Durability Properties of Ladle Slag Geopolymer Mortar Based on Fly Ash

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Abstract:
This paper presents the results of tests of physical-mechanical, durability and microscopic properties of geopolymer mortar mixtures based on fly ash and ladle slag. The mixtures are alkali-activated using sodium silicate and sodium hydroxide solution. Firstly, the effects of different fly ash (class „F“) particle sizes on the characteristics of the mortar mixtures were examined when binder and alkali activator were cured at 95 ºC for 24 h, also pozzolanic activity and strength activity index were investigated. After that, fly ash ground of optimal particle sizes (0,09 mm) was replaced with ladle slag, 0 to 20 % of the mass, the replacement steps being 5 %. The specimens having dimensions 4x4x16 cm were then cured in ambient conditions, and the effects of replacement of a part of fly ash with ladle slag were determined by testing water absorption, flexural and compressive strength, freeze-thaw resistance, sulfate attack, ultrasound velocity, FT-IR spectroscopy and leaching of heavy metals. According to the test results of compressive strength resistance of geopolymer mortars exposed to sulfate solution, the mortar made with fly ash and ladle slag showed better resistance to sulfate attack than the mortar made with fly ash only.

Keywords: Geopolymer; Particle size; Curing; Mechanical properties; Durability properties.

1. Introduction

In the last few decades, the new form material has been in the focus of attention: a geopolymer having characteristics very similar to cement composites [1]. Geopolymers are materials with some good characteristics as high compressive strength, low creep, good acid resistance, low shrinkage, etc. [2].

In theory, material that contains silicon and aluminum oxides in its chemical composition can be used as a solid binder material for the making of geopolymers [3]. Some of the most frequently used binders are the waste materials (byproduct) [4]originating from industrial production [5]. According to actual international standards, many industrial byproducts are no longer regarded as hazardous waste material. Instead, most of them are recognized as a secondary raw material [6]. The use of waste material in the production of new composite materials is a common practice which is in accordance with the environmental requirements [7]. So far, many performances of geopolymer mortar have been examined
where different variations of concentrations of alkali solutions necessary for activation of solid binder materials were investigated: NaOH [1, 8] and Na₂SiO₃, curing time and temperature [9,10], etc. The effect of curing temperature on the mechanical properties of a geopolymer was investigated by Rovnanik [11] and Bijeljić et al. [12]. Both research papers concluded that a higher temperature has an advantageous effect on achieving early strengths, but also the mechanical properties of 28 days-aged materials show lower values when specimens are temperature treated than when they are cured in ambient conditions. In terms of durability properties of geopolymer, the most commonly tested properties were freezing-thawing resistance [13-15] and sulfate resistance to the immersion of specimens in a sulfate solution. Bakharev [16] claims that the strength test results, of immersion of samples into a 5 \% sulfate solution, showed an increase of strength. Komljenović et al. [17] presented the result of the same test with the ratio of the relative strength after sulfate attack and of the reference samples which was higher than 1. Only several authors tested the characteristics of geopolymer mixtures made with ladle slag, while the tests were conducted on geopolymer paste. Natali et al. [18] investigated fiber-reinforced geopolymer made of ladle slag and metakaolin in proportion 3:2. Murri et al. [19] investigated high-temperature behavior of ambient cured geopolymer made of varying compositional ratios of ladle slag and metakaolin or ladle slag and fly ash. Bignozzi et al. [20] investigated durability properties of geopolymer based on metakaolin and ladle slag, while Češnovar et al. [21] investigated durability characteristics of geopolymer based on electric arc furnace steel slag and ladle slag, activated using potassium silicate (K₂SiO₃).

The main aim of this research was to investigate the possibility of using ladle slag as a co-binder material in the design of geopolymer mortars based on fly ash (class „F”) when mixtures are activated using sodium silicate and sodium hydroxide solution. The properties of these geopolymer mortar mixtures were compared to the properties of cement mortar mixtures when tested under the same conditions.

