

Co-utilization of construction and demolition with industrial wastes for the production of geopolymers

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Abstract

In the present experimental study the co-geopolymerisation potential of construction/demolition wastes (tiles, bricks and concrete) with fly ash, electric arc furnace slag and red mud is investigated. The effect of the molarity of alkaline activating solution (6, 8 or 10 M NaOH) and the different mixing ratios of the raw materials on the compressive strength of the produced geopolymers was studied. Geopolymers were synthesized by mixing the raw materials under continuous stirring with the alkaline solution prepared by dissolving NaOH anhydrous pellets in distilled water and sodium silicate solution. The pulp was cast in cubic metal moulds with an edge of 5 cm and heated at 80 or 90 °C for 7 days. After curing, the specimens were subjected to compressive strength testing. Analytical techniques, including X-ray diffraction (XRD), Fourier Transform Infrared Spectroscopy (FTIR) and Scanning Electron Microscopy (SEM) were used for the identification of the morphology of the final products.

Keywords

Construction and demolition wastes, industrial wastes, geopolymerisation, alkalinity

Introduction

Geopolymers are cementitious materials formed by alkali activation of aluminosilicates and are characterized by a partially or fully amorphous polymeric structure consisting of Si–O–Al bonds. The properties and the structure of geopolymers depend strongly on the chemical composition and particle size of the raw materials used, the concentration of the activating solution and the curing temperature. Their main properties include high compressive strength, low shrinkage and permeability, high acid resistance and thermal stability up to 1000 °C. The construction of building components with various properties as well as the encapsulation of hazardous elements and toxic wastes are some of the applications of geopolymers [1-4].

The potential of various industrial wastes such as fly ash, slag and red mud for the production of geopolymers has been investigated extensively during the last 25 years. The synthesis of geopolymers using construction/demolition wastes (CDW) such as bricks, tiles and recycled concrete still remains a challenge and a limited number of studies have been carried out so far [5-8].

The exact geopolymerisation mechanisms involving mainly dissolution, transportation and polycondensation, when wastes with complex mineralogy are used, can be to a certain extent elucidated with the use of several analytical techniques such as scanning electron microscopy (SEM), Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD) and thermogravimetric analysis (TG) [9, 10].

The present experimental study aims to investigate the co-geopolymerisation potential of construction and demolition wastes (tiles, bricks and concrete) with fly ash, ferronickel slag and red mud. The effect of the activating solution molarity and the different mixing ratios of the raw materials on the compressive strength of the produced geopolymers was also studied. XRD, FTIR and SEM were used for the identification of the morphology of the final products.

Materials and methodology

Construction and demolition wastes (CDW) namely tiles, bricks and concrete were collected from various demolished buildings of the Chania, Region of Crete, Greece, cleaned and dried prior to use. The industrial wastes used include fly ash from the Megalopolis power station in Peloponnese Greece, electric arc furnace slag from the “LARCO S.A” ferronickel plant in Larymna, Lokris, Greece, and red mud from the “Aluminium of Greece” in Agios Nikolaos, Veotia, Greece. All materials were pulverized using a Bico pulveriser Type UA and a FRITSCH pulveriser and homogenized. Grain-size

analysis was obtained using a Mastersizer S (Malvern Instruments) particle size analyser and is shown in Table 1. Table 2 shows the chemical composition of the raw materials in the form of oxides, as derived from an X-ray fluorescence energy dispersive spectrometer (XRF–EDS) Bruker-AXS S2 Range type. Loss of ignition (LOI) was determined by heating each raw material at 1050 °C for 4h.

Table 1. Particle size (μm) of raw materials

	Tiles (T)	Bricks (B)	Concrete (C)	Fly ash (F)	Slag (S)	Red mud (R)
size	<140	<140	<190	<121	<120	<76
d_{50}	14	7	10	10	12	4

Table 2. Chemical composition (%) of the raw materials

Component	Tiles (T)	Bricks (B)	Concrete (C)	Fly ash (F)	Slag (S)	Red mud (R)
SiO ₂	70.54	57.79	5.81	47.68	32.74	9.28
Al ₂ O ₃	9.80	14.95	1.49	18.44	8.32	15.83
CaO	8.78	8.79	65.42	9.94	3.73	10.53
Fe ₂ O ₃	5.39	6.00	0.75	7.52	43.83	41.65
Na ₂ O	-	1.03	0.57	0.37	-	2.26
K ₂ O	1.37	2.80	1.26	1.44	-	0.21
MgO	4.46	4.75	4.21	2.65	2.76	1.13
MnO	0.06	0.05	0.01	-	0.41	-
P ₂ O ₅	-	0.23	0.73	0.28	-	0.12
SO ₃	-	-	0.82	2.76	0.45	0.3
TiO ₂	0.77	0.85	0.03	0.76	-	4.73
Cr ₂ O ₃	-	-	-	-	3.07	-
CO ₂	-	-	-	3.87	0.40	-
LOI	0.23	1.89	21.59	4.3	-	16.77
Total	101.40	99.13	102.69	100.1	95.71	102.81

