Chapter

Introductory Chapter: Case Studies of Functional Geopolymers

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1. Introduction

Geopolymers are a relatively new material [1–5]. Basically, this term is applied to material class that is chemically transformed from low-crystallinity aluminosilicates to three-dimensional inorganic polymers (tectosilicates). The resulting material has properties similar to natural minerals, so it is called artificial rock [3, 6]. Actually these materials exhibit chemical composition and mineralogical structure similar to feldspar, feldspathoid, and zeolites consisting of a polymeric Si–O–Al framework, with a microcrystalline or an amorphous structure. Geopolymers were termed for this group of materials by Prof. Davidovits [1].

The major aim of developing the geopolymers is to find alternatives to portland cement and thus to reduce carbon dioxide emissions during cement processing [7]. But in recent years, there has been an observable development in geopolymers and their applications, which have been used in various fields such as construction, waste management, art, and decoration [6, 8]. The precursors of geopolymers are characterized by the availability, whether earth materials such as kaolinitic soil or waste such as fly ash. Many geopolymeric materials are still under development, but some products are already commercialized and used in different fields.

Although geopolymers have attractive engineering and environmental characteristics, there are some challenges in commercializing these materials [9, 10]. In this chapter, these challenges will be addressed along with introducing the functional geopolymers as one of the effective approaches to commercialize these materials and make them economically feasible. Functional geopolymers are defined as geopolymers with more than one use at a time, such as use in construction and water purification or use in construction and passive cooling of houses [11].

2. Functional geopolymers and their applications

In the following sections, some of the most important functional geopolymers and their applications are discussed.

2.1 Geopolymers for construction and water treatment

This research approach is related to the use of geopolymers not only for construction purposes but also for water purification. The major interest is based on

Kaolinite		Zeolitic tuff (ZK)	
Compound	**Composition%**	**Compound**	**Composition%**
MnO	0.01	MnO	0.04
Na_2O	0	Na_2O	0.77
CaO	0.06	CaO	14.66
K_2O	1.05	K_2O	3.42
MgO	0.93	MgO	2.76
P_2O_5	0.4	P_2O_5	0.05
Fe_2O_3	0.29	Fe_2O_3	1.36
Al_2O_3	33.57	Al_2O_3	11.04
SiO_2	41.14	SiO_2	58.35
TiO_2	0.36	LOI	7.55
LOI	11.8		

Table 1.
The chemical analysis of kaolinite and zeolitic tuff (ZK) [8].

Series	Zeolitic tuff/metakaolinite weight ratio
G1	0
G2	0.25
G3	0.50
G4	0.75

Table 2.
Composition of geopolymers [8].

the physical properties of materials as well as porosity. Therefore, in addition to the geopolymer porous matrix, natural zeolite is used as a filler or partial reactant.

Geopolymers were prepared using metakaolin, zeolitic tuff (ZK), and alkaline activators. The natural zeolitic tuff, mordenite, was collected from Kimolos Island, Greece. This mineral is associated with calcite and dolomite [8]. Metakaolin was prepared by calcination of kaolinite (Fluka, Germany) at 750°C for 3 to 4 h. The chemical composition of both the zeolitic tuff and kaolinite is reported in **Table 1**. Alkaline activators are prepared using sodium silicate solution and sodium hydroxide. The SiO2-to-Na2O molar ratio is 1, and the Na2O-to-Al2O3 ratio (from metakaolin) is 1. Finally the molar ratio of H2O/Na2O is 7. The zeolitic tuff is added in different ratios as reported in **Table 2**.

Geopolymers exhibit a nanoporous matrix gel as reported in **Figure 1** [8, 12–14]. This porous matrix assists in increasing the surface area and the physicochemical adsorption of micropollutants. The adsorption capacity of geopolymers with different zeolites/metakaolins was studied in terms of adsorption of Cu2+ ions at a pH of 3.

All the geopolymeric specimens exhibit high adsorption capacity of 8 mg Cu/g for samples G3 and G4 after 1 day (**Figure 2**). It is observed that the adsorption capacity of bulk disks of geopolymers is comparable with powdered zeolites in other findings [15]. **Figure 2** illustrates that increasing the zeolitic tuff percentages to 50% causes an increment in the adsorption capacity by several times. Therefore, this type of geopolymer can be used effectively in water treatment.

