



Compressive strength and hydrolytic stability of fly ash-based geopolymers

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Abstract: The process of geopolymerization involves the reaction of a solid aluminosilicate material with a highly alkaline silicate solution that yields an aluminosilicate inorganic polymer named a geopolymer, which may be successfully applied in civil engineering as a replacement for cement. In this study, the influence of the synthesis parameters: solid to liquid ratio, NaOH concentration and the ratio of Na₂SiO₃/NaOH, on the mechanical properties and hydrolytic stability of fly ash-based geopolymers in distilled water, sea water and simulated acid rain, were investigated. The highest value of compressive strength was obtained using 10 mol dm⁻³ NaOH and at a Na₂SiO₃/NaOH ratio of 1.5. Moreover, the obtained results showed that the mechanical properties of fly ash-based geopolymers are in correlation with their hydrolytic stability, *i.e.*, factors that increase the compressive strength also increase the hydrolytic stability of fly ash-based geopolymers. The best hydrolytic stability of the fly ash-based geopolymers was shown in seawater while the lowest stability was recorded in simulated acid rain.

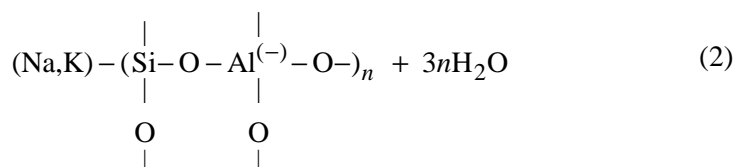
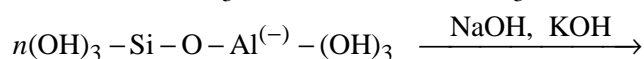
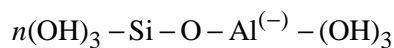
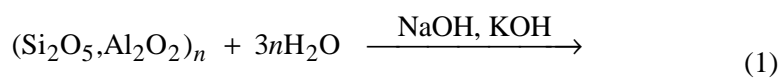
Keywords: geopolymerization; fly ash; compressive strength; hydrolytic stability.

INTRODUCTION

Geopolymerization is a relatively new, environmentally friendly technology that is based on the reaction of aluminosilicate materials with strongly alkali silicate solutions yielding three dimensional aluminosilicate structures known as

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geopolymers. Geopolymers are inorganic polymeric materials with Si–O–Al and Si–O–Si bonds. Depending on the reaction parameters, three types of geopolymers are considered: poly(sialate) (–Si–O–Al–O–), poly(sialate–siloxo) (–Si–O–Al–O–Si–O–) and poly(sialate–disiloxo), (–Si–O–Al–O–Si–O–S–O–), in which the ratios of Si:Al are 1, 2 and 3, respectively. Geopolymers with the poly(sialate) structure are mainly investigated and their structure is composed of tetrahedral $[\text{SiO}_4]^{4-}$ and $[\text{AlO}_4]^{5-}$.¹ The oxygen is sheared between two adjacent tetrahedral. Reaction mechanism of its formation may be presented as follows:²



In recent years, geopolymers have attracted much attention primarily due to their good mechanical properties and therefore are considered as a possible replacement for Portland cement. Moreover, they are characterized by good thermal stability,³ fire resistance^{4,5} and resistance to aggressive environments, especially under acid conditions,⁶ even better than those of cement-based materials. In addition, replacement of cement with geopolymers would have an environmental benefit, since cement plants contribute 5–10 % to the global emissions of CO_2 .⁷

Properties of geopolymers primarily depend on the choice of raw materials. Geopolymerization process may use a variety of raw materials, but the main advantage of geopolymerization is the possibility to utilize the waste materials. The essential requirement, regardless of the raw materials selection, is the high content of aluminum and silica oxides. Fly ash, metakaolin and blast furnace slag are mainly used for geopolymerization processes. Moreover, processing conditions, type and concentration of alkaline solution and solid to liquid ratio determine the characteristics of geopolymers, because they define the ratio between $\text{Na}_2\text{O}/\text{Al}_2\text{O}_3$ and $\text{SiO}_2/\text{Al}_2\text{O}_3$. In addition, temperature and time of curing affect the geopolymer properties.

The geopolymerization mechanism has not yet been fully understood and it is assumed that it consists of several steps. The first step is dissolution of the solid aluminosilicate materials in the alkaline medium. The next step is condensation of the oligomeric species, leading to the formation of aluminosilicate gel.

The final step consists of hardening of the gel and bonding of non-dissolved solid particles in the final geopolymeric structure.⁸

The aim of this work was to investigate the effect of the synthesis parameters on the compressive strength of fly ash-based geopolymers and their hydrolytic stability in different aquatic-environments.