2. Experimental Procedures

2.1. Materials

In this study fly ash was used as the main source material for making geopolymer mortars while ladle slag was used as an additive. Fly ash originates from thermal electric power plant Kostolac “B” – Serbia. Ladle slag was generated as a byproduct coming from steel production process by the company HBIS Group Iron & Steel-Serbia. Chemical compositions of fly ash and ladle slag are given in Tab. I, while in Figure 1 their photograph and SEM are displayed. According to the results of the chemical analysis of fly ash, the sum of SiO₂+Al₂O₃+Fe₂O₃ is more than 70 \% of total mass, while CaO content was less than 10 \% which sorts fly ash into class of “silicate ash” according to standard EN 450-1 or to “class F” according to standard ASTM C618. According to SEM images, the fly ash particles seem to be mostly spherical and different in size. Unlike fly ash, ladle slag particles seem to have irregular shape and sharp edges.

Sodium hydroxide and sodium silicate were used as alkali activators for making geopolymer mixtures. Sodium hydroxide of molarity 10M was mixed with sodium silicate of the starting module Ms 2,2 (Ms = SiO₂/Na₂O) in mass ratio 100:18.52. That way, an activator with the content of 10\% Na₂O of the solid binder mass was obtained, whereas Ms in sodium silicate was reduced to value 1,5. Solution prepared this way was used for making all geopolymer mortar mixtures.

Standard tap water was used in mortar production in all mixtures. SuperplasticizerSikaViscocrete 5380 was used to achieve the proper workability of mortar mixtures. Aggregate used in this research was a river sand that originating from South Morava (Serbia) with maximum grain size of 2 mm. Commercially available cements CEM II
A-L 42,5 R and cement CEM III/B 32,5 N-LH/SR were used as binder materials for making cement mortar mixtures.

Tab. I Chemical composition of used binders.

| Material         | SiO₂ | Fe₂O₃ | Al₂O₃ | CaO | MgO | SO₃ | P₂O₅ | TiO₂ | Na₂O | K₂O |
|------------------|------|-------|-------|-----|-----|-----|------|------|------|-----|
| Fly ash          | 51,68| 11,58 | 20,16 | 7,42| 2,41| 1,02| 0,12 | 1,04 | 0,88 | 1,04|
| Ladle slag       | 22,20| 6,82  | 15,60 | 44,21| -   | 0,1 | 0,04 | 0,01 | 0,01 |

Fig. 1. Photo and SEM display of used binder materials: (a) fly ash, (b) ladle slag.

2.2. Mix design

For the purpose of determining the effect of different particle size of fly ash on characteristics of geopolymer mixtures, three batches of mortar were first made. The first batch was made with fly ash of particles smaller than 0.125 mm („FA₀.₁₂₅”). The second batch was made with fly ash of particles smaller than of 0.09 mm („FA₀.₀₉”), while the third batch was made with fly ash of particles smaller than of 0.063 mm („FA₀.₀₆₃”). All mortar mixtures were made by using the same ratio of water/binder and binder/aggregate per mass. The samples prepared in this part of examination were firstly cured at an ambient temperature of 22 °C for 24 h, and then cured at 95 °C for another 24h. The five more batches of geopolymer mortar were made on the basis of fly ash with particles smaller than 0.09 mm, with added ladle slag of particles smaller than 0.09mm. Percentage of ladle slag mass in respect to the total mass of the binder was 0 to 20%, in 5 % steps of replacement. These mortar mixtures were all time cured in ambient conditions protected by using plastic foil to prevent loss of moisture. In view of comparing the characteristics of geopolymer and cement mortars, two batches of mortar were made with cement CEM II and CEM III. The binder/aggregate ratio was 1:3,
while the ratio of water/binder was 0.5. The mix design of all mortar mixtures is provided in Tab. II.