Geopolymers were synthesized by mixing the raw materials under continuous stirring with the alkaline solution prepared by dissolving NaOH anhydrous pellets (ACS-ISO for analysis) in distilled water and sodium silicate solution (Merck, Na₂O=7.5-8.5%, SiO₂=25.5-28.5%). Alkaline solutions were allowed to cool down at room temperature for 24 h prior to use. The resulting paste was cast in cubic metal moulds of 5 cm edge, which were vibrated for a few minutes to eliminate the presence of air voids within the reactive mass. The moulds remained at room temperature for one hour and when the paste hardened the specimens were demoulded and sealed in plastic bags to prevent evaporation of water and allow early initiation of geopolymeric reactions which favour the development of structural bonding. The specimens were then placed into a laboratory oven (ON-02G) and heated at 80 or 90 °C for 7 days. After curing, the specimens were subjected to compressive strength testing using a Matest C123N load frame. Control geopolymers were prepared by mixing each waste alone with the activating solution. Each experimental series was carried out in triplicate.

XRD analysis of the raw materials and geopolymers was performed using a Bruker D8 Advance diffractometer (Cu tube, scanning range from 3° to 70° 2 θ , step 0.03°, measuring time 4s/step) and the qualitative analysis using the Diffracplus Software (Bruker AXS). FTIR analysis on pellets produced after mixing a pulverized sample from each specimen with KBr at a ratio of 1:100 w/w, was carried out with a Perkin-Elmer Spectrum 1000 (USA). SEM analysis was carried out with a JEOL 6380LV scanning electron microscope equipped with an EDS INCA microanalysis system with low vacuum, pressure 30 Pa, voltage 20 kV and 10-12 mm working distance from the detector.

Results and discussion

Co-geopolymerisation of CDW and fly ash

The molar ratios of oxides in the initial paste used for the synthesis of selected CDW-based and control geopolymers, as well as their compressive strength, are given in Table 3 and discussed in the following paragraphs. In each case, the optimum heating temperature was used based on a previous study [11].

Table 3. Molar ratios of oxides of the initial paste for the synthesis of selected geopolymers (10 M NaOH)

	MPa	$\frac{SiO_2}{Al_2O_3}$	$\frac{SiO_2}{(Al_2O_3 + CaO)}$	$\frac{H_2O}{(Na_2O + K_2O)}$	$\frac{(Na_2O + K_2O)}{SiO_2}$	$\frac{SiO_2}{(Al_2O_3 + Fe_2O_3)}$
<i>T</i>	57.8	12.67	4.81	9.03	0.12	9.38
<i>B</i>	39.4	6.84	3.30	8.32	0.14	5.44
<i>C</i>	7.8	9.86	0.12	6.62	1.53	7.47
<i>F</i>	52.0	4.70	2.37	8.95	0.22	3.73
<i>S</i>	76.1	7.33	4.03	8.30	0.10	1.68
<i>R</i>	0.9	1.33	0.60	8.11	0.96	0.50
<i>80T-20F</i>	53.0	10.51	4.28	9.06	0.14	10.57
<i>80B-20F</i>	45.0	6.41	3.12	7.50	0.17	6.48
<i>80C-20F</i>	21.6	5.91	0.24	8.40	0.54	5.93
<i>50S-10T-10B-30C</i>	59.2	8.26	1.18	6.96	0.14	2.67
<i>25S-30T-30B-15C</i>	74.0	8.86	2.21	6.10	0.10	4.54
<i>90T-10R</i>	51.0	10.83	4.22	8.55	0.10	6.98
<i>50T-50R</i>	29.0	5.60	2.36	8.22	0.21	2.58
<i>90B-10R</i>	38.8	6.24	2.99	7.19	0.17	4.44
<i>50B-50R</i>	22.0	3.98	1.86	7.54	0.28	2.00
<i>90C-10R</i>	7.0	5.07	0.13	8.50	1.07	2.47
<i>50C-50R</i>	4.0	2.01	0.22	8.24	0.99	0.79

T: tiles, B: bricks, C: concrete, F: fly ash, S: slag, R: red mud, eg. 80T-20F: % w/w 80 tiles-20 fly ash

Figure 1 shows the compressive strength of geopolymers produced by mixing each CDW component, namely tiles, bricks and concrete with 10 and 20% w/w fly ash vs NaOH concentration. The compressive strength of the control specimens produced from geopolymerisation of each single component is also shown.