EXPERIMENTAL

The fly ash used for the synthesis of the geopolymers was supplied from the coal-fired power station Pljevlja. The chemical composition of the fly ash is given in Table I.

TABLE I. Chemical composition of the employed fly ash

Compound	Content, %
SiO ₂	49.45
Fe ₂ O ₃	5.23
Al ₂ O ₃	21.77
TiO ₂	0.66
CaO	13.34
Na ₂ O	0.46
ZnO	4.5·10 ⁻³
MgO	1.29
MnO	0.02
P ₂ O ₅	0.24
K ₂ O	1.4
Loss on ignition (LOI)	4.35

The fly ash was activated with alkali solutions made by mixing Na₂SiO₃ and NaOH solutions in the mass ratios 1, 1.5 and 2. A commercial sodium silicate solution (Na₂O = 8.5 %, SiO₂ = 28.5 %, density of 1.4 kg m⁻³) was used. The concentration of the NaOH solution was 7, 10 or 13 mol dm⁻³. Geopolymer pastes were prepared by mixing fly ash with an alkali solution in solid to liquid (S/L) ratios of 0.75, 1 and 1.25. The pastes were cast in closed plastic cylindrical moulds of dimensions 28 mm×60 mm and cured for 48 h at 65 °C. After the curing process, the samples were removed from the moulds after cooling and then left to rest for an additional 28 days at ambient temperature before any testing was performed. The samples were tested after 28 days because in most cases the strength requirements for cement-based materials were attained after aging for this time.

Three control geopolymer samples of each series were tested for compressive strength on an HP-400 hydraulic press at room temperature in air (standard test conditions). Before testing, the surfaces of the sample were polished flat and parallel to a height / diameter ratio of approximately 2.

Mineralogical investigations were realized by X-ray powder diffraction (XRPD) analysis employing a PHILIPS PW 1710 diffractometer operating in the step-scan mode (2θ range 4–90°, step 0.02°, time 0.8 s) using monochromatized Cu K_α radiation ($\lambda = 1.54178 \text{ \AA}$). The crystalline phases were identified from the obtained XRPD patterns by comparing the intensities and positions of the Bragg peaks with JCPDS (Joint Committee on Powder Diffraction Standards) data files.

The microstructural investigations were performed by scanning electron microscopy (SEM) in tandem using an FEI 235DB dual beam focused ion beam (FIB) system equipped

with an EDAX Genesis energy dispersive spectrometer (EDS).⁹ Cross sectioning of the porous microconstituents was performed using a 1000 pA gallium ion beam with an operating voltage of 5 kV. In order to minimize electron charging effects, a through lens back scattered electron detector (TLD-B) was used for image recording.

The hydrolytic stability of the geopolymers was investigated through dissolution tests in deionized water, seawater and simulated acid rain (H₂SO₄:HNO₃ = 40:60, pH 3). For this purpose, 2 g of geopolymer, granulation smaller than 90 μm, was mixed with 100 cm³ distilled water, sea water or acid rain and left in contact for 24 h. After the test, the leachates were separated by filtration and analyzed for their Al and Si content by ICP-OES (Spectro Arcos). The pH of the suspensions was recorded before and after the hydrolytic stability test.

RESULTS AND DISCUSSION

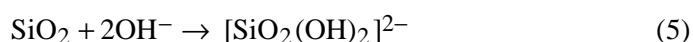
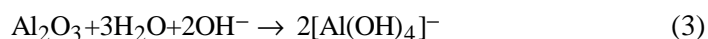
Compressive strength

The results obtained in the investigation of the influence of the solid to liquid ratio, alkalinity and silicate dosage on the compressive strength of the geopolymers are summarized in Table II.

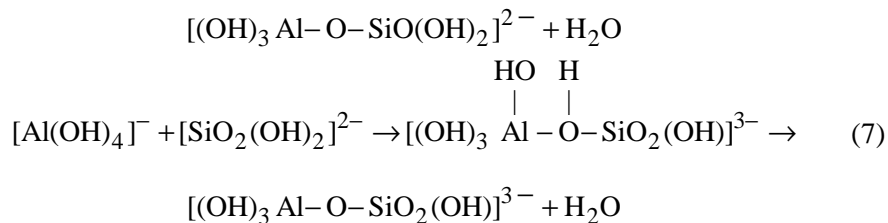
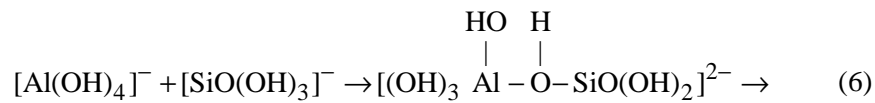
TABLE II. Changes in the compressive strength of the geopolymers in dependence on the reaction parameters