**Tab. II** Details of mortar mixtures.

| Mix no. | Designation | Mortar mixture quantity |
|---------|-------------|------------------------|
|         |             | FA | S | CEM II 42,5 R | CEM III 32,5 N | Sand | Extra water | SH 10 M | SS | SP [%] | w/b |
| 1       | FA 0.125   | 450 | 0.125 | - | - | 1350 | 40 | 56,16 | 303,23 | - | 0.45 |
| 2       | FA 0.090   | 450 | 0.090 | - | - | 1350 | 40 | 56,16 | 303,23 | - | 0.45 |
| 3       | FA 0.063   | 450 | 0.063 | - | - | 1350 | 40 | 56,16 | 303,23 | - | 0.45 |
| 4       | 0 S        | 450 | 0.090 | 0 | 0.090 | 1350 | 20 | 56,16 | 303,23 | 2 | 0.43 |
| 5       | 5 S        | 427.5 | 0.090 | 22.5 | 0.090 | 1350 | 20 | 56,16 | 303,23 | 1.5 | 0.42 |
| 6       | 10 S       | 405 | 0.090 | 45 | 0.090 | 1350 | 20 | 56,16 | 303,23 | 1 | 0.42 |
| 7       | 15 S       | 382.5 | 0.090 | 67.5 | 0.090 | 1350 | 20 | 56,16 | 303,23 | - | 0.41 |
| 8       | 20 S       | 360 | 0.090 | 90 | 0.090 | 1350 | 20 | 56,16 | 303,23 | - | 0.41 |
| 9       | E II       | - | - | - | - | 450 | 1350 | 225 | - | 0.2 | 0.50 |
| 10      | E III      | - | - | - | - | 450 | 1350 | 225 | - | 0.5 | 0.50 |

*FA-fly ash, S- ladle slag, SH-sodium hiroxide, SS-sodium silicate, SP- superplasticizer, w/b – water/binder ratio

### 2.3 Methods of examination

#### 2.3.1. Physical-mechanical examinations

Pozzolanic activity of used binding materials was determined according to the SRPS B.C1.018 standard. Mortar samples were made by using the mass ratio $m_l:m_p:m_s= 1:2:9$ and water/binder ratio 0.6 (where: $m_l$ is mass of slaked lime, $m_p$ is mass of tested pozzolan, $m_s$ is mass of CEN standard sand). Mortar was cast into molds and heated at 55 °C in the dryer for five days. The samples were tested for flexural and compressive strength. Based on these results, class of pozzolanic activity was determined.

The Activity index of used binding materials was determined according to the EN 450-1 standard. Activity index ratio (in percent) of the compressive strength of standard mortar bars is obtained with 75 % test cement and 25 % tested material by mass, to the compressive strength of standard mortar bars prepared with 100 % test cement, when tested at the same age. Preparation of standard mortar bars and determination of compressive strength (at the age from 28 and 90 days) shall be carried out in accordance with EN 196-1. The activity index at 28 days and at 90 days shall not be less than 75 and 85 %, respectively.

Water absorption: Determination of water absorption was performed according to the EN 1015-18 standard. In order to obtain absorption coefficients, $C$ and $C_m$, samples having dimensions 4x4x8 cm were tested.

Freeze–thaw resistance of fly ash-based mortar was determined according to the EN 14617-5 standard. The samples of mortar prisms, having dimensions 4x4x16 cm were frozen and thawed for 25 cycles.

Sulfate resistance of geopolymer mortars based on fly ash with addition of ladle slag was tested according to the performance testing report CEN/TR 15697. The samples were cured in ambient conditions to the age of 28 days after which they were immersed in 5% $Na_2SO_4$ solution for the duration of 180 days.
2.3.2 Instrumental techniques

Ultrasonic pulse velocity was used in this paper for testing the hardened mortar prisms of different ages, in order to monitor the hardening process, i.e. the degree of realized polymerization. Ultrasonic velocity was recorded on a Controls 58-E4800 ultrasonic pulse velocity tester.

FT-IR spectroscopy was used in this paper to identify changes in chemical combinations of Si-O and Al-O reaction zones. FTIR spectrum of investigated samples was recorded on a Nicolet 6700 spectrophotometer, using a KBr pellets technique. FT-IR sample analysis was done in the range from 4000 to 400 cm⁻¹. Since most of the reactions occur in frequency lower than 1200 cm⁻¹, only these signals were discussed.