It is deduced from Figure 1 that the compressive strength of the specimens produced after mixing fly ash with construction and demolition wastes is in accordance with the compressive strength of the specimens produced after geopolymerisation of the single components. The optimum molarity of the alkaline solution during co-geopolymerisation is in most cases 10 M NaOH, while mixing of fly ash with bricks or tiles in percentages up to 20% w/w results in specimens with very good compressive strength, exceeding 50 and 40 MPa, respectively. Mixing of fly ash with concrete improves the compressive strength of the concrete-control specimens to values just above 20 MPa. More specifically:

- The specimens produced from co-geopolymerisation of tiles and fly ash with a solution 6 M NaOH acquire compressive strength which is good, between 28 and 32 MPa, but considerably lower than the strength of the tile-control geopolymer which is 56 MPa. It is mentioned that the compressive strength of the fly ash-control geopolymer at 6 M NaOH is poor and does not exceed 7 MPa. When the molarity of NaOH increases to 8 M co-geopolymerisation is rather poor, as for the single components and the compressive strength just exceeds 10 MPa. On the other hand, when the molarity of NaOH increases to 10 M co-geopolymerisation is feasible since at this molarity also the single components are well geopolymerised. The percentage addition of fly ash, either 10 or 20% w/w, does not seem to affect the process and the final specimens acquire high compressive strength that exceeds 50 MPa.
- Co-geopolymerisation of bricks and fly ash is favored when the molarity of the alkaline solution is either 8 or 10 M since at these values bricks and fly ash-control geopolymers, respectively, acquire the highest compressive strength. At 10 M NaOH the specimens produced acquire compressive strength that exceeds 40 MPa, regardless of the percentage addition of fly ash.

- Co-geopolymerisation of fly ash and concrete is rather poor, even at 10 M NaOH where fly ash shows excellent geopolymerisation potential. The optimum compressive strength values at this molarity for both addition percentages of fly ash vary between 16 and 22 MPa.

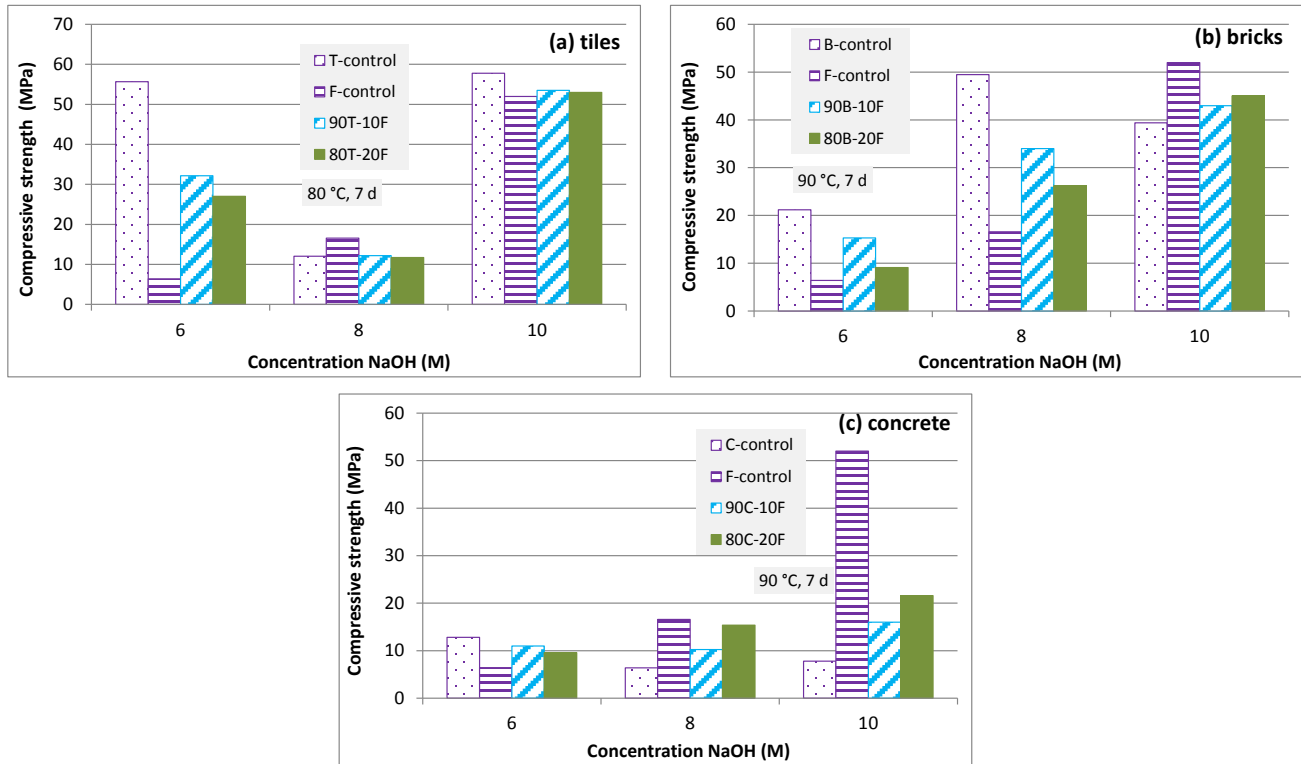


Figure 1. Compressive strength of geopolymers prepared by mixing (a) tiles, (b) bricks and (c) concrete with fly ash vs NaOH concentration (T: tiles, B: bricks, C: concrete, F: fly ash, eg. 90T-10F: % w/w 90 tiles-10 fly ash)

