Influence of the curing temperature on the properties of poly(phospho-ferro-siloxo) networks from laterite

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Abstract

The main objective of this work is to investigate the influence of the curing temperature on the properties of poly(phospho-ferro-siloxo) networks using laterite as an aluminoferosilicate source and phosphoric acid as a hardener. Poly(phospho-ferro-siloxo) networks were obtained by mixing phosphoric acid with calcined laterite and the fresh specimens were cast in different moulds. The prepared specimens were cured at room temperature, 40, 50, 60, 70, 80 and 90 °C for 24 h and then maintained at an ambient atmosphere of the laboratory for 28 days. The poly(phospho-ferro-siloxo) networks cured at room temperature were demoulded after 3 days due to its low rate of the hardening process. The obtained poly(phospho-ferro-siloxo) networks were characterized by measuring the compressive strengths, apparent density, X-ray diffractometry, infrared spectroscopy and scanning electron microscopy. The results show that the values of the compressive strengths of the final products decrease from room temperature (83 MPa) to 40 °C (48 MPa) and increase from 40 to 50 °C (65 MPa) afterwards decrease from 50 to 90 °C (24 MPa). It was found that the highest value of the compressive strength of poly(phospho-ferro-siloxo) network is around 83 MPa corresponding to the specimen demoulded after 3 days and maintained at room temperature for 28 days. Whereas, when the polycondensation reaction is accelerated, the most convenient curing temperature is around 50 °C which belongs to a compressive strength at about 65 MPa.

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Graphic abstract

Keywords Laterite · Phosphoric acid · Poly(phospho-ferro-siloxo) networks · Curing temperature · Compressive strength

1 Introduction

Geopolymer material is a binding system that hardens at room temperature like Portland cement paste, mortar or concrete [1]. It is important to note that this definition concerns geopolymer cements obtained using sodium or potassium waterglass as a hardener. However, Davidovits [1] reported that the geopolymer cement synthesizes in acidic medium route need an energy gradient which is necessary to promote the formation of a new 2D and/or 3D Si–O–P–O–Si network. Although this inorganic material hardens at room temperature when the alkaline solution was used as a hardener, some researchers studied the effect of the curing temperature on the properties of geopolymer cements. Regarding this investigation, Memon et al. [2] studied the effect of curing conditions on the strength of fly ash-based self-compacting geopolymer concrete. In this work, the authors cured the obtained specimens at 60, 70, 80 and 90 °C for 24, 48, 72 and 76 h. They reported that the compressive strength of geopolymer concrete cured at 70 °C for 48 h was higher compared to the others. Always in this perspective, Sindhunata et al. [3] prepared fly ash-based geopolymer cements and cured the obtained samples at 30, 50 and 75 °C for 24 h and concluded that the curing temperature increase with increasing the rate of reaction. Satpute et al. [4] studied the influence of the duration (6, 12, 16, 20 and 24 h) and

curing temperature (60, 90 and 120 °C) on the compressive strength of geopolymer concrete. The findings of this work showed that the compressive strengths increase with increasing the duration and the curing temperature. Whereas, Chen et al. [5] used metakaolin as aluminosilicate source for producing geopolymer cement which is cured at a different temperature such as 20, 40, 60, 80 and 100 °C for 24, 72 and 168 h. They concluded that the best condition to obtain geopolymer cement with higher mechanical properties was 60 °C for 168 h. van Jaarsveld et al. [6] investigated the effect of curing temperature on the properties of fly ash- and kaolinite-based geopolymers and concluded that the specimen cured at 70 °C seems to substantially improve the compressive strength compared to the one cured at 30 °C. Al Bakri et al. [7] investigated the curing temperature of geopolymer cements from fly ash as a raw material. In this work, authors cured the obtained geopolymer cements at room temperature, 50, 60, 70 and 80 °C and revealed that the maximum compressive strength was obtained at a temperature of 60 °C. Adam and Horiato [8] investigated the effect of temperature (80, 100 and 120 °C) and duration (4, 6 and 20 h) of curing on the strength of fly ash based geopolymer mortar. They reported that the highest compressive strength was obtained at the temperature and duration of curing of 120 °C and 20 h, respectively. Concerning the synthesis of geopolymer cement using phosphoric acid solution as a hardener, some researchers such as Cao et al. [9], Perera