Sample	S/L	$c(\text{NaOH}) / \text{mol dm}^{-3}$	$m(\text{Na}_2\text{SiO}_3)/m(\text{NaOH})$	Compressive strength, MPa
FA1	0.5	10	1.5	–
FA2	0.75	10	1.5	12.18
FA3	1	10	1.5	15.43
FA4	1.25	10	1.5	18.27
FA5	1	7	1.5	13.35
FA6	1	13	1.5	14.71
FA7	1	10	1	14.62
FA8	1	10	2	11.7

It is evident that with increasing S/L ratio, the value of compressive strength of fly ash-based geopolymers (samples FA1–4) increased. The highest value of compressive strength was attained for the mixture FA4 prepared at an S/L ratio of 1.25, which is attributed to the lowest water content in the geopolymer mixture. Water is necessary for the dissolution of solid fly ash particles and the hydrolysis of the dissolved Al³⁺ and Si⁴⁺, providing the aluminate and silicate monomers according to Eqs. (3)–(5).¹⁰ Al is present in the form of [Al(OH)₄][–] and Si may be present as [SiO(OH)₃][–] and/or [SiO₂(OH)₂]^{2–}. Depending on the pH of alkaline solution, the [SiO₂(OH)₂]^{2–}/[SiO(OH)₃][–] ratio changes. In highly alkaline solutions, [SiO₂(OH)₂]^{2–} species are dominant while in dilute solutions, the [SiO(OH)₃][–] species predominate.^{10,11}



The increase of water content is favorable from a standpoint of dissolution and the hydrolysis process because it accelerates the dissolution of Al and Si from the starting material. Simultaneously with dissolution and hydrolysis processes, the condensation process occurs between aluminate and silicate monomers, yielding to the formation of aluminosilicate network–aluminosilicate gel. However, contrary to the dissolution and hydrolysis process, water is being released during the condensation process according to the Eqs. (6) and (7).¹⁰



The content of excess water suppresses the condensation process, which results in a weakening of the geopolymer structure. This means that an increase in the S/L ratio leads to a lower water content in the geopolymer mixture and enhances the condensation process,¹² which results in an increase of the compressive strength. Moreover, an excess of water greatly affects the porosity of the samples, because the water evaporates leaving behind pores in the geopolymer structure. The systems with higher water contents had a higher porosity and a weaker structure.

The presence of water is also important from the standpoint of the workability of the geopolymer paste, which enables its molding. The highest value of compressive strength was achieved at S/L ratio of 1.25 but this mixture was also extremely difficult to mould and additional pressure had to be applied in order to provide molding. On the other hand, water excess (mixture FA1) resulted in shrinkage during the curing period, negatively affecting the compactness of the geopolymer samples. Therefore, the influence of NaOH concentration and composition of alkali silicate solution on the compressive strength and hydrolytic stability of fly ash-based geopolymers were limited to an S/L ratio of 1 (mixture FA3, FA5–8), when molding without additional pressure was possible.

The fly ash-based geopolymers were strengthened by increasing the NaOH concentration when keeping the Na₂SiO₃/NaOH and S/L ratios constant (samples FA3, 5 and 6). However, the positive influence of a higher NaOH concentration strengthening the geopolymer structure is limited. The fly ash-based geopolymers reached a maximum compressive strength at 10 mol dm⁻³ NaOH, at a constant

Na₂SiO₃/NaOH ratio. Further increases of the NaOH concentration reduced the compressive strength. A similar effect of alkaline dosage on the strength of fly ash-based geopolymers was also observed previously.^{8,13}

The influence of the NaOH concentration on the compressive strength of fly ash-based geopolymers may be considered through two aspects of the geopolymerization process: from a standpoint of the dissolution process and from a standpoint of the role of alkali metal in the geopolymerization process.

The function of NaOH in a geopolymerization process is twofold. The task of OH⁻ is to provide dissolution of Al and Si from the vitreous fly ash while the Na⁺ ions balance the negative charge on the tetrahedral AlO₄⁻ group in the geopolymer structure.