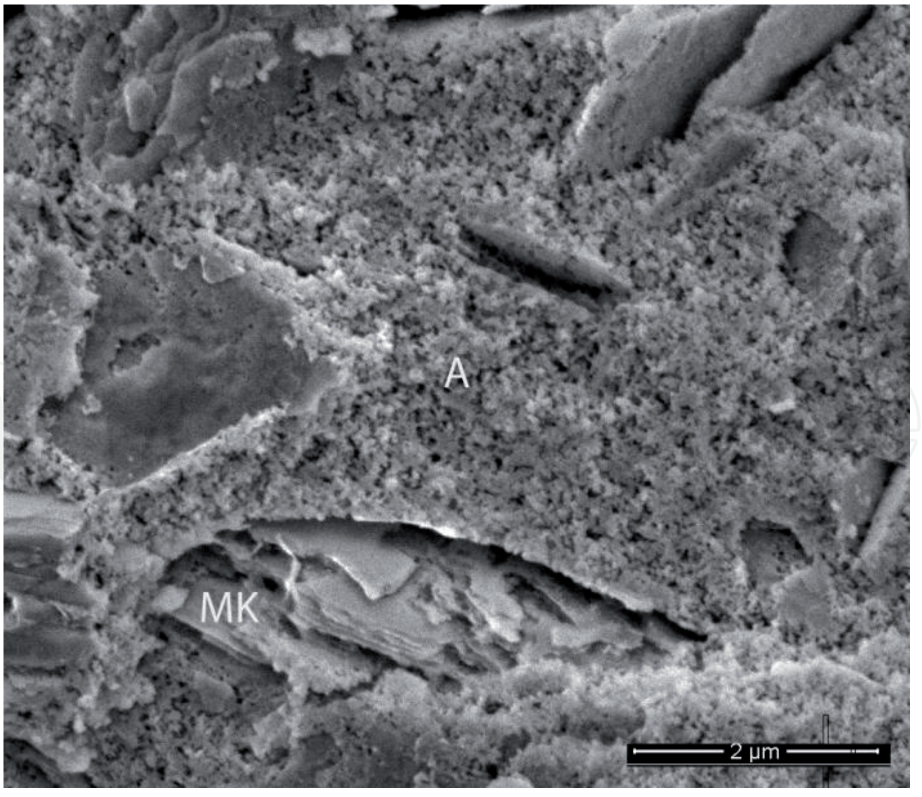

Figure 1.
SEM image of geopolymers. MK: Partially transformed metakaolinite. A: Geopolymer gel [8].

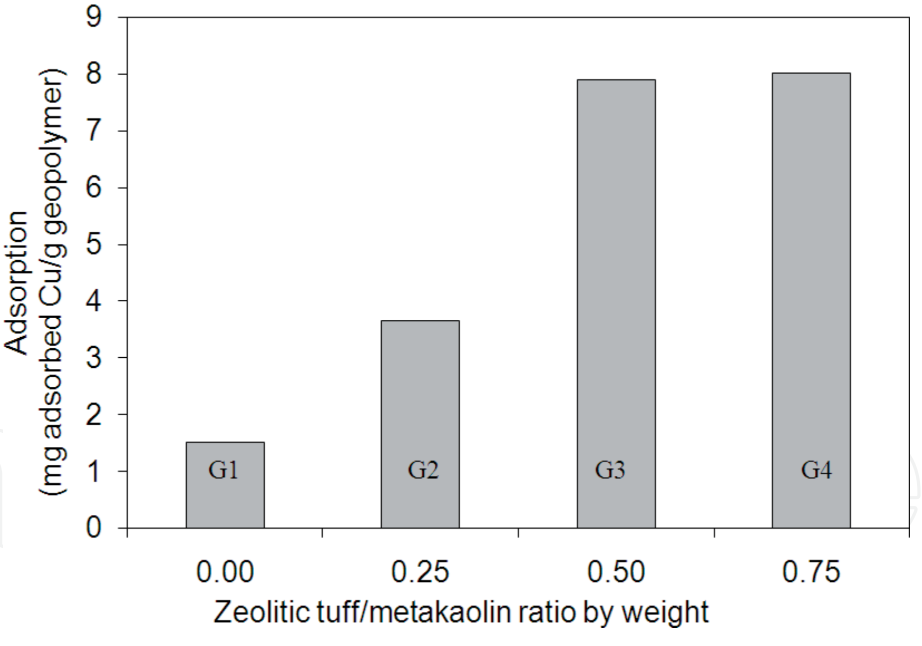

Figure 2.
Adsorption of Cu (II) onto geopolymeric disks, pH = 3 [8].

