

# The effect of the alkaline solution content on the mechanical properties of MK-based PVA fiber-reinforced geopolymers

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Érkezett: 2016. 12. 13. ▪ Received: 13. 12. 2016. ▪ <http://dx.doi.org/10.14382/epitoanyag-jsbcm.2017.3>

## Abstract

This paper studied the effect of the activation solution content on the mechanical properties of PVA fiber-reinforced geopolymers based on the activation of Metakaolin. Different fiber content (0%, 1% and 2% vol.) of PVA fibers was used to reinforce matrices with different composition ( $\text{SiO}_2/\text{Al}_2\text{O}_3$  molar ratios, i.e. 3.0, 3.4 and 3.8). The amount of activation solution was adjusted to maintain same workability for all fresh mixes and account for the fiber addition. The properties assessed were compressive and flexural strength; capillary sorption tests were used to estimate the durability of the composites. Results show that adjustments in the content of the activation solution slightly reduce the mechanical strength of geopolymers. Nonetheless, as the amount of activation solution increases in the mixes, so does the toughness of the PVA-reinforced composites, which indicates a good correlation between the amount of soluble silica in the fresh geopolymers and mechanical properties in bending.

Keywords: Mechanical properties; durability; metakaolin; geopolymers; fiber reinforced geopolymer composite; PVA fiber; sodium silicate solution

## 1. Introduction

Alkali-activated materials (AAM) are used for many applications, including binding materials for mortars and concretes; they may present several advantages to Portland cement (PC), such as early strength development [1], superior chemical [2-4] and thermal durability [5-6] as well as low carbon emissions [7-8]. AAM are as brittle as PC matrices; therefore, they also require fiber reinforcement to improve deformation, toughness and crack growth when subjected to flexion and tension stresses.

A great variety of fibers have been used to develop fiber-reinforced AAM. Poly vinyl alcohol (PVA) fibers are highly stable in alkaline environment and have been used in the development of high-performance Portland-cement composites, especially Engineered Cementitious Composites (ECC), i.e. those presenting strain-hardening behavior and high ductility (strain capacity of about 5%) [9-11]. Recent studies have proved that PVA fibers also present good bond to AAM [12] and may be used to develop composites with improved impact toughness [13] and excellent resistance to freeze-thaw cycling [14]. Short PVA fibers as a single reinforcement or in hybrid systems may be effective to provide deflection-hardening under flexion or strain-hardening behavior of AAM under direct tension [15-18].

Low calcium or calcium-free AAM are also known as geopolymers. The reinforcement of metakaolin (MK)-based

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geopolymers with short PVA fibers has been little exploited; few studies were focused on dry mixes for extruded concrete [13-14], where a MK alkali-activated matrix initially fixed in composition ( $\text{SiO}_2 / \text{Al}_2\text{O}_3 = 4.5$ ;  $\text{Na}_2\text{O} / \text{Al}_2\text{O}_3 = 0.8$  and  $\text{H}_2\text{O} / \text{Na}_2\text{O} = 6.4$ ) was altered with the addition of pulverized fly ash. Those studies, therefore, do not present the effect of the  $\text{SiO}_2 / \text{Al}_2\text{O}_3$  molar ratio on the mechanical properties and durability of PVA-reinforced composites, despite the fact that this parameter significantly affects the mechanical properties [20].

Many studies on geopolymer also neglect the fact that, from a production perspective, an alkaline solution of fixed composition will be employed and adjustments on its content may be the necessary onsite, either to account for the fiber reinforcement or unexpected changes in workability due to ambient conditions or aggregates moisture content. The objective of this paper is to study the mechanical performance of PVA-geopolymer made from the alkaline activation of MK. Densified silica fume (SF) was used in order to alter the composition of the matrices (namely  $\text{SiO}_2 / \text{Al}_2\text{O}_3$  molar ratio) without changing the composition of the activation solution. The amount of alkaline solution is increased to maintain same consistency for all fresh mixes. The mechanical behavior of the composites is discussed in terms of the composition of the matrices as well as the content of the alkaline activator of fixed composition.

## 2. Materials and methods

### 2.1 Materials

Commercial MK was supplied by Powerpozz; it has mean particle size of 4.5 μm and chemical composition shown in Table 1. Small quantities of SF (Table 1) replaced MK as binder. SF contained low percentage of Al<sub>2</sub>O<sub>3</sub>; therefore, small replacements of MK with SF increased the overall designed SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> molar ratio of the formulations without the need for altering the composition of the activator (another source of SiO<sub>2</sub>). The replacement of MK with SF to alter the SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> has been employed elsewhere [21]. The alkaline activators consisted of sodium hydroxide and sodium silicate solutions (Na<sub>2</sub>O = 14.7%, SiO<sub>2</sub> = 29.4%; H<sub>2</sub>O = 55.9% wt.). A very fine natural river sand was used (sieved to pass 600 μm), which is a common grading for fiber reinforced PVA composites [17-18]. The short PVA fibers were supplied by Kuraray Japan; its geometry and properties are shown in Table 2.