et al. [10], Le-ping et al. [11], Louati et al. [12–14], Douiri et al. [15], Tchakouté et al. [16–18] used metakaolin as an aluminosilicate source and phosphoric acid for producing geopolymer cement. These authors cured the obtained geopolymer cement at 60 °C for 24 h. Medina and Guida [19] attempted to stabilize lateritic soils using a different proportion of phosphoric acid. The obtained products are cured at room temperature for 6, 13 and 27 days. Whereas, Gualtieri et al. [20] investigated the mechanical and microstructural properties of inorganic polymers from laterite as starting materials using phosphoric acid and sodium waterglass as hardeners. These authors also cured the final products at 60 °C for 24 h in an oven. Looking at the results revealed in the literature, the most convenient curing temperature of geopolymer cement using the alkaline solution as a hardener and fly ash or metakaolin as aluminosilicate sources is between 60 and 120 °C. Kaze et al. [21] used laterite as raw material for producing poly(sialate-ferro-siloxo) network but in this work, these authors cured their specimens at room temperature. With respect to those obtained in acidic medium, the final products were cured up to now at 60 °C for 24 h.

The main target of this work is to investigate the effect of the curing temperature on the properties of poly(phospho-ferro-siloxo) networks using laterite as an aluminosilicate source and the obtained products were cured at room temperature, 40, 50, 60, 70, 80 and 90 °C. The properties of the obtained products were monitored using the compressive strength testing, apparent density, X-ray diffractometry, infrared spectroscopy and scanning electron microscope.

2 Materials and experimental methods

2.1 Materials

The laterite used in this work was gathered from the laterite deposit at Ngoa-Ekele (Yaounde-Cameroon). This raw material is currently used in roads construction by the Civil Engineering body of the Military Force in Yaounde, Cameroon. It is also sold by the local population for fabricating local bricks for construction. Once collected, the laterite was firstly broken with a hammer, dried in ambient air and ground into fine particle sizes afterwards sieved through a 200 µm. The obtained powder is denoted NCLAT-N. The powder of laterite (NCLAT-N) was calcined in an electrical furnace (MGS, Srl) for 4 h at 700 °C with a heating and cooling rate of 5 °C/min. The powder of calcined laterite was labelled CLAT-N. Phosphoric acid (H₃PO₄, 85%, purists. ACS, d = 1.60 g/mL) was used as a chemical reagent.

2.2 Experimental methods

2.2.1 Synthesis of the hardener

The reactive ingredient was prepared by diluting commercial phosphoric acid in a distilled water in order to obtain the hardener with molar concentration 10 M. This molar concentration was chosen according to the findings work of Tchakouté et al. [16].

2.2.2 Preparation of the poly(phospho-ferro-siloxo) networks

Poly(phospho-ferro-siloxo) networks were prepared by adding the hardener to the powder of calcined laterite and mixed for 5 min in the porcelain mortar. The liquid/solid mass ratio was kept at 0.80 to obtain suitable workability. The obtained fresh specimens were poured in cubic moulds 40 × 40 × 40 mm and rectangular moulds 40 × 40 × 15 mm. The obtained specimens were vibrated mechanically for 2 min in order to remove the entrapped air bubbles and then sealed in the plastics. The obtained specimens were cured at room temperature, 40, 50, 60, 70, 80 and 90 °C in an electrical oven (Genlab Prime) for 24 h. The obtained poly(phospho-ferro-siloxo) networks were then demoulded and stored at ambient temperature (25 ± 3 °C) with a relative humidity of 53% for 28 days. But, the specimens cured at room temperature were easily demoulded after 3 days. Poly(phospho-ferro-siloxo) networks cured at room temperature, 40, 50, 60, 70, 80 and 90 °C were denoted CLAT-N1, CLAT-N2, CLAT-N3, CLAT-N4, CLAT-N5, CLAT-N6 and CLAT-N7, respectively.

2.3 Methods of characterization of raw materials and poly(phospho-ferro-siloxo) networks

The chemical composition of the powder of laterite was carried out by X-ray fluorescence (XRF) using Bruker Tiger S8 in order to determine the number of different oxides present in this starting material.

The mechanical and physical properties of the poly(phospho-ferro-siloxo) networks were assessed by the determination of their compressive strengths and apparent densities, respectively. The structural properties of the powders of the laterite, calcined laterite and the selected poly(phospho-ferro-siloxo) networks were monitored by measuring the X-ray diffractometry and infrared spectroscopy. The microstructure of the poly(phospho-ferro-siloxo) networks was investigated using a scanning electron microscope (SEM).

