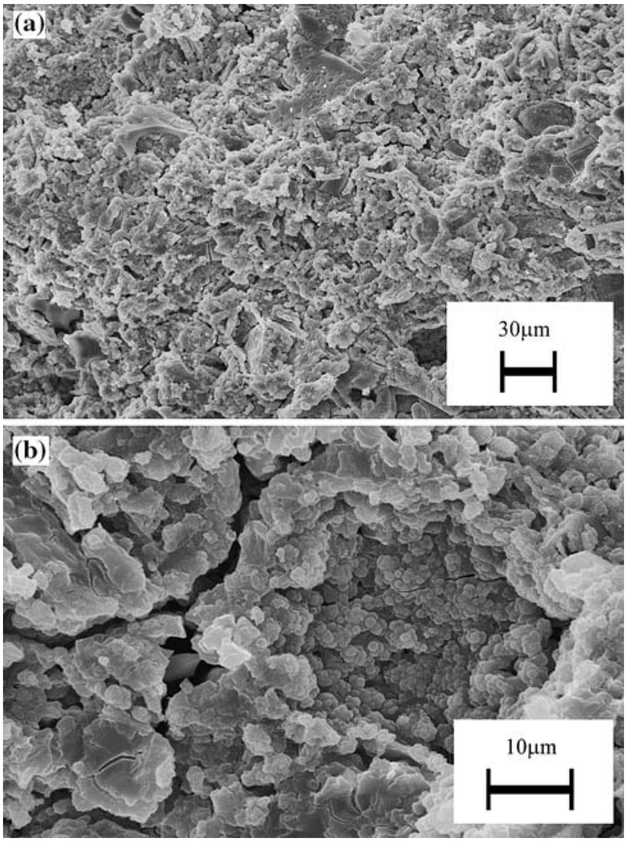

Fig. 10 SEM micrographs for selected systems; (**a**) pozzolana treated with NaOH 10 M (510×); (**b**) pozzolana treated with NaOH 10 M (2.34 K×)

compact than the other material with the presence of new formation morphologies like "needles" spreading out homogeneously throughout the sample surface (Fig. 9b).

Both activator solutions were capable of generating geopolymers whose finer microstructure did not permit to exclude the presence of crystalline phases within the primarily amorphous phase due to the reorganization of the pozzolana material. The presence of "germinated morphologies" or "needles morphologies" could confirm the XRD experimental results. This result represents a further evidence that the polysialate chemistry based on 4-coordinated Al is not capable of describing all to the phases of the geopolymers. As mentioned by van Deventer [14] this assumption will provide the basis for understanding the existence of different phases even crystalline that can operate in combination with the amorphous polysialate species affecting the final properties of the geopolymers.

Mechanical characterization of the geopolymers

Figure 11 displays the results of compression test reported in terms of uniaxial strength σ versus curing time for the several samples prepared.

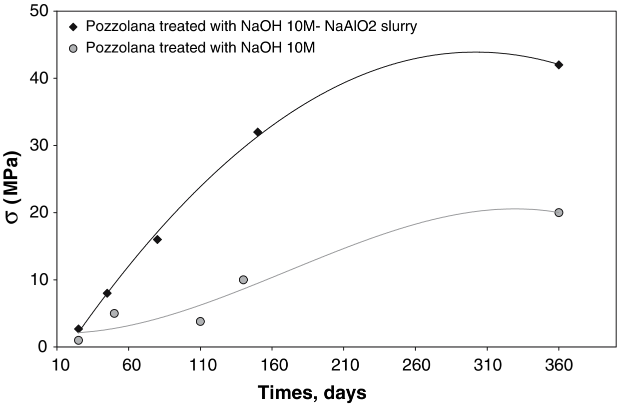

Fig. 11 Results of the uniaxial compression test on grouted pozzolana specimens

For both the activator systems adopted, an increase of uniaxial strength with curing time was observed. Furthermore, a higher uniaxial strength for the specimens grouted with the slurry between 10 M NaOH and $NaAlO_2$ was obtained (independently of curing time). For these specimens the maximum uniaxial strength reached after 1 year was about 42 MPa. The activator based on 10 M NaOH solution was unable to provide such mechanical improvements: in this case, in fact, the maximum measured uniaxial strength was about 10 MPa.

The experimental results show that the silico–aluminates network triggered by geo-polymerization reactions increase in strength with increase in time. However, in order to be realistically adopted on site, the time needed to obtain the desired increment of the mechanical properties cannot be larger than 60 days: for this reason the maximum value of the uniaxial strength obtained in 2 months (about 10 MPa) was assumed as the representative value for the grouted pozzolana.

Conclusions

Geopolymerization treatments of pozzolana soil with NaOH 10 M solution and slurry between NaOH solution and $NaAlO_2$ solid were carried out by using a hydrothermal curing process at room temperature. The results show that the utilization of geopolymerization represents a useful and effective method to consolidate pozzolana incoherent soils. In particular the activator consisting of slurry between NaOH 10 M solution and sodium–aluminate solid is able to trigger the formation of new phases in such a degree, which is higher than those obtained with the other activators as observed through compressive strength testing. These new phases are primarily amorphous and crystalline structures. XRD, NMR and FTIR analysis indicate that the consolidation mechanism is rather complex and further investigations are needed. Nevertheless it is evident that 4-coordinated Al atoms present in the neat pozzolana and in the sodium aluminate change their coordination state splitting between 6- and 4-coordinated atoms. In this way the traditional chemistry of polysialate is modified and the production of specific crystalline phases occur in the overall process.

In conclusion, it is worth pointing out that the applicability of such a methodology to consolidate incoherent soils is strictly connected to soil permeability and could be limited by the high costs of the raw materials. In the case of low permeability soils, the permeation of an alkaline solution can become very difficult because of the high initial viscosity of the activators. For this reason the "deep mixing" technique, which improves soil properties by remoulding it on site represents a valid technology to promote the application of the geopolymer synthesis to solve some geo-problems. As far as the elevated costs are concerned it is important to note that at the moment available large amounts of waste sodium aluminate from the recycling of metallic aluminium or from alumina from refineries are that could represent a source of aluminate at low costs. In this way it is possible to convert wastes in added-value products contributing to reduce the costs of the geopolymerization application to the soil consolidation.

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