Oxides	MK (%)	SF (%)
SiO <sub>2</sub>	54.54	95.53
Al <sub>2</sub> O <sub>3</sub>	44.16	2.48
CaO	-	0.58
Fe <sub>2</sub> O <sub>3</sub>	0.51	0.16
Na <sub>2</sub> O	-	0.10
K <sub>2</sub> O	-	1.01
SO <sub>3</sub>	-	0.12
TiO <sub>2</sub>	0.32	-
Specific gravity	2.5	2.3

Table 1. Chemical composition of MK and SF  
1. táblázat MK és SF kémiai összetétele

Type	Diameter (μm)	Length (mm)	Specific gravity (g/cm <sup>3</sup> )	Tensile Strength (MPa)	Elongation (%)	Young Modulus (GPa)
REC15	40	8	1.3	1600	6	41

Table 2. Properties of PVA fiber  
2. táblázat PVA szálak jellemzői

### 2.2 Preparation of geopolymer composites

Matrices with three different SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> molar ratio were produced, equal to 3.0, 3.4 and 3.8; their solution composition (Na<sub>2</sub>SiO<sub>3</sub> / NaOH wt. ratio) and molarity of NaOH solution were kept always constant, equal to 1.5 and 8 M, respectively, which gave rise to a fixed R = SiO<sub>2</sub>/Na<sub>2</sub>O molar ratio in the solution equal to 1.08. The 8-mm PVA fibers were employed at 1% and 2% volume fraction; unreinforced geopolymers were also used as reference matrices. The alkaline solution to binder (MK or MK+SF) ratio was 1.10 in mass for all geopolymers without PVA fiber; that amount of solution provides a consistency of 253-255 mm to the fresh mixes (Table 3), according to the flow table test given by BS 1015-3 [22]. The addition of PVA fibers alters the workability of the fresh mixes; so the solution to binder (s/b) was increased to 1.25 and 1.40 for geopolymers with 1% and 2% PVA fibers, respectively, in order to maintain the overall consistency between 253-261 mm. Table 3 shows the formulations, their mix design and consistency, as well as the activating parameters of the matrices (molar ratios). The formulation codes contain (i) the term MK to designate that the main precursor is metakaolin; (ii) the numbers 3.0, 3.4 or 3.8 to designate the SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> molar ratio (obtained from the chemical composition of MK, SF and solids in the activator) and (iii) the terms PVA\_1 and PVA\_2 to describe the inclusion of either 1% or 2% vol. PVA. It is possible to observe that the s/b ratio increased for mixes with PVA, but the H<sub>2</sub>O / Na<sub>2</sub>O molar ratio was kept constant (12.8) for all geopolymers. As water does not take place in the alkali reaction, any change in that activating parameter may adversely affect the porosity and transport properties such as permeability. The changes in the activation content, however, affected the Na<sub>2</sub>O/SiO<sub>2</sub> and Na<sub>2</sub>O/Al<sub>2</sub>O<sub>3</sub> molar ratio (Table 3), with consequences in the mechanical strength that will be discussed in section 3.1.

The alkaline solutions (Na<sub>2</sub>SiO<sub>3</sub> and NaOH) were mixed together on the day of casting to prepare the liquid activator and allowed to cool down before mixing. A Hobart mixer was used for mixing; firstly, the alkaline solution was added, then MK (or MK+SF) was added in small amounts while mixing. This procedure allowed for complete homogenization of the pastes, which were quite sticky. The dried sand (aggregate to binder ratio = 2.0 for all formulations) was subsequently added,

Formulation	PVA % vol.	s/b ratio	Flow table (mm)	s/b ratio	Composition of the alkaline solution			Activating parameters			
					NaOH (M)	Na <sub>2</sub> SiO <sub>3</sub> /NaOH (mass)	SiO <sub>2</sub> /Na <sub>2</sub> O (molar)	SiO <sub>2</sub> /Al <sub>2</sub> O <sub>3</sub>	H <sub>2</sub> O/Na <sub>2</sub> O	Na <sub>2</sub> O/SiO <sub>2</sub>	Na <sub>2</sub> O/Al <sub>2</sub> O <sub>3</sub>
MK 3.0	0	1.10	255	1.10	8	1.5	1.08	3.0	12.8	0.25	0.73
MK 3.4	0	1.10	257	1.10	8	1.5	1.08	3.4	12.8	0.25	0.79
MK 3.8	0	1.10	253	1.10	8	1.5	1.08	3.8	12.8	0.22	0.85
MK 3.0_PVA_1	1	1.25	258	1.25	8	1.5	1.08	3.0	12.8	0.27	0.81
MK 3.4_PVA_1	1	1.25	261	1.25	8	1.5	1.08	3.4	12.8	0.26	0.87
MK 3.8_PVA_1	1	1.25	257	1.25	8	1.5	1.08	3.8	12.8	0.25	0.94
MK 3.0_PVA_2	2	1.40	254	1.40	8	1.5	1.08	3.0	12.8	0.29	0.89
MK 3.4_PVA_2	2	1.40	260	1.40	8	1.5	1.08	3.4	12.8	0.28	0.96
MK 3.8_PVA_2	2	1.40	260	1.40	8	1.5	1.08	3.8	12.8	0.27	1.03