2.2 Natural fiber-reinforced geopolymers for construction and passive cooling systems

In a recent research, vascular natural fiber is used to improve the properties of end products to be used for more than one purpose. The use of natural fibers such as *Luffa cylindrica* fibers (LCF) as reinforcements for geopolymers has several objectives. In addition to improving mechanical properties, these vascular fibers improve the microstructural properties of the resulting material. In this research,

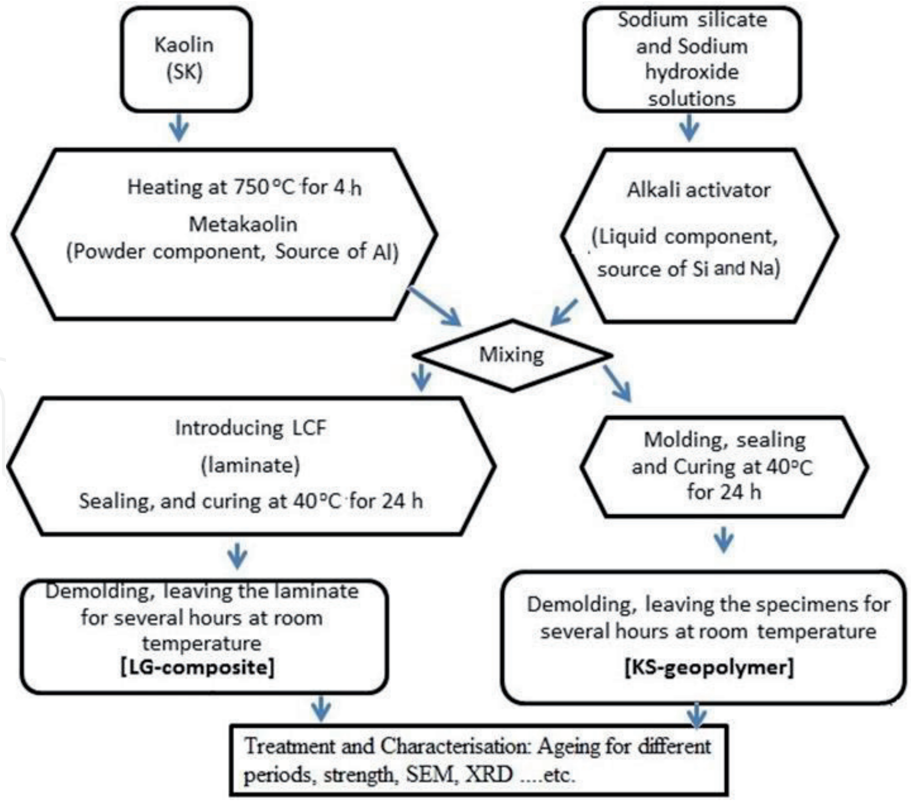

Figure 3.
The schematic diagram of the research methodology [11].