The increase of compressive strength of the fly ash-based geopolymers with increasing NaOH concentration is affected by the enhanced formation of an aluminosilicate gel.¹³ An increase of the concentration of OH⁻ promotes the dissolution of Al³⁺ and Si⁴⁺ from the fly ash^{14,15} leading to the formation of reactive monomeric species (Eqs. (3)–(5)), which accumulate during the induction period of the geopolymerization.¹⁶ These monomeric species condense and form oligomeric Si and/or Si–Al species,¹⁷ which continue further to condense leading to the formation of a gelatinous aluminosilicate network, *i.e.*, a geopolymer. An increase in the OH⁻ concentration leads to a reduction of the induction period of the geopolymerization process and faster aluminosilicate gel formation.¹⁸ As more gel is formed, it overwhelms the remaining fly ash particles and forms a continuous mass of gel, resulting in a denser geopolymer matrix¹³ and higher compressive strength of the geopolymers. However, on the other hand, an increase in the quantity of gel with increasing NaOH concentration above 10 mol dm⁻³ leads to a thickening of the solution, which results in lower mobility of the solution and ions and, hence, reduced dissolution of the fly ash¹³ and lower compressive strength.

Moreover, Al is easier to dissolve in NaOH solutions of concentrations below 10 mol dm⁻³ compared to Si¹⁹ and condensation between aluminate and silicate species is more probable. Increasing the NaOH concentration above 10 M accelerates Si dissolution giving more dissolved Si⁴⁺ when compared to the dissolved Al³⁺ and thus promoting condensation between silicate species,¹¹ which results in decreasing compressive strength.

In addition, increasing the NaOH concentration also leads to increasing concentrations of Na⁺ and thus, the effect of Na⁺ on the condensation process must be taken in consideration. Increasing the Na⁺ concentration causes a decrease in the rate of silica condensation²⁰ and hence, slightly decreases the compressive strength of the fly ash-based geopolymers. The NaOH concentration is also greatly influenced by the water content in the geopolymer system, which is essential for the hydrolysis process, according to Eqs. (3)–(5). An increase of the

NaOH concentration leads to a decrease in the water content available for the hydrolysis process, which may influence negatively the formation of dissolved Al and Si species in the aquatic phase of the geopolymer systems and thus, reduces the compressive strength.

The results of the investigation of the influence of the silicate dosage on the compressive strength of fly ash-based geopolymers showed that an increase in the silicate dosage, *i.e.*, an increase of the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio from 1 to 1.5 led to increases in compressive strength of the geopolymers (FA 3, 7 and 8). A further increase in the silicate/hydroxide ratio to 2 led to slight reductions in the strength of the geopolymers. The data presented here are in general agreement with earlier observations.^{13,21}

As Al is easier to dissolve in a highly alkaline solution compared to Si, the role of silicate solution in a geopolymer mixture is to provide a sufficient concentration of silicate species to condense with Al species and produce an aluminosilicate gel. The increase of silicate dosage has as a result a gradually shift in the chemical system from monosilicate, chains and cyclic trimers to species with larger rings and then to complex structures and polymers, leading consequentially, to increases in the mechanical properties of the resulting geopolymeric materials.⁸

The presence of soluble silicates affects an increase in the degree of geopolymerization and the evolution of mechanical strength.¹³ The decrease in the compressive strength of the fly ash-based geopolymers synthesized at a $\text{Na}_2\text{SiO}_3/\text{NaOH}$ mass ratio higher than 1.5 was influenced by inefficient workability of the geopolymer pastes.

Moreover, the silicate dosage influences the concentration of free hydroxide ions in solution, which are essential for the dissolution of the starting materials. An increase of the silicate dosage in alkali solution decreases the free hydroxide ions concentration because it is consumed during the polymerization of silica.²² This results in a decrease in the compressive strength.

Mineralogical and microstructural analysis

Mineralogical and microstructural analysis was restricted to FA3, the geopolymer with the highest compressive strength. The X-ray powder diffraction patterns of the fly ash and fly ash-based geopolymer are shown in Fig. 1.

The XRPD pattern of fly ash shows the presence of a non-crystallized, *i.e.*, amorphous, phase. The dominant crystalline phase was identified as quartz SiO_2 . It seemed possible that one member of a melilite solid solution (the two end members are gehlenite, $\text{Ca}_2\text{Al}_2\text{SiO}_7$ and akermanite, $\text{Ca}_2\text{MgSi}_2\text{O}_7$), as well as calcite, CaCO_3 , and anorthite, $\text{CaAl}_2\text{Si}_2\text{O}_8$, were present in very small quantities. However, because of their very small amount and low crystallinity their unambiguous identification based on XRPD measurements was not possible.