Table 3. Formulations studied  
3. táblázat Vizsgált összetételek

followed by another 2-3 minutes of mixing for homogenization. The PVA fibers were added at the end of the mixing process and the mortars were mixed for another 5 minutes to ensure proper dispersion of fibers.

The geopolymers were cast in 50 mm cubes for compressive strength, 50 × 100 mm (diameter × height) cylinders for capillary absorption tests and (50 × 50 × 240) mm beams for flexural strength tests. The specimens were cured at 45°C for 24h and subsequently at room temperature for 27 days prior to testing.

### 2.3 Mechanical Properties

Compressive strength testing was performed after 28 days in conformity with ASTM C39 [23]; four specimens for each formulation were tested and the average and standard deviation reported. The flexural strength was carried out using a third-point loading test according to ASTM C 1609 [24]; mid-span displacement was monitored by means of a Linear Variable Differential Transducer (LVDT) and the load was applied with a servo-hydraulic universal INSTRON machine at standard displacement rate of 0.025-0.075 mm/min. The main parameters calculated as per ASTM C1609 were the flexural first-peak strength,  $f_1$ , (Eq. 1), flexural peak strength,  $f_p$ , (Eq. 2).

$$f_1 = \frac{P_1 L}{bd^2} \tag{1}$$

$$f_p = \frac{P_p L}{bd^2} \tag{2}$$

Where  $P_1$  and  $P_p$  are first-peak load and peak load, respectively,  $L$  is the span length (180 mm),  $b$  is the average width (~50 mm) of the specimen at the fracture and  $d$  is the average depth (~50 mm) of the specimen at the fracture. Four samples of each geopolymer formulation were tested and a representative curve is presented. The average toughness of the composites was also calculated, from the area under the Load × Mid-span deflection curves until imminent fracture of the composites, when the test was stopped.

The estimation of the durability of the FRGC was carried out by capillary sorptivity tests, following the recommendation of ASTM C1585 [25], but using cylindrical samples with other dimension (50 × 100, diameter × height). The test consists of monitoring the gain of weight over time as water passed into the dried sample through capillary suction until 72 h of testing. Five cylinders were used per geopolymer and the average of the capillary sorptivity ( $g/cm^2$ ) was calculated and plotted against the square root of time. The slope of the curves, known as the coefficient of capillary suction ( $g/cm^2 \cdot h^{1/2}$ ) was used as a parameter to estimate the durability of the composites studied.

## 3. Results and discussion

### 3.1 Mechanical properties

Fig. 1 shows the compressive strength of the geopolymers. A large standard deviation indicates that the results were quite variable. Fig. 1a shows that the PVA fiber inclusion decreased