The experimental results show that the compressive strength of the specimens after co-geopolymerisation depends on the molarity of the alkaline solution but more importantly on the molar ratios of specific oxides ($\text{SiO}_2/\text{Al}_2\text{O}_3$, $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{SiO}_2$, $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{CaO})$ and $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$) in the initial paste which are affected by the high content of SiO_2 in fly ash (47.68% SiO_2). More specifically:

- High molarity of NaOH provides sufficient alkalinity in the mixture and enables dissolution of Si and Al ions from the raw materials that participate in geopolymeric reactions for the formation of Si–O–Al bonds [11].
- Tile- and brick-control geopolymers which show excellent geopolymerisation potential (at 10 M and 8 M, respectively) have high ratios of $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{CaO})$. The addition of fly ash which contains 47.68% SiO_2 , 18.44% Al_2O_3 , 9.94% CaO and 7.52% Fe_2O_3 modifies these and other ratios shown in Table 3 and affects the properties of the final products. For example, during co-geopolymerisation of tiles or bricks with 20% fly ash, where the highest compressive strength exceeding 45 MPa is acquired, the ratios of $\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{H}_2\text{O}/(\text{Na}_2\text{O}+\text{K}_2\text{O})$ and $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{SiO}_2$ vary between 6.42-10.51, 7.5-9.06 and 0.14-0.17, respectively and are quite similar to the respective ratios in tile- or brick-control geopolymers which also acquire similar compressive strength. On the other hand, during co-geopolymerisation of concrete and fly ash, where rather poor compressive strength is acquired, these three ratios are different (5.91, 8.40 and 0.54, respectively) even for the 80C-20F geopolymer that acquires strength of 22 MPa. Also the $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{CaO})$ ratio is extremely low (0.24) due to the high content of CaO in concrete (65.42%) and this is probably the main reason for the low compressive strength since CaO may consume NaOH rendering it unavailable for the dissolution of aluminosilicates from the raw materials.
- The lowest $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$ ratio, 3.73, is shown for fly ash-control geopolymer due to the high Fe_2O_3 content of fly ash (7.52%), while this ratio increases for brick and tile-control geopolymers when Fe_2O_3 content in raw materials decreases accordingly. It seems, however, that the strength of the final products may be affected by both the SiO_2 and Fe_2O_3 content of the raw materials, thus during mixing of the raw materials the ratio $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$ should be considered in combination with other ratios such as $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{CaO})$. For example, in geopolymer

80T-20F that acquires high strength (53 MPa) all the above ratios are high (10.57, 10.51 and 4.28, respectively) as shown in Table 3.

Co-geopolymerisation of CDW and ferronickel slag

The compressive strength of geopolymers produced by mixing CDW with ferronickel slag in various percentages at 8 or 10 M NaOH is presented in Figure 2. The compressive strength of the control geopolymers produced from slag and single components of CDW at 10 M NaOH is also shown for comparison. Since slag, tiles and bricks are well geopolymerised it is anticipated that the compressive strength values for most specimens involving mixtures of these components will be high.

When 8 M NaOH is used the strength of the specimens is around 55 MPa for all mixing combinations studied and is 30% lower than the strength of slag-control geopolymer. The use of 10 M NaOH has a positive effect on the compressive strength, for all mixing combinations, reaching 75 MPa when low percentages of concrete (10-15% w/w) are present in the initial paste.

Low percentage of concrete in the starting mixture maintains high $\text{SiO}_2/\text{Al}_2\text{O}_3$ molar ratios, which are 8.86 for the 25S-30T-30B-15C and 8.5 for the 50S-20T-20B-10C geopolymeric paste, respectively. It is mentioned that the respective ratio for the slag-control geopolymer is 7.33 (Table 3). When the concrete addition percentage increases to 25 or 30 % w/w, the compressive strength of the specimens decreases by 26% compared to the slag-control geopolymer but remains still high and varies between 56 and 59 MPa. The decrease of strength is mainly due to the high CaO content in the geopolymeric mixture, as a result of the addition of concrete. This addition results in lower $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{CaO})$ ratios, 1.58 for 25S-25T-250B-25C and 1.18 for 50S-10T-10B-30C geopolymers compared to the value of 4.03 for the respective ratio in the slag-control geopolymer.

The values of the ratio $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$ are affected mainly by the addition percentage of slag which contains 43.83% Fe_2O_3 and become 2.67-3.18 and 4.34-4.54 for the paste with 50 and 25% slag, respectively. This ratio is very low (1.68) as expected in the slag-control geopolymeric paste. Also, this ratio is increased by the addition of tiles with a very high SiO_2 content (70.54%), i.e from 2.67 to 3.18 when the tile addition percentage increases from 10 to 20% (50S-10T-10B-30C and 50S-20T-20B-10C geopolymer, respectively) and the compressive strength increases accordingly from 59 to 76 MPa.