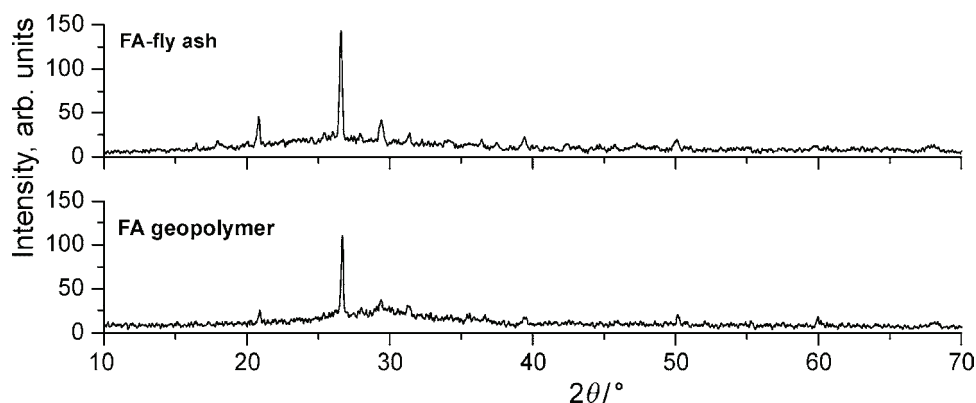


Fig.1. XRPD Pattern of the fly ash (FA) and fly ash-based geopolymer (FA geopolymer).

The XRPD pattern of FA3 geopolymer showed that it was mainly X-ray amorphous, as was expected. Some non-dissolved components, quartz, and probably very small quantities of calcite, anorthite and melilite remained from the non-reacted fly ash but no new crystalline phase was formed because of the geopolymerization reaction.

A cross-sectional SEM microphotograph of the same sample of fly ash-based geopolymer is shown in Fig. 2a. The microstructure of the fly ash-based geopolymer consisted of flat regions, amorphous phase – gel (point 1) and porous regions, which represent partially reacted or non-reacted fly ash (point 2). Microcracks connecting the porous regions were formed during the compression testing. Typical EDS spectra from the porous and flat regions are shown in Figs. 2b and 2c, respectively. Silica, aluminum, oxygen and sodium are the main constituents of the aluminosilicate gel phase. The average Si/Al ratio in the gel phase was two, which is in agreement with previous observations that geopolymers with the Si/Al ratios of 1, 2 or 3 show the best mechanical properties.²

Hydrolytic stability of the fly ash-based geopolymers

The geopolymers in contact with distilled water and acid rain generated a highly alkaline suspension with pH of 11.1 and 10.9, respectively. The excess of Na⁺ ions that remained non-reacted after the geopolymerization process were deposited in the pores of the geopolymer.²³ In contact with aquatic media, these ions were dissolved, which led to the increase of the pH values of the suspensions. In addition, presence of water caused hydrolysis of gel and the leaching of a part of the incorporated sodium,¹⁷ which also contributed to the increase of the pH values of the suspensions.

On the other hand, the pH of geopolymer suspension with seawater before testing was 9.3 but it had decreased to a value of 8.4 after the test.

