INSTITUT ZA RUDARSTVO I METALURGIJU BOR YU ISSN: 1451-0162
KOMITET ZA PODZEMNU EKSPLOATACIJU MINERALNIH SIROVINA UDK: 622

UDK: 691.53:662.613.11(045)=861 doi:10.5937/rudrad1204161J

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MEHANIČKE KARAKTERISTIKE MALTERA KOJI SADRŽI LETEĆI PEPEO TRETIRAN RAZLIČITIM FIZIČKIM POSTUPCIMA[**]

Izvod

U ovom radu su prikazani rezultati laboratorijskih ispitivanja čiji je cilj bio da se utvrdi uticaj letećeg pepela koji je tretiran različitim fizičkim postupcima (mehanička aktivacija, mlevenje i prosejavanje) na mehaničke karakteristike maltera, odnosno njegovu čvrstoću na pritisak i savijanje. Leteći pepeo je u ovim ispitivanjima korišćen kao supstituent za cement u hidrauličnim vezivima. Supstitucija portland cementa letećim pepelom kretala se od 10 do 70% maseno. Najpovoljniji rezultati su dobijeni prilikom zamene portland cementa letećim pepelom koji je prethodno mehanički aktiviran u laboratorijskom vibro mlinu sa prstenovima.

Ključne reči: *pepeo, cement, malter, čvrstoća*

1. UVOD

Pucolanski materijali (pucolani) su silikatni ili alumosilikatni materijali koji sami po sebi poseduju vrlo malo ili nimalo cementacionih svojstava. Međutim, veoma važna karakteristika pucolanskih materijala je njihova sposobnost da reaguju sa krečom ili portland cementom u prisustvu vode. Naime, SiO_2 i Al_2O_3 koji ulaze u sastav pucolanskih materijala reaguju sa kalcijum hidroksidom, $Ca(OH)_2$, pri čemu nastaju hidratisana kalcijum silikatna kao i hidratisana kalcijum aluminatna jedinjenja. Ova jedinjenja nisu rastvorna u vodi.

Pucolanski materijali se dele na prirodne (vulkanski pepeo, plovućac, dijatomejska zemlja) i veštačke (leteći pepeo, mikrosilika, metakaolin i sl.). Svojstvima pucolanskih materijala, kao i njihovom uticaju na karakteristike različitih građevinskih materijala posvećena je velika pažnja u svetskoj literaturi [1-6].

Leteći pepeo predstavlja fino dispergovani produkt sagorevanja uglja iz ter-

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[**] *Ovaj rad je proistekao kao rezultat Projekta br. 34006 „Mehanohemijski tretman nedovoljno kvalitetnih mineralnih sirovina" i Projekta br. 37001 „Uticaj rudarskog otpada iz RTB-a Bor na zagađenje vodotokova sa predlogom mera i postupka za smanjenje štetnog dejistva na životnu sredinu" koga finansira Ministarstvo za prosvetu, nauku i tehnološki razvoj Republike Srbije.*

moelektrana, izdvojen iz dimnih gasova, čija se veličina zrna kreće od 0 do 1 mm. To je heterogeni materijal sastavljen iz čestica različitih fizičkih, hemijskih, mineraloških i morfoloških svojstava, što je uslovljeno kvlitetom uglja, kao i uslovima i tehnologijom sagorevanja. Prema literaturnim podacima, godišnja proizvodnja letećeg pepela u Srbiji iznosi više od 5 000 000 tona [7].

Zahvaljujući pucolanskim svojstvima letećeg pepela, ovaj materijal se može primeniti u proizvodnji hidrauličnih veziva i betona (posebno u proizvodnji portland-cementnog klinkera, kao aktivna komponenta koja delimično može zameniti cement, ili kao agregat u betonu).

Da bi leteći pepeo mogao delimično da zameni cement mora da zadovolji određene zahteve standarda u pogledu hemijskih i fizičko-mehaničkih osobina.