Leaching of heavy metals test was performed according to the DIN 38414-S4 standard. The characterization analysis of industrial by-products was performed in order to determine concentration of pH value, electric conductivity, and toxic metals samples with the highest concentration of admixtures and cement reference.

Dry mortar mass (100 g), particles smaller than 10 mm, and demineralized water (1000 ml), were mixed in rotary agitator (150 rpm) for 24 h. The samples were then filtered and the liquid phase was analyzed.

3. Results and Discussion

Pozzolanic activity and activity index: The results of pozzolanic activity tests are presented in Tab. III. According to the results, the fly ash binder has the pozzolanic activity class 10, while the tests of mechanical characteristics of mortar made with ladle slag do not satisfy the minimum requirements for class 5. Pozzolan class can be in relation to material reactivity. Therefore, higher pozzolanic class could be an indicator of material reactivity. The values of the activity index tests are presented in Tab. IV. The mortar made of fly ash has achieved very high activity index. This might be connected to pozzolanic class activity, but also to high fly ash particle fineness. In testing results of mortar made with ladle, activity index did not point out insufficient value according to appropriated criteria.

Tab. III Pozzolanic activity of used by-product materials.

| By-product  | Flexural strength (MPa) | Compressive strength (MPa) | Class |
|-------------|-------------------------|----------------------------|-------|
| Fly ash     | 3,04                    | 10,38                      | 10    |
| Ladle slag  | 1                       | 2,65                       | /     |

*FA-fly ash, S- ladle slag

Tab. IV Activity index of used by-product materials.

| Tested material | Compressive strength, 28 days (MPa) | Compressive strength, 90 days (MPa) | Activity index (%) | Criteria EN 450-1 (%) |
|-----------------|--------------------------------------|-------------------------------------|--------------------|-----------------------|
| Fly ash         | 51,58                                | 60,23                               | 28 days - 97       | 28 days - 75          |
|                 |                                      |                                     | 90 days - 96       | 90 days - 85          |
| Ladle slag      | 40,73                                | 44,09                               | 28 days - 76       | 28 days - 75          |
|                 |                                      |                                     | 90 days - 70       | 90 days - 85          |
| OPC             | 53,3                                 | 62,62                               | -                  | -                     |

*OPC-Ordinary Portland cement
Effects of different fly ash particle size on properties of geopolymer mortar: The effects of different fineness of the main binder material – fly ash, cured at 95 °C, flexural strength, workability (by using flow test) and compressive strength of geopolymer mortar are given in Figure 2a) and b), respectively. As it can be seen, flow value increased with increase in fly ash fineness. One of the possible reasons can be the lower porosity of finer grains of fly ash. Compressive strengths of the mixtures „FA0.063” and „FA0.09” amount to 47.81 and 42.08 MPa, respectively (at the age of 28 days), whereas the compressive strength of the mixture „FA0.125” the compressive strength was 36.43 MPa. Higher compressive strength in „FA0.063” is a result of better reactivity of small particles of fly where ratio in this mixture is higher compared to the other two mixtures. Taking into account the aspect of compressive strength and lower cost of raw product preparation, geopolymer mixtures with fly ash of particles smaller than 0.09 mm were used.

**Fig. 2.** Effect of different fly ash particle size on strength of specimens cured at 95°C for 24h and workability: (a) Flexural strength and flow value and (b) compressive strength development of the geopolymer mortar.

**Mechanical properties:** The test results of compressive and flexural strengths are presented in Figure 3 a) and b). As opposed to the reference samples „E II“ and „E III“, early strengths of geopolymer mortars which hardened in ambient conditions are low. Observing the flexural strength diagram at the sample age of 28 days, it can be observed that the mixture „5 S“(7.35 MPa) has the highest value and it is approximately equal to the „E II“ mixture. The achieved flexural strength at the age of mortar samples of 90 days are higher for 4-6 % than the strengths measured on the mortar samples of the same series at 56 days. Based on this, it can be concluded that polymerization is almost fully completed at the age of samples of 56 days.
According to the compressive strength test results of the samples at 28 days of age, all mixtures exhibited approximately the same values. Yet, the „20 S“ mixture exhibited a slightly higher value than 44.30 MPa but it is for about 2.80 MPa less than the „E II“ mixture. Such trend is observable at the age of 56 days, when the strength of the „20 S“ mixture was 47.80 MPa. The achieved value of compressive strength of mortar made with fly ash only at the age of 90 days is for 9 % higher than the one of mortar samples of the same series at the age of 56 days, while in the case of the samples containing the addition of ladle slag the change of compressive strength at the mentioned ages is only slightly higher than 2 %. Ladle slag has a positive effect on the initial increase of compressive strength of the mortar samples cured in ambient conditions proportionally to their percentage of presence, but their increase after 28 days is negligible.