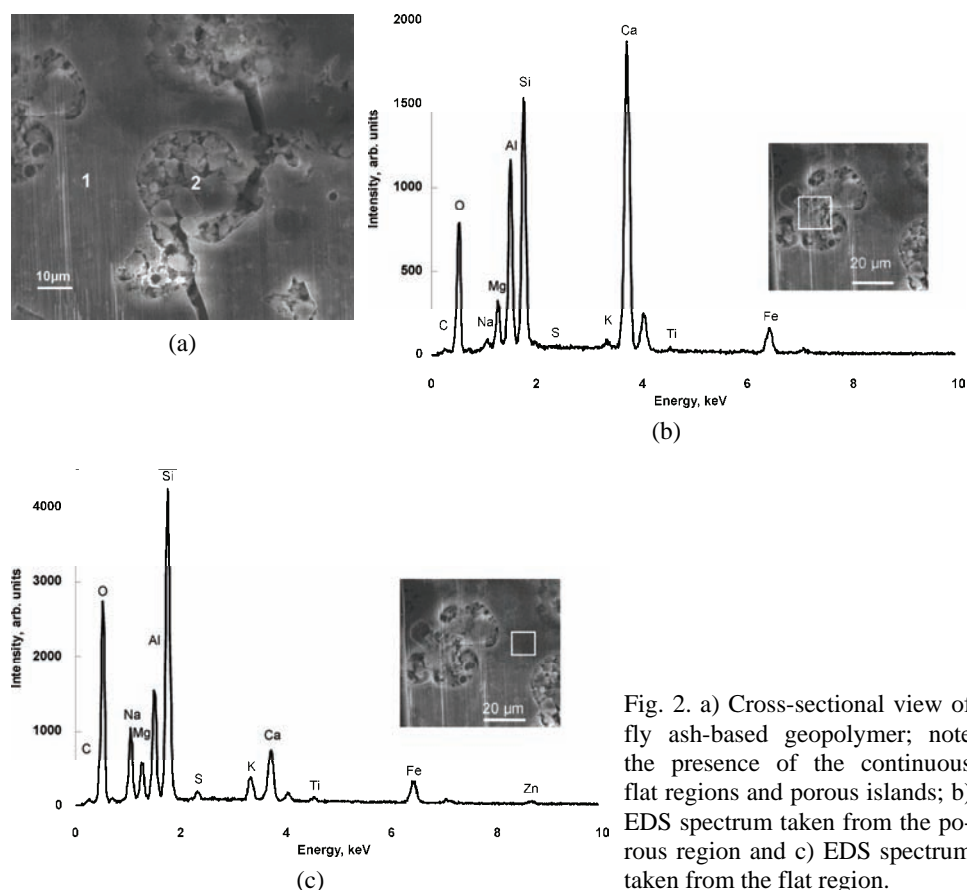


Fig. 2. a) Cross-sectional view of fly ash-based geopolymer; note the presence of the continuous flat regions and porous islands; b) EDS spectrum taken from the porous region and c) EDS spectrum taken from the flat region.

The results of the investigation of the hydrolytic stability of the geopolymers are given in Fig. 3. The hydrolytic stability of the geopolymers is reflected in the stability of the aluminosilicate gel in different aquatic conditions. Under the influence of water, scission of Si–O–Si bonds in the gel with the release of Si occurs,²⁴ which forms silicic acid in an aqueous environment (mono or poly).²⁵ In addition, the presence of Al ions in the leachate indicates a certain degree of dealumination due to the degradation of Al–O–Si bonds. However, Al is dissolved in lower quantities compared to Si, which is consistent with the considerably higher quantities of Si in geopolymer mixtures due to the higher Si content in the fly ash and addition of soluble silicates. Geopolymers are hydrolytically stable if smaller amounts of Si and Al are released into the aquatic environment. Fly ash-based geopolymers are almost insoluble in seawater, *i.e.* the highest hydrolytic stability the geopolymers were shown in seawater, given that the lowest concentrations of Si were evidenced, while the Al concentrations were below the detection limit. On the other hand, the lowest hydrolytic stability of geopolymers was

observed in acid rain. The geopolymers exhibited somewhat higher hydrolytic stability in distilled water than in acid rain. The similar behavior of the geopolymers in distilled water and acid rain is probably influenced by the similar pH values of the suspensions (Table III).

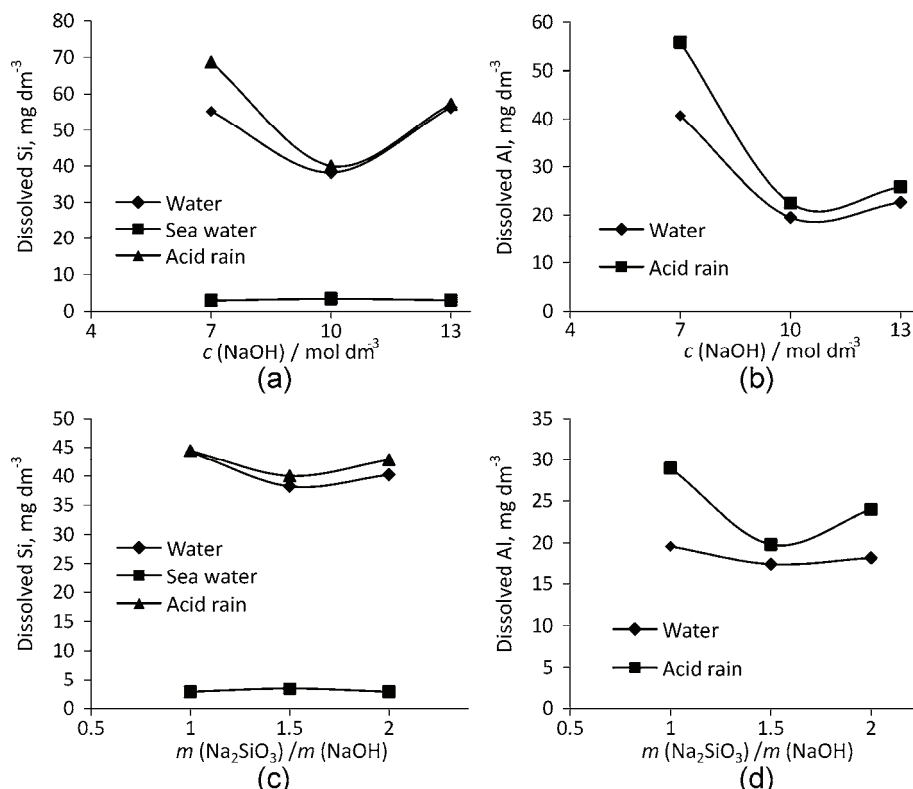


Fig. 3. Hydrolytic stability of the examined geopolymers according to the dissolved amount of Al and Si as functions of the investigated parameters (NaOH concentration, Na₂SiO₃/NaOH mass ratio and type of the aquatic medium).