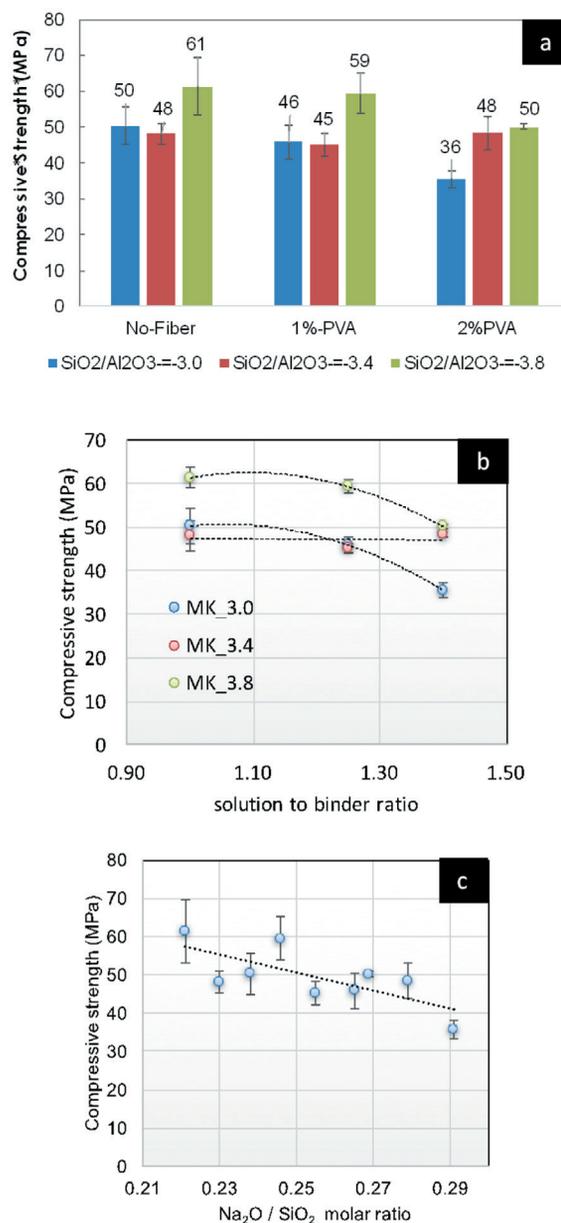


Figure 1. Compressive strength of geopolymers as a function of (a) volume of PVA fibers; (b) activator content; (c) Na<sub>2</sub>O/SiO<sub>2</sub> molar ratio.

1. ábra Geopolimerek nyomószilárdsága (a) a PVA száladagolás függvényében, (b) az aktivátor tartalom függvényében, (c) a Na<sub>2</sub>O/SiO<sub>2</sub> moláris arány függvényében

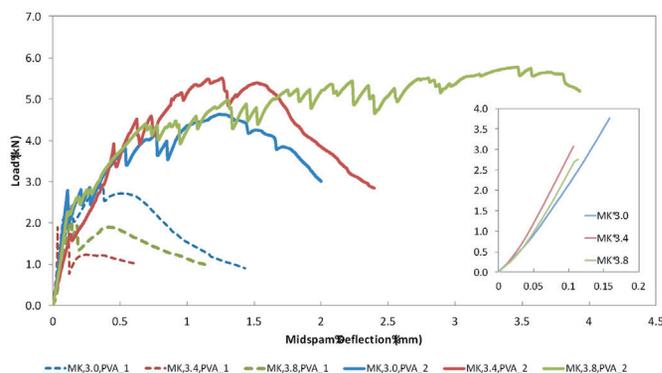


Figure 2. Load (kN) versus mid-span deflection (mm) curves for MK-based geopolymers

2. ábra Teher (kN) lehajlás (mm) ábrák MK bázisú geopolimerekre

the average compressive strength in MK 3.0\_PVA\_1 and MK 3.0\_PVA\_2, compared to their counterpart MK 3.0 (from 50 MPa without fiber to 36 MPa with 2% PVA). The drop in the compressive strength, however, is neither observed in PVA-geopolymers with SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> with 3.4 nor statistically significant in those with SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> = 3.8, despite the remarkable reduction in the average strength from 61 MPa in MK 3.8 to 50 in MK PVA\_2. Fig. 1b shows that the reduction in strength may be not associated with the fiber addition, but rather with the increase in the amount of solution (s/b from 1.10 to 1.40). In fact, a rise in the solution content to account for the fiber addition corresponds to an increase in the Na<sub>2</sub>O/SiO<sub>2</sub> molar ratio in the geopolymers, with consequent reduction in the strength. Indeed, Fig. 1c shows that the strength drops when the Na<sub>2</sub>O / SiO<sub>2</sub> increases from 0.21 to 0.29, which is the case for the formulations with 1% and 2% PVA (all with Na<sub>2</sub>O / SiO<sub>2</sub> > 0.25). It is possible to see that the rise in the s/b from 1.0 to both 1.25 and 1.45 ensured suitable workability for PVA-reinforced geopolymers; however, the higher amount of Na<sub>2</sub>O available in the systems also reduced the strength. Previous research [26] has indicated that the optimum Na<sub>2</sub>O / SiO<sub>2</sub> molar ratio is approximately 0.25 for higher compressive strength, which is in line with Fig. 1c.

The higher strength for MK 3.8 compared to MK 3.0 and MK 3.4 is in accordance with the studies of De Silva et al [30], who found that the compressive strength of MK-based geopolymers increases with higher SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> molar ratios varying from 2.5 to 5.0, especially observed at later stages.

Fig. 2 shows the Load (kN) × mid-span (mm) deflection curves for the geopolymer studied after third-point loading tests. The reference formulations (MK 3.0, MK 3.4 and MK 3.8) curves are enlarged in the inset of the graph for clarity. A deflection-hardening behavior was observed for composites reinforced with 2% PVA, i.e. MK 3.0\_PVA\_2, MK 3.4\_PVA\_2 and MK 3.8\_PVA\_2. These composites presented a ratio between the peak strength and first peak strength (f<sub>p</sub> / f<sub>1</sub>) equal to 1.7, 1.8 and 2.2, respectively, as shown in Table 4.