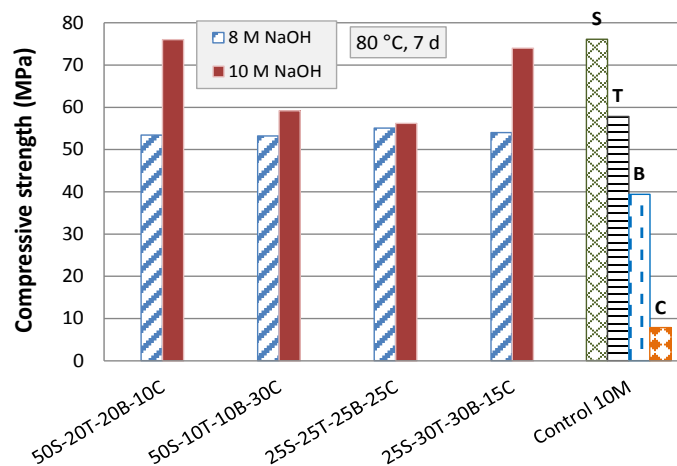


Figure 2. Compressive strength of geopolymers prepared by mixing CDW with slag in various percentages (eg. 50S-20T-20B-10C: % w/w 50 slag-20 tiles-20 bricks-10 concrete)

Co-geopolymerisation of CDW and red mud

Figure 3 shows the compressive strength of geopolymers prepared using each of the CDW components (tiles, bricks and concrete) and red mud in two different mixing percentages (90-10 and 50-50% w/w, respectively). Since concrete and especially red mud are poorly geopolymerised it is anticipated that the compressive strength of all specimens will be reduced to a higher or lower extent.

When geopolymers are synthesized using tiles and 10% w/w red mud (geopolymer 90T-10R) the compressive strength decreases slightly from 57.8 MPa to 51 MPa for the tile-control geopolymer. When equal amounts of tiles and red mud are mixed (50T-50R) the compressive strength remains acceptable but drops sharply to 29 MPa. A similar behaviour is shown

for brick-red mud geopolymers, where lower strength is acquired compared to the previous case (38.8 and 22 MPa for 90B-10R and 50B-50R, respectively). The high compressive strength of 90T-10R and 90B-10R geopolymers is mainly related to the favourable molar ratios of the oxides shown in Table 3, which do not vary significantly compared to the ratios of the respective control tile- and brick-geopolymers. For 50T-50R and 50B-50R geopolymers that acquire lower strength, with a substantially higher percentage of red mud in the starting paste, the molar ratios of the oxides shown in Table 3 are significantly affected, for example the $\text{SiO}_2/\text{Al}_2\text{O}_3$ ratio of 50T-50R specimen is almost 60% lower compared to that of tile-control geopolymer (5.60 and 12.57, respectively).

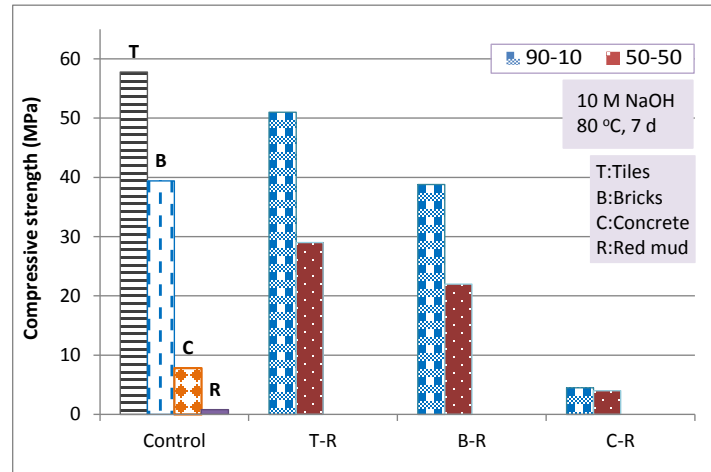


Figure 3. Compressive strength of geopolymers prepared by mixing tiles (T), bricks (B) and concrete (C) with red mud (R) at % w/w 90-10 and 50-50, respectively

When concrete is mixed with red mud by 10 or 50 % w/w, the strength of the specimens produced decreases from 7.8 MPa (concrete-control geopolymer) to 4 MPa. This result is anticipated since both materials, and especially red mud, exhibit poor geopolymerisation potential. The addition of red mud results in increased Al_2O_3 content in the starting mixture (red mud contains 15.83% Al_2O_3) and therefore most oxide molar ratios are affected. For example for 50C-50R specimen, $\text{SiO}_2/\text{Al}_2\text{O}_3$ and $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{Fe}_2\text{O}_3)$ ratios decrease significantly from 9.86 to 2.01 and from 7.47 to 0.79, respectively, indicating that Si is not sufficient in the initial mixture for the creation of geopolymeric bonds. It is mentioned that in red mud which is not geopolymerised at all (compressive strength acquired barely exceeds 1 MPa) the ratio $\text{SiO}_2/\text{Al}_2\text{O}_3$ is very low (1.33 as shown in Table 3).