Experimental investigations on the influence of the NaOH concentration and Na₂SiO₃/NaOH ratio showed that the hydrolytic stability of geopolymers in distilled water and acid rain correlates with the mechanical properties, *i.e.*, the factors that increase the compressive strength also improve the hydrolytic stability (Fig. 3).

Increasing the NaOH concentration from 7 to 10 mol dm⁻³ decreased the dissolution of Si and Al in water and acid rain. A further increase in the concentration to 13 mol dm⁻³ led to increased solubility of Si and Al. Similarly, an increase of the Na₂SiO₃/NaOH ratio from 1 to 1.5 led to reduced degradation of the aluminosilicate gel, *i.e.*, decreases in the Si and Al concentrations in the

leachates, while a further increase of this ratio led to increased solubility of Si and Al, *i.e.*, to a decrease in the hydrolytic stability. The lowest concentrations of Si and Al in the leachate after the hydrolytic test, *i.e.* the highest hydrolytic stability of the geopolymers, was recorded at a concentration of 10 mol dm^{-3} NaOH and a $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio of 1.50, under which conditions, the highest value of compressive strength was observed.

TABLE III. pH values of geopolymer suspension in distilled water, seawater and acid rain before and after the hydrolytic test

Medium	pH before test	pH after test
Distilled water	11.1	10.9
Seawater	9.3	8.4
Acid rain	10.9	10.6

The presence of aluminum in an aluminosilicate gel is very important from the standpoint of hydrolytic stability of the gel in an aqueous environment. Previous studies demonstrated that the hydrolytic stability of a sodium silicate gel may be improved by aluminum incorporation.^{17,26} From this point of view, the availability of Al to participate in the geopolymerization reaction is of great importance for the stabilization of the resulting gel in different aquatic environments.

In this sense, factors that increase the dissolution of fly ash are of primary importance for the hydrolytic stability of fly ash-based geopolymers.

As an increase in the concentration of NaOH to a value of 10 mol dm^{-3} enhanced the dissolution of fly ash¹⁹, a greater quantity of Al participated in gel formation, which improved the hydrolytic stability of the geopolymers in distilled water and acid rain environments. The resulting decrease in the hydrolytic stability on increasing the NaOH concentration to 13 mol dm^{-3} was the consequence of a lower participation of Al in the gel phase due to a decrease in Al dissolution from fly ash.¹⁹ Besides, the decrease in hydrolytic stability of the geopolymers when the NaOH concentration was increased to above the 10 mol dm^{-3} was reflected in a considerably higher dissolution of Si into distilled water and acid rain in comparison to Al dissolution, which is in agreement with the higher participation of Si in the gel due to the enhanced dissolution of Si from the fly ash.¹⁹

On the other hand, the hydrolytic stability of the fly ash-based geopolymers did not change considerably on changing the silicate dosage. Some significant dissolution of Al and a slight dissolution of Si from the geopolymer matrix in distilled water and acid rain were observed when changing the $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio from 1 to 1.5. A further increase in this ratio slightly increased the hydrolytic stability.

CONCLUSIONS

The microstructure of fly ash-based geopolymers consists of a porous phase (non-reacted or partially reacted fly ash) and a flat aluminosilicate gel. The main constituents of the gel are Si, Al, O and Na.

Analysis of influence of the synthesis parameters on the compressive strength of the fly ash-based geopolymers showed that the strength might be increased by increasing the S/L ratio due to a reduction in the water content of the geopolymer mixture and by increasing the NaOH concentration and the Na₂SiO₃/NaOH ratio. However, the increase in strength with increasing NaOH concentration and Na₂SiO₃/NaOH ratio reaches a maximum and then decreases. The highest value of compressive strength was attained using 10 mol dm⁻³ NaOH and a Na₂SiO₃/NaOH ratio of 1.5.

The change in the hydrolytic stability of the fly ash-based geopolymers with change of the investigated parameters followed the change in the mechanical properties, *i.e.*, the conditions that increased the compressive strength also improved the hydrolytic stability. The hydrolytic stability of fly ash-based geopolymers was the best in seawater and the lowest in acid rain. The geopolymers exhibited a somewhat higher hydrolytic stability in distilled water than in acid rain.