	MK 3.0	MK 3.0	MK 3.0	MK 3.4	MK 3.4	MK 3.4	MK 3.8	MK 3.8	MK 3.8
	PVA_1	PVA_2	PVA_2	PVA_1	PVA_2	PVA_2	PVA_1	PVA_2	PVA_2
(f <sub>p</sub> /f <sub>1</sub> )	1.0	1.5	1.7	1.0	1.0	1.8	1.0	1.0	2.2
Ductility index (δf <sub>p</sub> /δf <sub>1</sub> )	1.0	3.5	12.0	1.0	1.0	4.8	1.2	1	23.5
Toughness (J)	0	3	8	0	3	10	0	2	20

Table 4. Average f<sub>p</sub> / f<sub>1</sub> ratio, ductility index and toughness of the AAM  
4. táblázat Átlagos f<sub>p</sub> / f<sub>1</sub> arány, duktilitási index és szívósság

Table 4 also presents results of the ductility ratio (δf<sub>p</sub> / δf<sub>1</sub>) and toughness of the composites. Is it possible to see that the toughness was substantially increased at 2% PVA addition for all geopolymers. Table 4 shows that an increase from 1% to 2% PVA yielded a toughness 2.7 and 10 times higher for matrices with SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> equal to 3.4 and 3.8, respectively. Indeed, a higher SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> molar ratio increased the deformation and toughness of the PVA-geopolymers: MK 3.8\_PVA\_2 presented toughness 2.5× and 2× higher and ductility index 2.0× and 4.9×

higher than MK 3.0\_PVA\_2 and MK 3.4\_PVA\_2, respectively. So, it is possible to observe that a higher SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> has a positive effect in the ductility and toughness of AAM for a fixed PVA percentage equal to 2%. This is also evident on the fractured samples after bending tests (Fig. 3). It is possible to observe that the composites with 2% PVA presented several cracks but MK 3.8\_PVA\_2 was the only one with multi-cracking behavior typical from high-ductile composites.

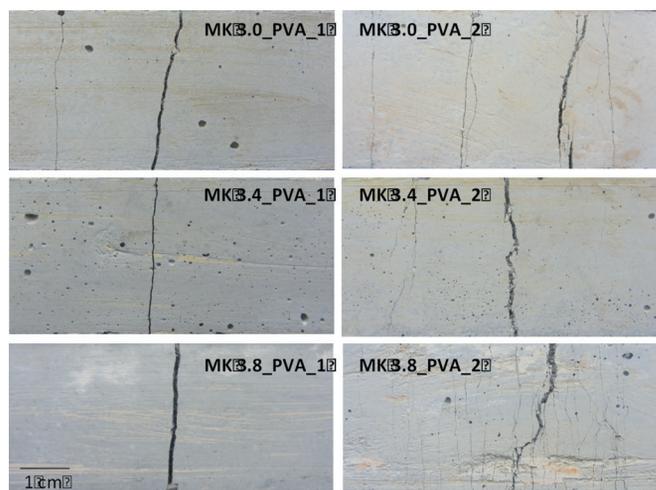


Figure 3. Cracked samples after bending tests  
3. ábra Megrepedt próbatetek hajlítózvizsgálat után

Fig. 4 confirms that the improvement in toughness is related not only to the SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> molar ratio but also to the amount of solution in the fresh mixes. Irrespective of the matrix composition, a significant increase in toughness is observed as the solution to binder content increased (Fig. 4a), which also corresponds to a rise in the soluble silica content (Fig. 4b).

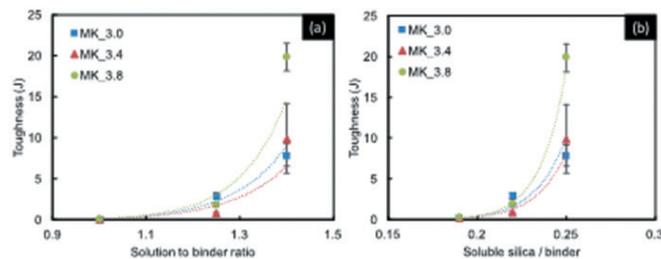


Figure 4. Toughness of the PVA-geopolymer as a function of (a) solution to binder ratio and (b) soluble silica / binder  
4. ábra PVA geopolimerek szívóssága (a) az oldat/kötőanyag arány függvényében, (b) az oldható szilika/kötőanyag arány függvényében

### 3.2. Capillary sorption

Fig. 5 shows the capillary sorption of the geopolymers studied, as well as the coefficient of capillary suction C (g/cm<sup>2</sup>.h<sup>1/2</sup>). It is possible to see that the addition of PVA fibers with employment of a higher solution to binder content increased the capillary sorption compared to the plain matrices (Fig. 5 and Fig. 6); this is in line with the compressive strength results, which show a reduction in strength with fiber addition. Nonetheless, the rise in C with the employment of 2% PVA fibers (compared to the unreinforced matrix) is similar for matrices with different SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> molar ratio: 47% in MK 3.0\_PVA\_2 (0.53 against 0.36 g/cm<sup>2</sup>.h<sup>1/2</sup>); 51% in MK 3.4\_