Another aspect that affects the geopolymerisation of mixtures of raw materials containing red mud, is the high inherent alkalinity present in this alumina production by-product. Further studies should probably focus on reduction of this alkalinity prior to geopolymerisation or the addition of other raw materials that will control the most important oxide ratios in the starting mixture.

Characterization and morphology of the final specimens

Figure 4 shows the XRD patterns of selected geopolymers synthesized from CDW, fly ash, slag and red mud under the optimum synthesis conditions. It is mentioned that from the mineralogical analysis of CDW (data not shown) it is deduced that concrete consists of calcite and small quantities of quartz; bricks consist of quartz, calcite, hematite, diopside and albite; while tiles consist of calcite, quartz and orthoclase.

Partially reacted or unreacted crystalline phases which are present in geopolymers are also detected in the raw materials. This partial dissolution is also indicated by the decrease of the intensity of the crystalline peaks compared to the respective peaks of the raw materials.

Pirssonite, $\text{Na}_2\text{Ca}(\text{CO}_3)_2 \cdot 2\text{H}_2\text{O}$, which is an evaporite formed as a result of atmospheric carbonation, is mainly favored in concrete-based geopolymers due to the high CaO content in concrete (~65%) and the consumption of Na ions from the activating solution, which becomes thus unavailable for an advanced dissolution of aluminosilicates from the raw materials. Therefore, the formation of pirssonite is an indicator that can be used for the prediction of the low-strength geopolymers. Faujasite, which belongs to the zeolite family, is formed in small quantities in geopolymers prepared with 80% bricks and

20% w/w fly ash (80B-20F). Its presence may be related to the slightly higher strength of this geopolymer compared to brick-control geopolymer (45 and 39.4 MPa, respectively), indicating that the dissolved Si and Al are sufficient for the development of geopolymeric bonds while the remaining quantity participates in the formation of faujasite.

The FTIR spectra band assignments of the specimens characterized by XRD analysis are shown in Figure 5. The bands at 3450, 2950, 2340 and 1830 cm^{-1} are assigned to stretching and bending H–O–H vibrations of bound water molecules. The bands between 1420 and 1490 cm^{-1} as well as at 880 cm^{-1} are due to atmospheric carbonation, asymmetric stretching and out of plane bending modes of CO_3 . These bands, which are attributed to the modes of CO_3 in CaCO_3 , are quite strong in concrete-control geopolymer (C) and geopolymer 25S-30T-30B-15C containing 15% concrete.

The broad peaks at 1050 cm^{-1} are shown in geopolymers that acquired compressive strength higher than 40 MPa. This peak is the fingerprint of the geopolymeric matrix and is attributed to Si–O–Si or Al–O–Si asymmetric stretching vibrations during geopolymerisation. Therefore, the formation of the amorphous aluminosilicate gel due to dissolution of the raw materials under highly alkaline conditions is indicated. No such peaks are shown in concrete (C) and red mud (R) specimens that acquire low strength (7.8 and 0.9 MPa, respectively). The bands at around 460 and 710 cm^{-1} are detected in all specimens and are due to in plane Si–O bending and Al–O linkages as well as Si–O–Si and O–Si–O vibrations [11].

In Figure 6, SEM images of selected geopolymers synthesized from slag, bricks, red mud as well as by mixing raw materials (90C-10R, 25S-30T-30B-15C and 80T-20F) are illustrated. The slag-control geopolymeric matrix (Fig. 6, upper row, left) exhibits a certain degree of homogeneity that improves the final strength of the specimen. In brick-control, 25S-30T-30B-15C and 80T-20F specimens (Fig. 6, lower row, left to right), the geopolymeric networks present act as binders between grains. High content of Si and Al is detected in all the above mentioned geopolymers according to EDS analysis (not shown), thus contributing to high final strength varying between 40 and 76 MPa. The matrix of red mud-based specimen as well as of 90C-10R geopolymer (Fig.6, upper row, right and center, respectively) is quite heterogeneous and grains of various sizes are detected, indicating limited reaction of initial red mud or concrete during alkali-activation and thus very low compressive strength for the final products (around 1 and 7 MPa, respectively). As also deduced from EDS analysis, Fe and Ca are the main components detected in R and 90C-10R geopolymers, while Si and Al, which are the main elements required for the formation of geopolymeric bonds, are detected in limited quantities.