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ИЗВОД

ПРИТИСНА ЧВРСТОЋА И ХИДРОЛИТИЧКА СТАБИЛНОСТ ГЕОПОЛИМЕРА
НА БАЗИ ПЕПЕЛА

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Процес геополимеризације укључује реакцију чврстих алумосиликата са јаким алкалносилкатним раствором при чему настаје алумосилкатни полимер назван геополимер, који се успешно може користити у грађевинарству као замена за цемент. У овом раду испитиван је утицај параметара синтезе: односа чврсто-течно, концентрације NaOH и односа Na₂SiO₃/NaOH на механичке особине и хидролитичку стабилност геополимера на бази пепела у дестилованој води, морској води и симулираној киселој киши. Нјвеће вредности притисне чврстоће су добијене коришћењем 10 mol dm⁻³ NaOH

при односу $\text{Na}_2\text{SiO}_3/\text{NaOH}$ од 1,5. Осим тога, резултати су показали да су механичке особине геополимера на бази пепела у колерацији са њиховом хидролитичком стабилношћу. Фактори који повећавају притисну чврстоћу повећавају и хидролитичку стабилност геополимера на бази пепела. Најбољу хидролитичку стабилност геополимери показују у морској води док је најслабија стабилност забележена у киселој киши.

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REFERENCES

1. F. Pacheco-Torgal, J. Castro-Gomes, S. Jalali, *Constr. Build. Mater.* **22** (2008) 1305
2. J. Davidovits, *J. Therm. Anal.* **37** (1991) 163
3. D. L. Y. Kong, J. G. Sanjayan, *Cem. Concr. Compos.* **30** (2008) 986
4. T. W. Cheng, J. P. Chiu, *Miner. Eng.* **16** (2003) 205
5. R. E. Lyon, P. N. Balaguru, A. Foden, U. Sorathia, J. Davidovits, M. Davidovics, *Fire Mater.* **21** (1997) 67
6. T. Bakharev, *Cem. Concr. Res.* **35** (2005) 658
7. E. Gartner, *Cem. Concr. Res.* **34** (2004) 1489
8. D. Panias, I. P. Giannopoulou, T. Perraki, *Colloids Surf., A* **301** (2007) 246
9. <http://ncem.lbl.gov/frames/FIB.html> (October 15, 2012)
10. L. Weng, K. Sagoe-Crentsil, *J. Mater. Sci.* **42** (2007) 2997
11. K. Sagoe-Crentsil, L. Weng, *J. Mater. Sci.* **42** (2007) 3007
12. Z. Zuhua, Y. Xiao, Z. Huajun, C. Yue, *Appl. Clay Sci.* **43** (2009) 218
13. U. Rattanasak, P. Chindaprasirt, *Min. Eng.* **22** (2009) 1073
14. C. Panagiotopoulou, E. Kontori, T. Perraki, G. Kakali, *J. Mater. Sci.* **42** (2007) 2967
15. A. Hajimohammadi, J. L. Provis, J. S. J. van Deventer, *Chem. Mater.* **22** (2010) 5199
16. A. Palomo, M. W. Grutzeck, M. T. Blanco, *Cem. Concr. Res.* **29** (1999) 1323
17. D. Dimas, I. Giannopoulou, D. Panias, *J. Mater. Sci.* **44** (2009) 3719
18. C. A. Rees, *PhD Thesis*, University of Melbourne, Australia, 2007
19. C. Li, Y. Li, H. Sun, L. Li, *J. Am. Ceram. Soc.* **94** (2011) 1773
20. L. Kobera, R. Slavík, D. Koloušek, M. Urbanová, J. Kotek, J. Brus, *Ceram. Silik.* **55** (2011) 343
21. S. Songpiriyakij, T. Kubprasit, C. Jaturapitakkul, P. Chindaprasirt, *Constr. Build. Mater.* **24** (2010) 236
22. I. L. Svensson, S. Sjöberg, L. O. Öhman, *J. Chem. Soc., Faraday Trans.* **82** (1986) 3635
23. P. Duxson, G. C. Lukey, F. Separovic, J. S. J. van Deventer, *Ind. Eng. Chem. Res.* **44** (2005) 832
24. T. Skorina, I. Tikhomirova, *J. Mater. Sci.* **47** (2012) 5050
25. M. Dietzel, *Geochim. Cosmochim. Acta* **64** (2000) 3275
26. I. Giannopoulou, D. Panias, *J. Mater. Sci.* **45** (2010) 5370.