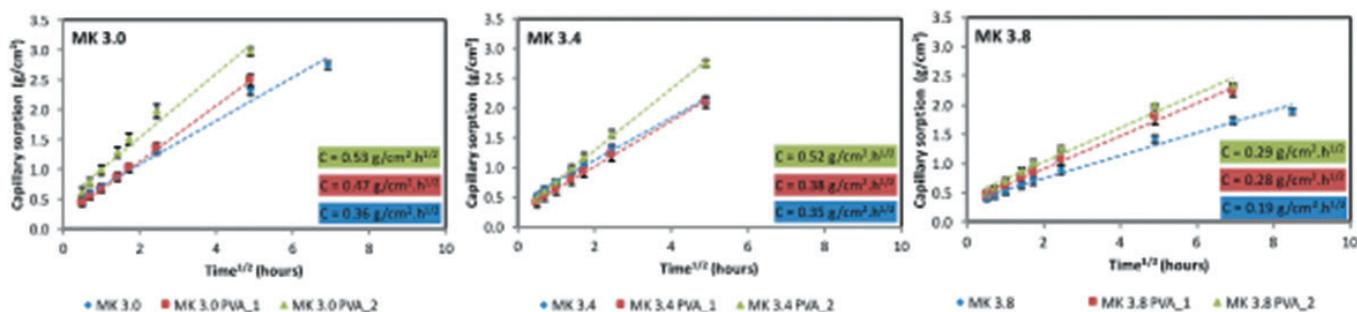


Figure 5. Capillary sorption of AAM studied  
5. ábra A vizsgált AAM minták kapilláris szorpciója

PVA\_2 (0.52 against 0.35 g/cm<sup>2</sup>·h<sup>1/2</sup>); 53% in MK 3.8\_PVA\_2 than MK 3.8 (0.29 against 0.19 g/cm<sup>2</sup>·h<sup>1/2</sup>). Fig. 5 and Fig. 6 also indicate that the matrix with SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> = 3.8 has reduced capillary sorption when compared to the others matrices with lower ratios, i.e. 3.0 and 3.4. The highest C is 0.29 g/cm<sup>2</sup>·h<sup>1/2</sup> for MK 3.8\_PVA\_2, which is even lower than C in unreinforced matrices with SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> = 3.0 and 3.4 (MK 3.0 with C = 0.36 and MK 3.4 with C = 0.35 g/cm<sup>2</sup>·h<sup>1/2</sup>). The results indicate that MK 3.8\_PVA\_2 is a matrix which not only exhibits better mechanical properties (highest peak strength,  $f_p/f_1$ , ductility index and toughness, ~50 MPa compressive strength), but also displays better durability-related properties (lower capillary sorption) among the investigated matrices.

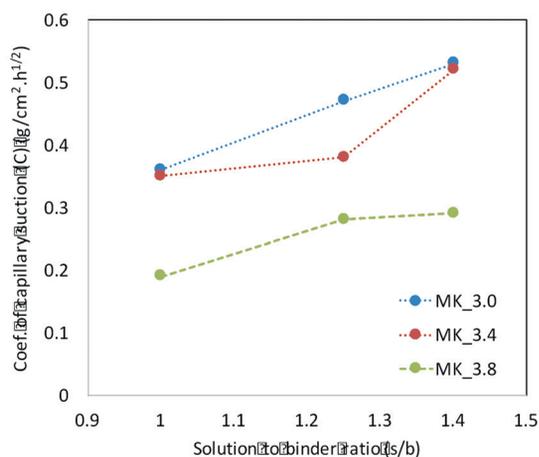


Figure 6. Coefficient of capillary sorption as a function of the solution to binder ratio  
6. ábra Kapilláris szorpciók együttható az oldat/kötőanyag arány függvényében

## 4. Conclusions

This paper studied the mechanical and durability-related properties of unreinforced metakaolin (MK)-based geopolymers with different SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> molar ratios (3.0, 3.4 and 3.8) and also reinforced with short PVA fibers with volume fraction of 1% and 2%. The effect of solution content on the mechanical properties was also discussed. The following conclusions can be drawn:

1. PVA fibers may be used to reinforce MK-based geopolymers; the amount of activating solution, however, needs adjustments as the PVA content increases (herein up to 2%) in order to maintain the

workability of the fresh mixes (253-261 mm using the flow table test).

2. The employment of higher solution to binder ratio to account for fiber addition has a slightly negative impact on the average compressive strength and capillary sorption. A rise in the solution content with fixed composition may represent an increase the Na<sub>2</sub>O/SiO<sub>2</sub> molar ratio to a level that exceeds the optimum value (0.25) to achieve better mechanical properties.
3. The addition of PVA fibers at 2% vol. allows for the development to geopolymers with deflection-hardening behavior in flexion. Improved toughness and ductility are related not only to the SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> molar ratio but also to the amount of soluble silica in the fresh mixes (i.e. amount of sodium silicate); a significant increase in toughness is observed as the solution to binder content or soluble silica to binder ratio (by mass) increased. The toughness is also higher when a matrix of higher SiO<sub>2</sub> / Al<sub>2</sub>O<sub>3</sub> molar ratio is designed. Overall it is possible to conclude that the reduced mean strength and higher capillary sorption of geopolymer made with fibers and higher solution content are compensated with better deformation and toughness.