The compressive strengths of geopolymer cements were performed using an automatic hydraulic press with a 250 kN capacity and loading rate of 0.500 MPa/s. After the

measurement of the compressive strength, the fragments of the selected specimens were used for SEM observations.

XRD patterns of the powders of the laterite, calcined laterite and the selected poly(phospho-ferro-siloxo) networks were carried out using a Bruker D4 diffractometer generating CuK α radiation ($\lambda = 1.5405 \text{ \AA}$) between 5° and 80° (2θ) for 7 h in steps of $0.03^\circ 2\theta$.

The IR absorption spectra of the powders of laterite, calcined laterite and the selected poly(phospho-ferro-siloxo) networks were performed using the KBr method (Bruker Vertex 80v). For each spectrum, 1 mg of sample was mixed with 200 mg KBr in order to obtain a pellet. Each spectrum was obtained using 32 scans with a resolution of 2 cm^{-1} .

The fragments of the selected poly(phospho-ferro-siloxo) networks after gold-coating were used for microstructure observations using a JEOL JSM-6390A Scanning Electron Microscope (SEM).

Poly(phospho-ferro-siloxo) networks moulded in the rectangular moulds ($40 \times 40 \times 15 \text{ mm}$) were used for measuring the apparent density by Archimedes' method using an automatic instrument (Ceramic Instrument mod. DDA/2).

3 Results and discussion

3.1 Characterization of laterite and calcined laterite

3.1.1 Chemical composition

The chemical composition of laterite named NCLAT-N is showing in Table 1. It can be seen that this starting material is mainly constituted of Fe_2O_3 (58.43 wt%), SiO_2 (32.27 wt%) and Al_2O_3 (22.68 wt%). The higher iron oxide content is ascribed to the presence of iron minerals in the structure of laterite. The presence of these oxides in the structure of laterite implies that this material is an alumino-ferro-silicate. Besides these oxides, this material is also composed of TiO_2 (4.53 wt%), K_2O (0.13 wt%), Na_2O (0.03 wt%) and Mn_3O_4 (0.10 wt%) as impurities. The higher TiO_2 content could be attributed to the presence of anatase or rutile in the structure of alumino-ferro-silicate.

3.1.2 X-ray patterns

The X-ray patterns of laterite (NCLAT-N) and calcined laterite (CLAT-N) are given in Fig. 1. The X-ray patterns of both specimens revealed the presence of the reflection peaks

of kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$, PDF 1-00-001-0527), hematite (Fe_2O_3 , PDF 2-01-073-2234), anatase and quartz (SiO_2 , PDF 45-01-085-0457). The low intensity of the main peaks of kaolinite on the X-ray pattern of calcined laterite is related to the partial transformation of kaolinite to metakaolinite during the dehydroxylation process. The presence of metakaolinite is justified by the apparition of the diffuse halo structure from 15° to 30° (2θ). Besides these minerals, the X-ray pattern of raw laterite (NCLAT-N) exhibits the reflection peaks of goethite ($\text{FeO}(\text{OH})$, PDF 45-00-029-0713). This mineral disappears on the X-ray pattern of calcined laterite owing to the dehydroxylation of goethite to hematite. A similar result was obtained by Gualtieri et al. [20] and Kaze et al. [21]. The transformation of goethite to hematite is confirmed by the higher intensity peaks of hematite observed on the X-ray pattern of calcined laterite, CLAT-N.

3.1.3 Infrared spectra

The infrared spectra of laterite and calcined laterite measured in the range $4000\text{--}400 \text{ cm}^{-1}$ using KBr method are given in Fig. 2. The absorption bands at 3616 and 3695 cm^{-1} on the IR spectrum of raw laterite are ascribed to the hydroxyl groups (OH) of kaolinite [22, 23]. This is consistent with the X-ray pattern of laterite which shows the reflection peaks of kaolinite (Fig. 1). According to Walter et al. [24], the absorption band at 3145 cm^{-1} belongs to the vibration modes of O–H groups. The absorption bands located at 1010 , 1040 and 1096 cm^{-1} on the IR spectrum of NCLAT-N correspond to the symmetrical stretching vibration modes of Si–O–Si bonds of kaolinite [25]. The findings work of Munasir et al. [26] reported that the absorption bands at 464 and 1096 cm^{-1} is also assigned to the vibrations of Fe–O–Si bonds due to the presence of the higher amount of Fe_2O_3 (Table 1) in the structure of laterite. The absorption bands at 419 , 464 and 750 cm^{-1} correspond to the deformation vibration of Si–O bonds [27]. The bands at 912 and 539 cm^{-1} are assigned to the O–H deformation of Al–OH and bending vibrations of $\text{Al}^{\text{VI}}\text{--O--Si}$ bonds, respectively. The absorption band at 539 cm^{-1} on the IR spectrum of NCLAT-N appears at 543 cm^{-1} on the IR spectrum of CLAT-N. The displacement to this band toward higher wavenumber could be related to the calcination effect. Those at 690 and 799 cm^{-1} are attributed to the vibrations of siloxane groups of quartz [28]. After calcination of laterite, we observed the disappearance of the absorption bands at 690 , 750 , 799 , 912 , 1010 , 1040 and 1096 cm^{-1}