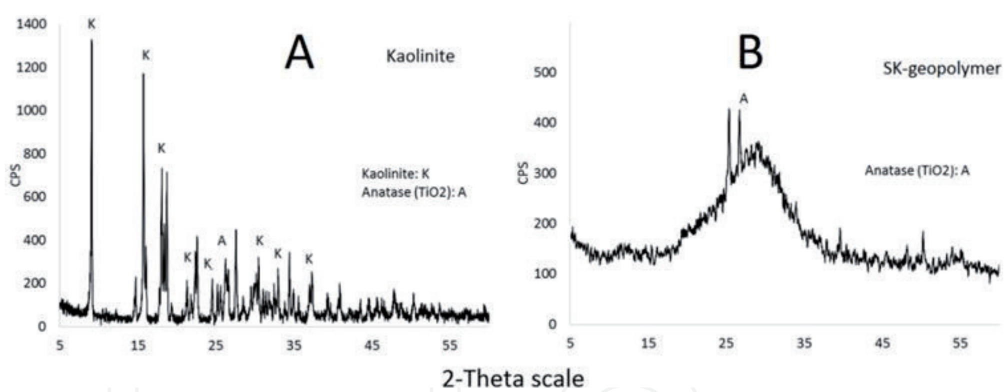

Figure 4.
XRD patterns corresponding to kaolin and the resultant geopolymer [11].

geopolymers (Sk-geopolymer) and LCF-reinforced geopolymers (LG composite) were made for reference and polymer composites using fiber as a reinforcing material with volume percentage of 10% as shown in **Figure 3**. The composition of the Sk-geopolymer was reported in our previous work [11].

As can be seen from X-ray tests, **Figure 4**, kaolinitic soil is transformed to an amorphous geopolymer gel as a result of the calcination at 750°C and the subsequent geopolymerization reactions [11, 16, 17]. These XRD results are in agreement with the SEM images as reported in **Figure 5**. The kaolin layers in **Figure 5A** break down by the geopolymerization process to obtain geopolymers with a semi-uniform nano-pore network as shown in **Figure 5B**. We also note the presence of bundles of tubes forming LC fiber. Both phases, whether the porous geopolymeric matrix or vascular LCF, help to increase the surface moisture of the material, which helps in the applications of passive cooling systems, especially in hot and dry regions.

On the other hand, we note that introducing LCF contributed significantly in improving the mechanical properties of geopolymeric products, where the

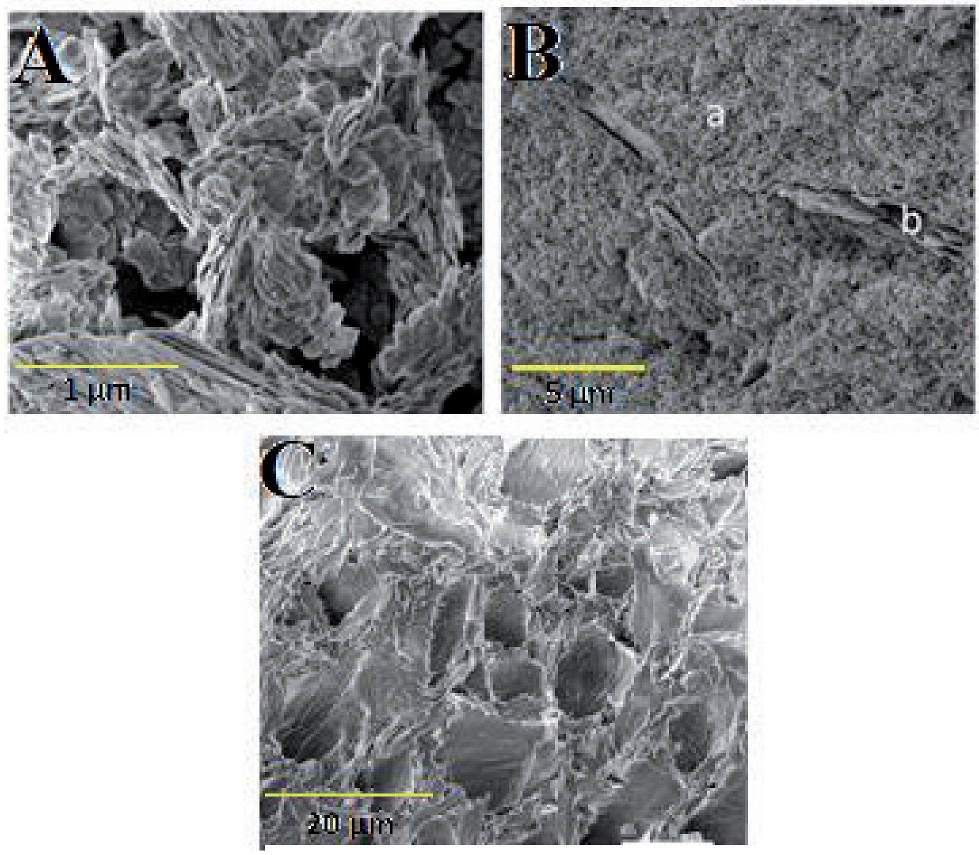

Figure 5.
SEM images of the precursor (A), geopolymer matrix (B), and the LCF cross section (C) [8, 11].