## 5. Acknowledgements

The financial support of Canada-India Research Center of Excellence (IC-IMPACTS) in this research is highly appreciated. Paulo H. R. Borges would like to thank CNPQ, (Conselho Nacional de Desenvolvimento Científico e Tecnológico), of the Ministry of Science, Technology and Innovation of Brazil for funding his stay at the University of British Columbia, where this research was carried out (grant 201091/2014-3).

## References

- [1] Fernández-Jiménez, A. M. – Palomo, A. – López-Hombrados, C. (2006): Engineering properties of alkali-activated concrete. *ACI Materials Journal* (103) (2), p. 106-112. <https://doi.org/10.14359/15261>
- [2] Palomo, A. – Blanco-Varela, M. T. – Granizo, M. L. – Puertas, F. – Vazquez, T. – Grutzeck, M. W. (1999): Chemical stability of cementitious materials based on metakaolin. *Cement and Concrete Research* (29), p. 997-1004. [https://doi.org/10.1016/S0008-8846\(99\)00074-5](https://doi.org/10.1016/S0008-8846(99)00074-5)
- [3] Bakharev, T. (2005): Resistance of geopolymer materials to acid attack. *Cement and Concrete Research* (35), 658-670. <https://doi.org/10.1016/j.cemconres.2004.06.005>

- [4] Bakharev, T. (2005): Durability of geopolymer materials in sodium and magnesium sulfate solutions. *Cement and Concrete Research* (35) (6), p. 1233-1246. <https://doi.org/10.1016/j.cemconres.2004.09.002>
- [5] Kong, D. L. Y. – Sanjayan, J. G. (2008): Damage behavior of geopolymer composites exposed to elevated temperatures. *Cement and Concrete Composites* (30) p. 986–991 <https://doi.org/10.1016/j.cemconcomp.2008.08.001>
- [6] Kong, D. L. Y. – Sanjayan, J. G. (2010): Effect of elevated temperatures on geopolymer paste, mortar and concrete, *Cement and Concrete Research* (40) (2), p. 334-339. <https://doi.org/10.1016/j.cemconres.2009.10.017>
- [7] McLellan, B. C. – Williams, R. P. – Lay, J. – van Riessen, A. – Corder, G. D. (2011): Costs and carbon emissions for geopolymer pastes in comparison to ordinary portland cement, *Journal of Cleaner Production* (19) (9–10) p. 1080-1090. <https://doi.org/10.1016/j.jclepro.2011.02.010>
- [8] Turner, L. K. – Collins, F. G. (2013): Carbon dioxide equivalent (CO<sub>2</sub>-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and Building Materials* (43), p. 125-130. <https://doi.org/10.1016/j.conbuildmat.2013.01.023>
- [9] Li, V. – Kanda, T. (1998): Innovations Forum: Engineered Cementitious Composites for Structural Applications. *Journal of Materials in Civil Engineering* (10) (66), p. 66-69. [https://doi.org/10.1061/\(ASCE\)0899-1561\(1998\)10:2\(66\)](https://doi.org/10.1061/(ASCE)0899-1561(1998)10:2(66))
- [10] Li, V. C. (1998): Engineered Cementitious Composites – Tailored Composites Through Micromechanical Modeling, In: *Fiber Reinforced Concrete: Present and the Future*, Eds: N. Banthia, A. Bentur, and A. Mufti, Canadian Society of Civil Engineers, 213 p.
- [11] Li, V. C. (2003): On Engineered Cementitious Composites (ECC) – A review of the material and its applications. *Journal of Advanced Concrete Technology* (1) (3), p. 215-30.
- [12] Li, Z. – Zhang, Y. – Zhou, X. (2005): Short Fiber Reinforced Geopolymer Composites Manufactured by Extrusion. *Journal of Materials in Civil Engineering* (17) (6), p. 624–631. [https://doi.org/10.1061/\(ASCE\)0899-1561\(2005\)17:6\(624\)](https://doi.org/10.1061/(ASCE)0899-1561(2005)17:6(624))
- [13] Zhang, Y. – Sun, W. – Li, Z. (2006): Impact behavior and microstructural characteristics of PVA fiber reinforced fly ash-geopolymer boards prepared by extrusion technique. *Journal of Materials Science* (41) (10), p. 2787-2794. <https://doi.org/10.1007/s10853-006-6293-5>
- [14] Zhang Y. – Sun, W. – Li, Z. – Zhou X. – Eddie, Chau C. (2008): Impact properties of geopolymer based extrudates incorporated with fly ash and PVA short fiber. *Construction and Building Materials* (22) (3), p. 370-383. <https://doi.org/10.1016/j.conbuildmat.2006.08.006>
- [15] Nematollahi, B. – Sanjayan, J. – Uddin, F. – Shaikh, A. (2014): Comparative deflection hardening behavior of short fiber reinforced geopolymer composites. *Construction and Building Materials* (70), p. 54-64. <https://doi.org/10.1016/j.conbuildmat.2014.07.085>
- [16] Nematollahi, B. – Sanjayan, J. – Shaikh, A. F. (2015): Tensile Strain Hardening Behavior of PVA Fiber-Reinforced Engineered Geopolymer Composite. *Journal of Materials in Civil Engineering* (27) (10), p. 5696-5704. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0001242](https://doi.org/10.1061/(ASCE)MT.1943-5533.0001242)
- [17] Ohno, M. – Li, V. C. (2014): A feasibility study of strain hardening fiber reinforced fly ash-based geopolymer composites. *Construction and Building Materials* (57), p. 163-168. <https://doi.org/10.1016/j.conbuildmat.2014.02.005>
- [18] Shaikh, F. U. A. (2013): Deflection hardening behavior of short fibre reinforced fly ash based geopolymer composites. *Materials and Design* (50), p. 674-682. <https://doi.org/10.1016/j.matdes.2013.03.063>
- [19] Zhang Y. – Sun W. – Li Z. – Zhou X. (2009): Geopolymer Extruded Composites with Incorporated Fly Ash and Polyvinyl Alcohol Short Fiber *ACI Materials Journal* (106) (1), p. 3-10. <https://doi.org/10.14359/56310>
- [20] Duxson, P. – Provis, J. L. – Lukey, G. C. – Mallicoate, S. W. – Kriven, W. M. – van Deventer, J. S. J. (2005): Understanding the relationship between geopolymer composition, microstructure and mechanical properties. *Colloids and Surfaces A: Physicochemical and Engineering Aspects* (269), p. 47-58. <https://doi.org/10.1016/j.colsurfa.2005.06.060>
- [21] Yunsheng, Z. – Wei, S. – Zongjin, L. (2010): Composition design and microstructural characterization of calcined kaolin-based geopolymer cement, *Applied Clay Science* (47) (3-4), pp. 271-5. <https://doi.org/10.1016/j.clay.2009.11.002>
- [22] BS EN 1015-3, Methods of test for mortar for masonry – Part 3: Determination of consistence of fresh mortar (by flow table), 6 p.
- [23] ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens.
- [24] ASTM C 1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading).
- [25] ASTM C1585-13 Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes, 6 p.
- [26] Barbosa, V. F. – MacKenzie K. J. – Thaumaturgo C. (2000): Synthesis and characterisation of materials based on inorganic polymers of alumina and silica: sodium polysialate polymers. *International Journal of Inorganic Polymers*, (2), p. 309–17.
- [27] De Silva, P. – Sagoe-Crenstil, K. – Sirivivatnanon, V. (2007): Kinetics of geopolymerization: Role of Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub>, *Cement and Concrete Research* (37) (4), pp. 512-8. <https://doi.org/10.1016/j.cemconres.2007.01.003>