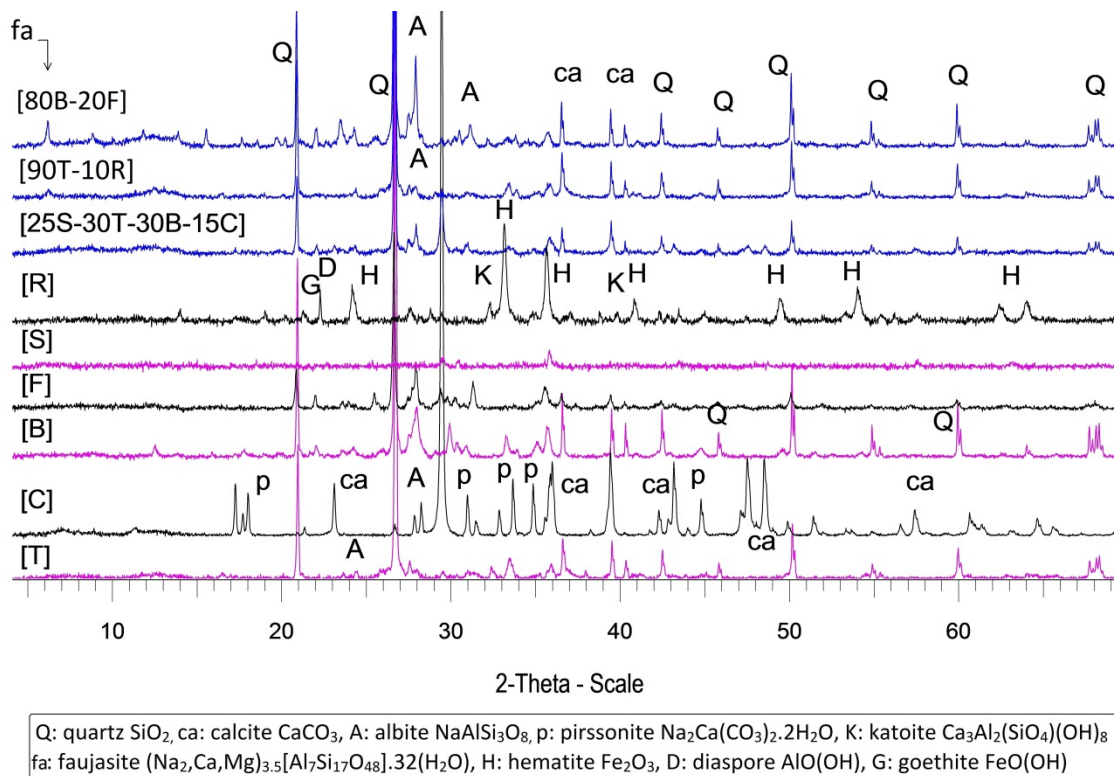


Figure 4. XRD patterns of selected geopolymers synthesized from CDW and industrial wastes (B: bricks, T: tiles, C: concrete, F: fly ash, S: slag, R: red mud)

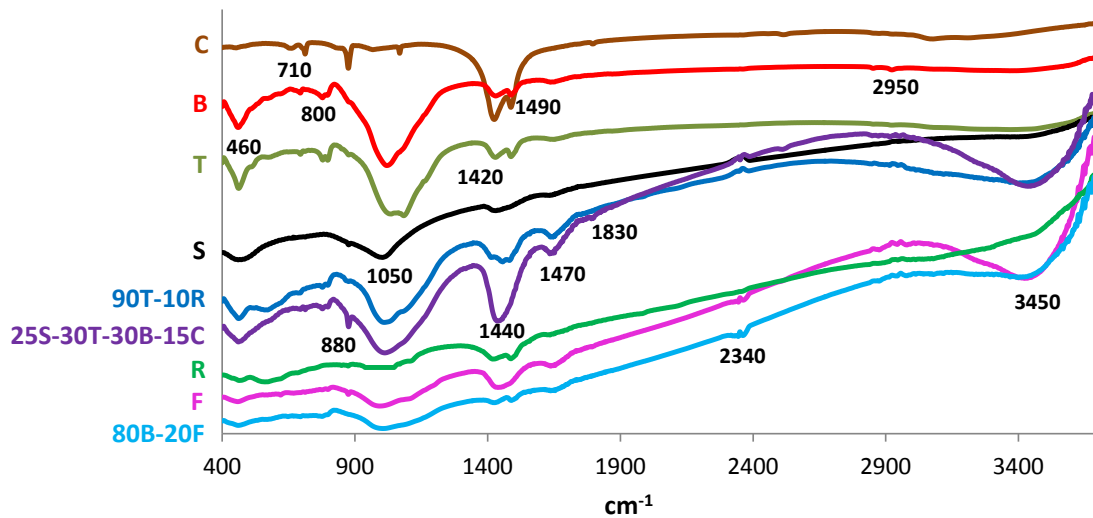


Figure 5. FTIR spectra of selected geopolymers synthesized from CDW and industrial wastes (B: bricks, T: tiles, C: concrete, F: fly ash, S: slag, R: red mud)