![Graph a)

Fig. 3. Effect of different percentage of ladle slag on: (a) Flexural strength and (b) compressive strength development of the geopolymer mortar.

**Water absorption:** The results of average water absorption coefficient are presented in Tab. V. The lowest value of the water absorption coefficient was measured on the samples of the reference „E II“ mortar and it is 0.28 kg/(m²·min⁰.⁵). Among the geopolymer mortar samples, the least value of absorption coefficients was measured on the „0 S“ (0.32 kg/(m²·min⁰.⁵)) mix, and the value of the coefficient increases with the increase of percentage of S. The highest value was measured on the „20 S“ mixture and it is 0.56 kg/(m²·min⁰.⁵), so according to the results, it can be concluded that the water absorption coefficient increases with the increase of percentage of presence of ladle slag in the mass.
**Tab. V** Average water absorption coefficients.

| Mix. | Average water absorption coefficient $C$ [kg/(m$^2$·min$^{-0.5}$)] | Average water absorption coefficient $C_m$ (kg/m$^2$) |
|------|-------------------------------------------------|-----------------|
| 0 S  | 0,32                                            | 11,97           |
| 5 S  | 0,40                                            | 12,43           |
| 10 S | 0,49                                            | 12,47           |
| 15 S | 0,52                                            | 12,51           |
| 20 S | 0,56                                            | 13,24           |
| E II | 0,28                                            | 6,33            |
| E III| 0,31                                            | 6,11            |

**Freeze–thaw resistance:** Test results of the mass loss and flexural and compressive strength resistance after 25 cycles are presented in Tab. VI. The loss of mass of all the tested mixtures is negligible, lower than 0,1%. The flexural strength test of all geopolymer mixtures detected the increase of flexural strength. Also, in the samples of geopolymer mixtures labeled as: „0 S“; „5 S“ and „10 S“ an increase of compressive strengths of more than 7 % in comparison to the reference samples of the same composition which were not exposed to freezing and thawing cycles was recorded, while in the „15 S“; „20 S“; „E II“ and „E III“ specimens a decrease of strengths of 2 % i.e. 9 %, respectively was observed. The appearance of the mortar mixture specimens are presented in Figure 4. This might be explained by the fact that freeze-thaw resistance mostly depends on pore structure of the material. As the freeze-thaw resistance of geopolymer mortar decreases with the increase of ladle slag portion (while water absorption coefficient increases), it can be expected that such mixtures have the higher content of unbound water in the material. This could be the reason of internal material cracking which affects the reduction of materials strength.

![Fig. 4. Specimens of geopolymer mortar after freeze-thaw resistance test: „0 S“; „5 S“; „10 S“; „15 S“ and „20 S“.

**Sulfate resistance:** The initial pH value of the 5% Na$_2$SO$_4$ solution was 7, and in Tab. VII the results of flexural and compressive strength resistance after 180 days of immersion in 5% Na$_2$SO$_4$ are given. The measured values of compressive strength resistance indicated that due to the immersion of mortar specimens into the sulfate solution, there was an increase of compressive strength in respect to the reference specimens of the same composition which were not exposed to the sulfate solution action. As opposed to the specimens of reference mixtures where a decrease of strength was measured, the specimens of all series of
geopolymer mortar mixtures continued to increase strength, and the coefficient of compressive strength resistance was in the range 1.05 to 1.26 (in the mixtures „0 S” and „5 S”, respectively). Physical changes on the tested specimens were not visible. This can be explained by the fact that the geopolymer binder and alkali activators, after exposure to the solution, continue to retain their interior stability and continue to harden, without reacting to the exterior effects.