Ref:

Borges, Paulo H. R. – Bhatta, Aamer – Teixeira Bavuzo, Luiggi – Banthia, Nemkumar: *The effect of the alkaline solution content on the mechanical properties of MK-based PVA fiber-reinforced geopolymers* Építőanyag – Journal of Silicate Based and Composite Materials, Vol. 69, No. 1 (2017), 13–18. p. <http://dx.doi.org/10.14382/epitoanyag-jsbcm.2017.3>

**Lúgos oldat tartalom hatása PVA szálerősítésű MK bázisú geopolimerek mechanikai jellemzőire**

A cikk bemutatja PVA szálerősítésű, aktivált metakaolin bázisú geopolimerek mechanikai tulajdonságait az aktiváló oldat tartalom változtatásának hatására. Az alkalmazott PVA száltartalom 0 V%, 1 V% és 2V % volt. A vizsgált geopolimerek SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> moláris hányada 3,0-3,4-3,8 volt. Az aktiváló oldat mennyiségét úgy választották meg, hogy a friss keverékek bedolgozhatósága azonos legyen mindegyik száltartalom esetén. Vizsgált jellemzők: nyomószilárdság, hajlító-húzószilárdság, kapilláris vízfelvétel (tartóssági jellemzők becslésére). A vizsgálatok kimutatták, hogy az aktiváló oldat mennyiségének hatása van a mechanikai jellemzőkre. Az aktiváló oldat mennyiségével arányosan változott a geopolimerek szívóssága, és az oldható szilika tartalom jó korrelációt mutatott a hajlítóvizsgálatokból megkapható mechanikai jellemzőkkel. Kulcsszavak: Mechanikai jellemzők; tartósság; metakaolin; geopolimer; szálerősítésű geopolimer kompozit; PVA szál; nátrónvízűveg oldat



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