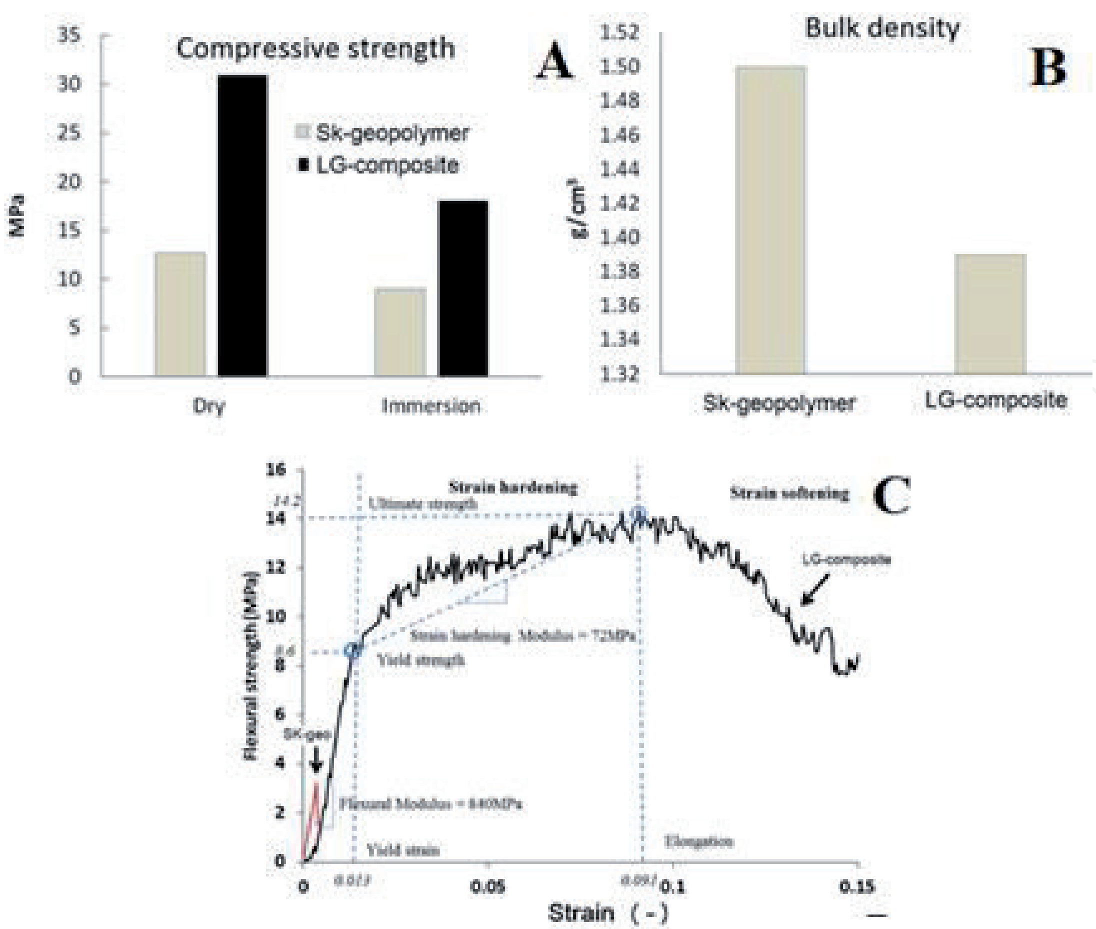

Figure 6.
Mechanical and physical properties of geopolymers (Sk-geopolymer) and geopolymer composite (LG-composite): Compressive strength (A), Bulk density (B), and Stress-strain curve (C) [11].