**Tab. VI** Mass, flexural and compressive strength resistance (%) after 25 cycles of freeze-thaw test.

| Mix. | 0 S  | 5 S  | 10 S | 15 S | 20 S | E II | E III |
|------|------|------|------|------|------|------|-------|
| Mass resistance | 0,98 | 1 | 0,99 | 0,98 | 1 | 0,99 | 0,99 |
| KMf 25 | 126 | 108 | 103 | 102 | 102 | 75 | 101 |
| KMc 25 | 109 | 108 | 107 | 98 | 98 | 91 | 92 |

*KMf 25 – flexural strength resistance = flexural strength after 25 freeze-thaw cycles/value of unfrosted specimens (%)

*KMc 25 compressive strength resistance = compressive strength after 25 freeze-thaw cycle /value of unfrosted specimens (%)

**Tab. VII** Flexural and compressive strength resistance after 180 days of immersion in 5% Na₂SO₄.

| Mix. | Reference samples (σr) | Sulfate attack at 28 + 180 days exposed to 5% Na₂SO₄ (σs) | Strength loss index |
|------|------------------------|-------------------------------------------------|-------------------|
|      | Flexural strength (σfr) | Compress. strength (σrc) | Flexural strength (σsf) | Compress. strength (σsc) | (σsf)/(σfr) | (σsc)/(σrc) |
| 0 S  | 8,68 | 50,60 | 9,15 | 53,21 | 1,05 | 1,05 |
| 5 S  | 7,78 | 45,24 | 9,10 | 57,02 | 1,17 | 1,26 |
| 10 S | 7,88 | 45,21 | 8,98 | 53,34 | 1,14 | 1,18 |
| 15 S | 7,97 | 46,15 | 9,09 | 54,24 | 1,14 | 1,18 |
| 20 S | 7,30 | 48,08 | 8,40 | 52,76 | 1,15 | 1,10 |
| E II | 10,01 | 63,34 | 9,35 | 56,04 | 0,93 | 0,88 |
| E III | 5,88 | 49,54 | 10,03 | 47,07 | 1,71 | 0,95 |

*strength loss index = relative strength after sulfate attack / compared to reference samples

Ultrasound pulse velocity was analyzed on the hardened prisms and presented in Tab. VIII. The reason for testing was to determine dependence of the achieved mechanical strengths and degree of polymerization. By observing the table, on may detect the increase of ultrasonic pulse velocity especially at the ages of 3, 7 and 28 days. Variation of the ultrasonic pulse velocity is in accordance with the variation of mechanical strengths in time. It can be concluded that one the basis of the passage velocity of ultrasonic pulse, the degree of achieved polymerization can be predicted.

FT-IR spectroscopy: The infrared spectra of the tested mortar mixtures are given in Figure 5. FT-IR test results show several pronounced signals at: 420-430 cm⁻¹, 850-900 cm⁻¹ and 1100 cm⁻¹. The strongest band is at 1100 cm⁻¹ and it is related to Si-O-Si stretching vibrations. Stretching vibrations of Si-O-Si can represent a degree of realized polymerization, and they occur in the range 950-1200 cm⁻¹. At the same time, the medium intensity bands that appear in the mentioned range could originate from extensively Si-O-Si vibrations of presented quartz. The next strongest band is at 420-430 cm⁻¹ and it is assigned to Si-O-Al deformation vibrations, while the some of these absorption maximums refer to Si-O-Mg
deformation vibrations. The third signal occurs in the 880-900 cm\(^{-1}\) region and it is related to Si-OH/Al-OH stretching vibrations. These results confirm previously given chemical composition, that is the presence of Si, Al, Mg. As expected, a FT-IR cement mortar spectrum is quite different from geopolymer mortar spectra.