Table 1 Chemical composition of laterite, wt %

Sample	Oxides								
	SiO_2	Al_2O_3	Fe_2O_3	K_2O	Na_2O	CaO	TiO_2	MgO	MnO
NCLAT-N	35.53	28.21	36.32	0.25	0.82	0.21	1.81	0.25	0.05

Fig. 1 X-ray patterns of laterite (NCLAT-N) and calcined laterite (CLAT-N). K, G, Q, H and A denote peaks of kaolinite, goethite, quartz, hematite and anatase, respectively

and the appearance of those at 806 and 1070 cm^{-1} on the IR spectrum of calcined laterite (CLAT-N). Park et al. [29] founded that the band at 1070 cm^{-1} is attributed to the Fe–O–Si and Si–O–Al bonds. This could be related to the formation of amorphous phase (metakaolinite) and the partial replacement of Al by Fe^{3+} or Fe^{2+} on the tetrahedral network of the calcined laterite [30] whereas the one at 806 cm^{-1} is ascribed to the amorphous silica.

3.2 Characterization of poly(phospho-ferro-siloxo) networks

3.2.1 X-ray patterns

Figure 3 displays the X-ray patterns of the selected poly(phospho-ferro-siloxo) networks. This figure indicates that the X-ray patterns of the selected poly(phospho-ferro-siloxo) networks show the reflection

peaks of quartz, hematite, anatase and aluminum phosphate hydrate ($\text{AlPO}_4 \cdot \text{H}_2\text{O}$, PDF 129-00-015-0259). This latter mineral that the main peak appears at $7.07\text{ \AA}$ is formed by dealumination of calcined laterite during the depolymerization process. The dealumination process could be related to the reaction between the residual kaolinite observed on the X-ray pattern of calcined laterite (Fig. 1) with phosphoric acid leading to the formation of aluminum phosphate hydrate. The formation of poly(phospho-ferro-siloxo) networks is confirmed by the presence of the broad hump structure between 17° and 40° (2θ) on the X-ray patterns of CLAT-N1, CLAT-N2, CLAT-N3, CLAT-N4 and CLAT-N7 which appears in the range 15° – 30° (2θ) in the X-ray pattern of calcined laterite (Fig. 1). It can be seen that the intensity of this broad hump structure is lower on the X-ray pattern of CLAT-N7 compared to the others suggesting thus the reduction of poly(phospho-ferro-siloxo) chain.

Fig. 2 Infrared spectra of laterite (NCLAT-N) and calcined laterite (CLAT-N)

3.2.2 Infrared spectra

Figure 4 exhibits the infrared spectra of poly(phospho-ferro-siloxo) networks cured at different temperature using laterite as an aluminoferrasilicate material. It indicates the broad band at around 3367 cm^{-1} and the weak one at 1650 cm^{-1} corresponding to the O–H to the stretching vibrations of O–H and H–O–H bonds, respectively [31, 32]. The band at 467 cm^{-1} belongs to the stretching vibrations of Si–O and Si–O–Fe bonds [33]. The absorption band at 535 cm^{-1} is assigned to the vibration modes of Al–O–P of AlPO_4 chains [34] confirming the presence of the aluminum phosphate hydrate observed on the X-ray patterns of poly(phospho-ferro-siloxo) networks. It is important to note that this band appears at 543 cm^{-1} on the IR spectrum of calcined laterite (Fig. 2). The shift of this band toward lower wavenumber could be related to the fact that the cations Al^{3+} from calcined laterite leached out during the dealumination process and react with a part of PO_4^{3-} from phosphoric acid implying the formation of $\text{AlPO}_4 \cdot \text{H}_2\text{O}$. The low intensity of the band at 799 cm^{-1} and the shoulder one at 912 cm^{-1} are assigned to the Si–O–P and asymmetric stretching vibrations of P–O–P, respectively [12, 35, 36]. The main absorption band of the prepared poly(phospho-ferro-siloxo) networks is the same for all specimens. It appears at 1089 cm^{-1} and belongs to

the phospho-ferro-siloxo—Si–O–P–O–Si–O–Fe bonds. This band appears at 1070 cm^{-1} on the IR spectrum of calcined laterite (Fig. 2) and the shift of this band toward higher wavenumber could be related to the incorporation of PO_4 units in the network of the final product. This is in agreement with the broad hump structure observed on the X-ray patterns of the selected poly(phospho-ferro-siloxo) network.