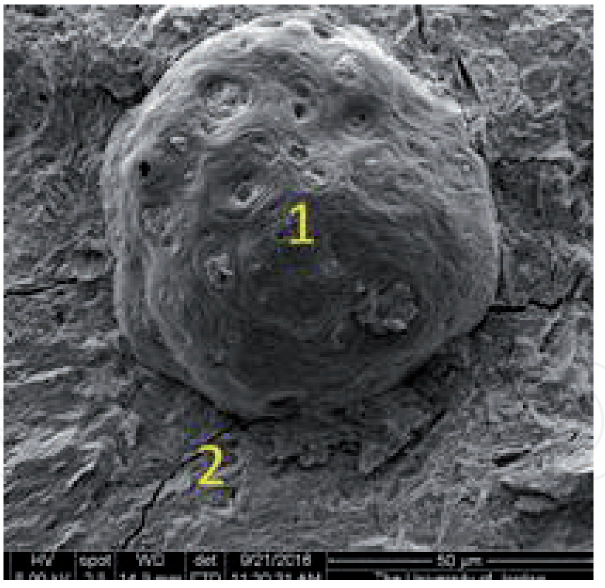

Figure 7.
HFO granules (point 1) in the geopolymeric matrix (point 2).

Element	Toxicity (IUPAC) [19]	HFO (ppm)	HFO geopolymer matrix (ppm)
Na	X	21.6	179.2
Ca	X	0.6	1.6
Zn	X	164.0	0.0
Mg	X	0.1	0.6
Fe	X	3.3	0.1
Mn	X	1.0	0.0
Al	X	189.0	39.2
Ni	Toxic	32.0	0.0
Co	Toxic	0.1	0.0
Pb	Toxic	1.6	0.0
Cu	Toxic	1.2	0.0
Cr	Toxic	4.1	0.0

Table 3.
Concentration (ppm) of leached metals from crude HFO and HFP geopolymer matrix after immersion in pH = 7 for 1 day.

compressive strength was doubled as shown in **Figure 6A**. It was observed also that the density of products was reduced by up to 10%, **Figure 6B**, thanks to the addition of vascular LC fiber as reinforcement. This reduction in density is due to the fact that these fibers exhibit low bulk density compared to the geopolymer matrix. The most important influence for LC fibers on the mechanical properties of geopolymers is to significantly increase the tensile strength as shown in **Figure 6C**. Brittle geopolymer matrix also acquires the ductile failure thanks to LC fibers.

It is observed in this research that the LCF geopolymer composites have attracted mechanical and physical properties. In addition, the presence of multiple structures of porous networks, whether the geopolymeric matrix or the vascular LC fibers, plays an active role in the manufacture of passive cooling materials. Thus, these materials can be used as construction materials and in reducing the energy consumed in the indoor conditioning.

2.3 Immobilization and stabilization of toxic wastes in geopolymers

Geopolymers have been used in recent years as a matrix for immobilization and stabilization of toxic wastes. The finished products can be used for specific construction purposes as well. Therefore, this geopolymerization process achieves several goals at once. In this study [18], heavy oil fly ash (HFO) containing toxic elements such as Ni, Cr, Pb, etc. was added to the geopolymeric matrix as a filler. As can be seen in **Figure 7**, the granules of the HFO are fixed in the geopolymers. The resultant HFO geopolymer exhibits mechanical properties comparable with pure geopolymer [18]. As for the examination of the immobilization of toxic elements, it is observed in **Table 3** that these elements were fixed in the geopolymeric matrix and they were not leached in water after a full day of immersion in water. Accordingly, this research achieves several objectives: the use of geopolymers in the recycling of HFO as a waste and the stabilization of toxic elements, in addition to its use as construction materials in specific applications.

3. Conclusions

There are several challenges and drawbacks facing the commercialization of geopolymers as an alternative to conventional cement and other conventional materials in construction. One important strategy to overcome these challenges is the manufacture of functional geopolymers with multiple uses. Three different applications of polymers in the fields of water purification, passive cooling systems, and waste recycling were presented in this introductory chapter. It is noticeable that the results are of great importance in many applications and confirm that this strategy will play a key role in the commercialization of geopolymers as products with multiple uses in engineering and environmental applications.