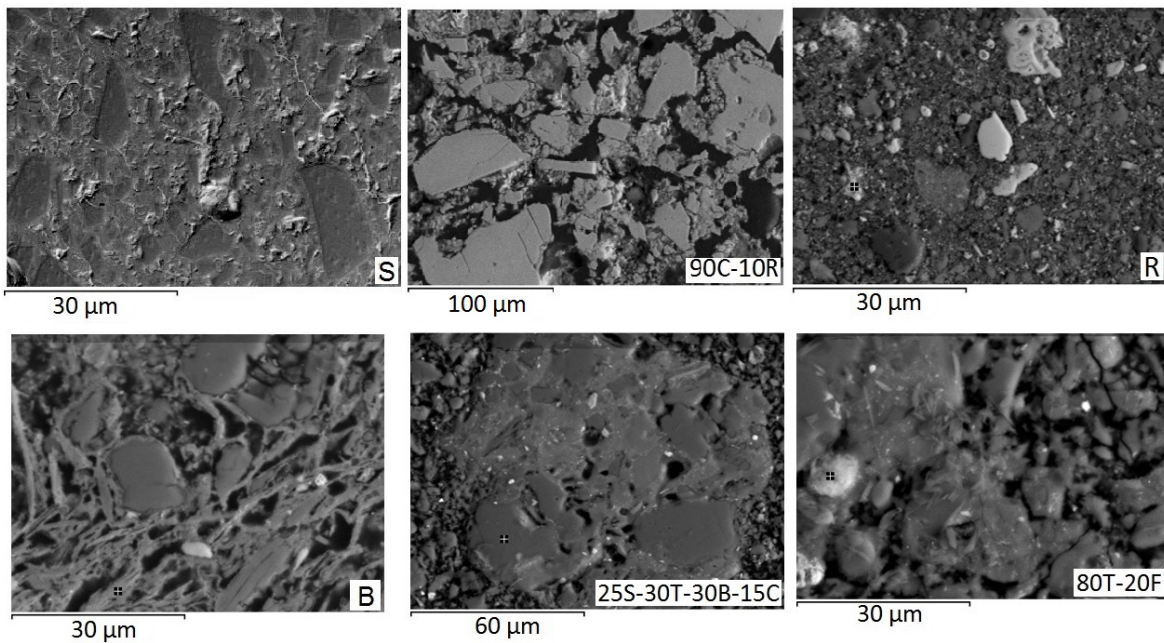


Figure 6. SEM images of selected geopolymers synthesized from CDW and industrial wastes (B: bricks, T: tiles, C: concrete, F: fly ash, S: slag, R: red mud)

Conclusions

Several industrial wastes, namely fly ash, slag and red mud can be successfully co-geopolymerised with construction and demolition wastes for the production of specimens that acquire compressive strength up to 76 MPa. The best geopolymerisation potential is shown for geopolymers prepared by mixing % w/w 50 slag-20 tiles-20 bricks-10 concrete, 90 tiles-10 fly ash and 90 tiles-10 red mud acquiring strength of 76, 54 and 51 MPa, respectively. Bricks, tiles, slag and fly ash can be successfully geopolymerised when mixed alone with alkaline activating solution reaching a compressive strength of 40 to 76 MPa due to the high SiO_2 and Al_2O_3 and low CaO content, while low strength (1-8 MPa) was obtained for concrete and red mud geopolymers.

The strength increase of geopolymers is related to the increased molarity of the activating solution. The optimum NaOH molarity is 10 M, while lower concentrations (8 M) do not provide sufficient alkalinity in the mixture and thus less Si and

Al ions are dissolved. The strength is also related to the values of the molar ratios $\text{SiO}_2/\text{Al}_2\text{O}_3$, $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{CaO})$ and $(\text{Na}_2\text{O}+\text{K}_2\text{O})/\text{SiO}_2$ which are mainly affected by the content of SiO_2 in the geopolymeric mixture. For example, for the geopolymer prepared from % w/w 50 slag-20 tiles-20 bricks-10 concrete the high $\text{SiO}_2/\text{Al}_2\text{O}_3$ and low $\text{SiO}_2/(\text{Al}_2\text{O}_3+\text{CaO})$ ratios (8.50 and 2.5, respectively) are in accordance with its high strength (76 MPa).

XRD, FTIR and SEM analyses provide very useful insights on the microstructure and the characterization of the produced geopolymers. The presence of the major fingerprints of the aluminosilicate geopolymeric matrix for high strength geopolymers, is revealed by FTIR analysis. Specimens prepared using bricks, tiles, slag and fly ash are characterized by a quite homogeneous matrix through SEM studies, with high content in Si and Al due to the sufficient dissolution of the raw materials under highly alkaline conditions. On the other hand, in specimens prepared using concrete or red mud limited or partial reaction of the initial materials is shown. In concrete-based geopolymers, as revealed by XRD analysis, the formation of pirssonite as a result of atmospheric carbonation is an indication of low strength geopolymers.

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