Tab. VIII Ultrasonic pulse velocity.

| Mix. | 3 days | 7 days | 28 days | 56 days | 90 days |
|------|--------|--------|---------|---------|---------|
| 0 S  | 2023   | 2651   | 3131    | 3269    | 3456    |
| 5 S  | 1944   | 2817   | 3005    | 3042    | 3113    |
| 10 S | 2102   | 2899   | 2947    | 3008    | 3128    |
| 15 S | 2238   | 2880   | 2912    | 3134    | 3255    |
| 20 S | 2309   | 2933   | 3062    | 3213    | 3250    |
| E II | 3636   | 3893   | 3898    | 3970    | 4000    |
| E III| 3404   | 3490   | 3714    | 3783    | 3769    |

Fig. 5. FT-IR spectra of geopolymer mortar mixtures cured in ambient conditions.

Leaching: test results show toxic metals, electric conductivity and pH value of the specimen obtained after filtering the eluate, and they are given in Tab. IX. The contents of ladle slag in geopolymer mixtures causes increase of pH values and electrical conductivity. According to the toxic metals leaching from the eluates of the mixture specimens labeled as „20 S“ and by comparing them to the maximum values (MDK) prescribed by the Code, a 56 % and 12 % increase of boron and nickel toxic metals leaching respectively, was observed. In the mix „0 S“ the measure values of toxic metals leaching were lower than all MDK values.
Tab. IX Toxic metals, pH, electric conductivity values after leaching test and comparison to the maximum permissible values.

| Mixture | 0 S   | 20 S  | EII  |
|---------|-------|-------|------|
| pH      | 10    | 10,3  | 11,6 |
| EC (μS/m) * | 1880  | 2000  | 2000 |
| Initial pH | 7    |       |      |

Mixture | Maximum values (MDK)** mg/l | Measured values mg/l |
|---------|-----------------------------|----------------------|
| Al      | 1,656                       | 2,981                |
| B       | 0,881                       | 1,56                 |
| Cd      | 0,003                       | 0                    |
| Cr      | 0,0162                      | 0,0359               |
| Fe      | 0,6348                      | 1,948                |
| Hg      | 0                           | 0                    |
| Pb      | 0,0326                      | 0,0975               |
| Zn      | 0,1392                      | 0,2852               |
| Ar      | 0,05                        | -                    |
| Ni      | 0,0607                      | 0,112                |
| F       | 1,50                        | -                    |
| Cu      | 0,10                        | -                    |

*EC – Electric conductivity,
** According to the Code on permissible quantities of hazardous and harmful matter in soil and irrigation water and methods for their testing „Off. Gazette of RS” 23 of 18/3/1994.
***no permissible value has been specified.

4. Conclusion

In this paper, a study of the effect of ladle slag as a co-binder material on physical-mechanical, durability and microscopic properties of geopolymer mortar was carried out. Mortar mixtures were designed by adding ladle slag in the amount of up to 20 % of the total binder in order to improve geopolymer properties.

The results can be summarized as follows:

Different particle size of fly ash affects workability (measured by using flow test) and strength test of geopolymer mortar mixtures based on fly ash. Flow value and strength of measured mortars increases with decreasing of fly ash particle size.

Test results of compressive strength indicated that early strength of geopolymer mortar mixtures with the addition of ladle slag, cured in ambient conditions is low, while 90 % of total strength was achieved already after 56 days. It can be concluded that polymerization is almost fully achieved at that age.

Ultrasonic pulse velocity variation is related to the variation of mechanical strength in time. It is a general conclusion that based on the ultrasonic velocity pulse, the degree of achieved polymerization of geopolymer specimens can be assessed.

The water absorption coefficient rises with the increase of replacement ratio of fly ash with ladle slag. The highest coefficient is for the mix in which 20 % of the basic binder was replaced with ladle slag.

All geopolymer mortar showed better freezing/thawing resistance after 25 cycles than the mortar made with cement, and this property the highest in a mixture made only of fly ash as a binder.
The compressive strength resistance of all geopolymer mortars to 5 % Na₂SO₄ was better than in cement mortars for the period of 180 days, whereby ladle slag affected its increase.

The use of the by-product material in geopolymer mortar has a positive influence on local waste reduction.

5. References

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