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References

[1] Davidovits J. Geopolymers: Inorganic polymeric new material. Journal of Thermal Analysis. 1991;**37**:1633-1656

[2] Ferone C, Liguori B, Capasso I, Colangelo F, Cioffi R, Cappelletto E, et al. Thermally treated clay sediments as geopolymer source material. Applied Clay Science. 2015;**107**:195-204

[3] Alshaaer M. Two-phase geopolymerization of kaolinite-based geopolymers. Applied Clay Science. 2013;**86**:162-168

[4] Kuenzel C, Grover LM, Vandeperre L, Boccaccini AR, Cheeseman CR. Production of nepheline/quartz ceramics from geopolymer mortars. Journal of the European Ceramic Society. 2013;**33**:251-258

[5] Geraldes CFM, Lima AM, Delgado-Rodrigues JJ, Mimoso M, Pereira SRM. Geopolymers as potential repair material in tiles conservation. Applied Physics A: Materials Science and Processing. 2016;**122**:197

[6] Alshaaer M, Cuypers H, Wastiels J. Stabilisation of kaolinitic soil for construction purposes by using mineral polymerisation technique. In: Resheidat M, editor. Proceedings of the 6th International Conference Technology for Developing Countries. Vol. 3. pp. 1085-1092. Jordan; 2002

[7] Davidovits J. Global warming impact on the cement and aggregates industries. World Resource Review. 1994;**6**(2):263-278

[8] Alshaaer M, Zaharaki D, Komnitsas K. Microstructural characteristics and adsorption potential of a zeolitic tuff–metakaolin geopolymer. Desalination and Water Treatment. 2014;**56**:338-345. DOI: 10.10 80/19443994.2014.938306.2014

[9] Van Deventer J, Provis J, Duxson P. Technical and commercial progress in the adoption of geopolymer cement. Minerals Engineering. 2012;**29**:89-104

[10] McLellan BC, Williams RP, Lay J, van Riessen A, Corder GD. Costs and carbon emissions for geopolymer pastes in comparison to ordinary Portland cement. Journal of Cleaner Production. 2011;**19**(9-10):1080-1090

[11] Alshaaer M, Abu Mallouh S, Al-Kafawein J, Al-Faiyz Y, Fahmy T, Kallel A, et al. Fabrication, microstructural and mechanical characterization of Luffa cylindrical fibre-reinforced geopolymer composite. Applied Clay Science. 2017;**143**:125-133

[12] Azimi EA, Abdullah MMAB, Ming LY, Yong HC, Hussin K, Aziz IH. Review of dolomite as precursor of Geopolymer materials. In: MATEC Web of Conferences. Vol. 78. 2016. p. 01090. DOI: 10.1051/matecconf/20167801090

[13] Komnitsas K, Zaharaki D. Geopolymerisation: A review and prospects for the minerals industry. Minerals Engineering. 2007;**20**:1261-1277

[14] Komnitsas K, Zaharaki D, Perdikatsis V. Effect of synthesis parameters on the compressive strength of low-calcium ferronickel slag inorganic polymers. Journal of Hazardous Materials. 2007;**161**:760-768

[15] El-Eswed B, Yousef RI, Alshaaer M, Khalili F, Khoury H. Alkali solid-state conversion of kaolin and zeolite to effective adsorbents for removal of lead from aqueous solution. Desalination and Water Treatment. 2009;**8**:124-130

[16] Alzeer M, MacKenzie KJD. Synthesis and mechanical properties of novel composites of inorganic polymers (geopolymers) with unidirectional

natural flax fibres. Applied Clay Science. 2013;**75-6**:148-152

[17] Hajjaji W, Andrejkovičová S, Zanelli C, Alshaaer M, Dondi M, Labrincha JA, et al. Composition and technological properties of geopolymers based on metakaolin and red mud. Materials and Design. 2013;**52**:648-654

[18] Alshaaer M, Shqair M, Abdelwahed HG, Abuhasel K, Zamorano M. International Journal of Applied Engineering Research. 2017;**12**(4):488-497

[19] The International Union of Pure and Applied Chemistry (IUPAC). United States: Research Triangle Park, NC 27709-3757 . Available from: https://iupac.org/