3.2.3 Apparent densities and compressive strengths

The values of the apparent densities and the compressive strengths as function as curing temperature are illustrated in Fig. 5. It can be seen that the values of the apparent densities of poly(phospho-ferro-siloxo) network CLAT-N1, CLAT-N2, CLAT-N3, CLAT-N4, CLAT-N5, CLAT-N6 and CLAT-N7 are 2.33 , 2.32 , 2.43 , 2.32 , 2.26 , 2.32 and 2.04 g/cm^3 , respectively. It appears that the values of the apparent densities are slightly decrease from room temperature to 40°C (i.e. from 2.33 to 2.32 g/cm^3), and increase from 40 to 50°C afterwards decrease from 50 to 90°C . The increase of the values of apparent densities from 40 to 50°C could be related to the low amount of evaporating of the unbound water which implying the slight shrinkage and tends to bring even closer the particles of poly(phospho-ferro-siloxo) network and therefore contributes to the

Fig. 3 X-ray patterns of the selected poly(phospho-ferro-siloxo) networks, CLAT-N1, CLAT-N2, CLAT-N3, CLAT-N4 and CLAT-N7. Al, Q, H and A denote peaks of aluminum phosphate hydrate, quartz, hematite and anatase, respectively

densification of the specimens. The decrease of the values of the apparent densities from 50 to 90 °C could be ascribed to the excessive loss of unbound water which results to the extensive shrinkage and therefore reduces the chain of the poly (phospho-ferro-siloxo) network. The reduction is in accordance with the X-ray pattern of CLAT-N7 which indicates the low intensity of the broad hump structure between 17° and 40° (2θ) (Fig. 3).

The values of the compressive strengths of CLAT-N1, CLAT-N2, CLAT-N3, CLAT-N4, CLAT-N5, CLAT-N6 and CLAT-N7 are 82.64, 47.93, 65.31, 46.37, 42.13, 31.87 and 23.85 MPa, respectively. It appears that the compressive strengths decrease from room temperature to 40 °C and increase from 40 to 50 °C afterwards decrease up to 90 °C. The recent works [4] done using metakaolin or fly ash as raw materials and alkaline solution as a hardener indicate that the compressive strengths increase with increasing the curing temperature. By contrary in this work, the compressive strength of poly(phospho-ferro-siloxo) network decreases from 50 °C when the curing temperature increases. These results were the same trend of the thermal behaviour of poly(phospho-siloxo) network [37] and geopolymer cements from

alkaline solution [38, 39] which show that the compressive strengths of geopolymer cement obtained in acidic medium decrease with increasing the curing temperature whereas those from alkaline medium are firstly increased and then decrease. This difference implies poly(phospho-ferro-siloxo) network is not fireproof compared to the (Na or K)-poly(sialate-siloxo) network. Davidovits [1] reported that geopolymer cement obtained in acidic medium required an energy gradient which is necessary to promote the formation of the binder. It is important to note that this conclusion concerns metakaolin because the preliminary work (not published) indicates that phosphate based-geopolymer cements from metakaolin do not harden at room temperature even after 28 days. Whereas, this work indicates that calcined laterite-phosphate-based geopolymer cement hardens at room temperature after 3 days. This shows that the raw material used for producing poly(phospho-siloxo) network plays a crucial role in its hardening process. Concerning the laterite used as starting material to prepare geopolymer cement, Subaer et al. [40] and Kaze et al. [41] prepared geopolymer cements using laterite as an aluminoferosilicate source and sodium waterglass

Fig. 4 Infrared spectra of the selected poly(phospho-ferro-siloxo) networks, CLAT-N1, CLAT-N2, CLAT-N3, CLAT-N4 and CLAT-N7

Fig. 5 Compressive strength and apparent density of poly(phospho-ferro-siloxo) networks, CLAT-N1, CLAT-N2, CLAT-N3, CLAT-N4, CLAT-N5, CLAT-N6 and CLAT-N7

as a hardener. These authors cured the final products at 70 °C for 1 h and at room temperature, respectively. Subaer et al. [40] obtained the compressive strengths between 39 and 43 MPa while Kaze et al. [41], their compressive strengths are in the range 10–18 MPa. By comparison with this work, the compressive strengths of the synthesis poly(phospho-ferro-siloxo) network obtained at room temperature (83 MPa) are highest than those obtained by Subaer et al. [40] and Kaze et al. [41]. Some researchers such as Louati et al. [12], Tchakouté et al. [16–18] assigned the higher compressive strengths of geopolymer cements obtained in acidic medium to the formation of berlinite which reinforces the structure of poly(phospho-ferro-siloxo) network. But we think that this could be ascribed to the fact that poly(phospho-ferro-siloxo) network consolidates into a ceramic [1] i.e. the particles of poly(phospho-ferro-siloxo) are well connected forming a cross-linking geopolymer framework. The highest value of the compressive strength of poly(phospho-ferro-siloxo) network demoulded after 3 days and cured at room temperature for 28 days is about 83 MPa. The lower value of the compressive strength of poly(phospho-ferro-siloxo) network, CLAT-N7 is in agreement with the lower value of its apparent density and the lower intensity of the broad hump structure between 17° and 40° (2 θ) observed on the X-ray pattern of CLAT-N7 (Fig. 3). It was typically found that when poly(phospho-ferro-siloxo) network from calcined laterite required an energy gradient, the most convenient curing temperature is around 50 °C.

3.2.4 Scanning electron microscope

The micrograph images with 200 $\times$, 1000 $\times$ and 5000 $\times$ magnification of the selected poly(phospho-ferro-siloxo) networks are recorded in Fig. 6. These micrographs indicate some cracks in their structures. These cracks could appear during the compressive strengths measurement. The presence of the air bubbles observed on the micrographs of the specimens CLAT-N1 and CLAT-N2 could be just air trapped in these samples during the mixture. These specimens and CLAT-N3 show some pores in their structure. The SEM images of poly(phospho-ferro-siloxo) network CLAT-N1, CLAT-N2 and CLAT-N3 are more compact microstructure confirming the assertion that phosphate-based geopolymer cement consolidates into a ceramic [1]. This is also corroborated with the higher values of their

compressive strengths (Fig. 5). The micrograph images of CLAT-N4 and CLAT-N7 with magnification 5000 $\times$ are seen a spongy appearance corresponding to their lower values of the apparent densities and compressive strengths especially for poly(phospho-ferro-siloxo) networks, CLAT-N7, cured at 90 °C whereas those with magnification 200 and 1000 $\times$ seem to be compact.

4 Conclusion

The main target of this was to study the effect of the curing temperature on the mechanical, physical, structural and microstructure of the poly(phospho-ferro-siloxo) networks using calcined laterite as an aluminoferosilicate source and phosphoric acid as a hardener. The final specimens were cured at room temperature, 40, 50, 60, 70, 80 and 90 °C for 24 h. The X-ray patterns of laterite and calcined laterite show the presence of kaolinite, hematite, anatase and quartz. Besides these minerals, the X-ray pattern of laterite indicates the presence of goethite which is transformed to hematite during the calcination process. The one of calcined laterite recorded the formation of metakaolinite. The X-ray patterns of the final products indicate the appearance of the broad hump structure between 17° and 40° (2 θ) implying the formation of the poly(phospho-ferro-siloxo) networks. The intensity of this diffuse halo structure is lower on the X-ray pattern of the sample cured at 90 °C corresponding to the formation of a lower chain. The higher value of the apparent density is around 2.43 g/cm³ corresponding to the poly(phospho-ferro-siloxo) network cured at 50 °C. The micrographs of the poly(phospho-ferro-siloxo) networks indicate that these specimens consolidate into ceramics. The compressive strength of the poly(phospho-ferro-siloxo) network cured at room temperature is higher than those cured in an oven. But this specimen is demoulded after 3 days maintained at the ambient atmosphere of the laboratory. The most convenient curing temperature when poly(phospho-ferro-siloxo) network required an energy gradient is around 50 °C. It was concluded that the poly(phospho-ferro-siloxo) network from laterite as an aluminoferosilicate source cured at room temperature or at 50 °C could be used to produce paving stones which could be used for the construction of the pedestrian road, bicycle-track and the quarter's roads construction.

Fig. 6 Micrograph images of poly(phospho-ferro-siloxo) networks

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Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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