Leteći pepeli koji se proizvode na teritoriji Republike Srbije su takvog kvaliteta da se mogu uspešno primeniti kao građevinski materijali (ne samo u industriji cementa i betona već i za izgradnju puteva, solidifikaciju tla i slično). Uprkos tome, najveće količine letećeg pepela još uvek nisu našle svoju primenu i locirane su u okviru deponija pepela. Uzimajući u obzir ovu činjenicu, neophodno je preduzeti određene mere kako bi se razmotrila i obezbedila svaka mogućnost njegove upotrebe.

Pored toga što se primenom letećeg pepela u komercijalne svrhe smanjuje njegov negativan uticaj na životnu sredinu, posredno se doprinosi očuvanju prirodnih mineralnih sirovina, snižavaju se troškovi potrebni za njihovu eksploataciju i odlaganje, kao i troškovi vezani za deponovanje pepela. U skladu s tim, treba imati u vidu da se prilikom izgradnje deponije letećeg pepela moraju ispoštovati sve predviđene zakonske odredbe [8] što, takođe može imati uticaja na troškove deponovanja.

2. KARAKTERIZACIJA I PRIPREMA POLAZNIH UZORAKA

2.1. Karakterizacija polaznih uzoraka

Polazni uzorak letećeg pepela koji je korišćen u ovim ispitivanjima uzet je iz termoelektrane "Nikola Tesla" – Obrenovac. Prema svom hemijskom sastavu (koji je prikazan u tabeli 1) ovaj pepeo se odlikuje visokim sadržajem hemijski aktivnog SiO_2 i visokim sadržajem kiselih oksida (SiO_2 + Al_2O_3 + Fe_2O_3) kao i niskim sadržajem baznih oksida (CaO, MgO). Na osnovu toga, a prema standardu SRPS B.C1.018, ovaj pepeo se može svrstati u veštačke pucolane – silikatne leteće pepele. Granulometrijski i mineraloški sastav ovog uzorka prikazani su na slikama (1 i 2).

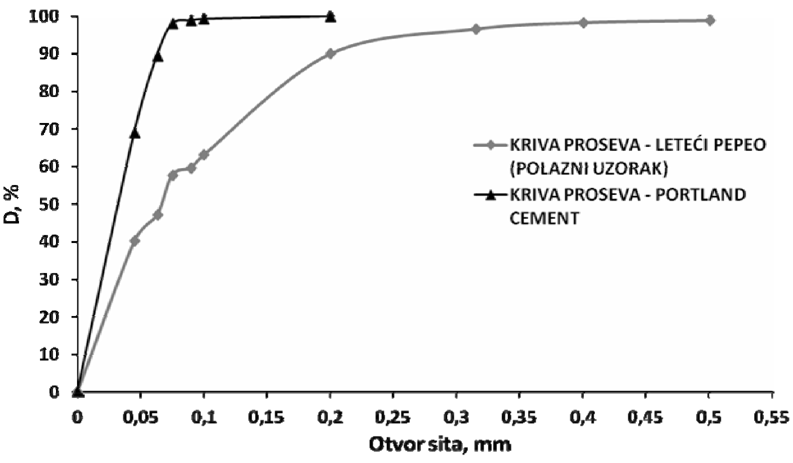
Uzorak portland cementa uzet je iz fabrike cementa "Titan Cementara Kosjerić" za potrebe ovih ispitivanja. Cement je visokog je kvaliteta, oznake PC 52,5 N (SRPS B.C1.011), a dobijen je mlevenjem portland cementnog klinkera uz dodatak kalcijum sulfata do 5%. U pogledu hemijskih, fizičkih i mehaničkih osobina ovaj cement je u potpunosti ispunjavao sve zahteve propisane standardom. U tabelama 1 i 2 prikazani su njegov hemijski sastav i fizičko-mehaničke karakteristike, a na slikama 1 i 3 njegov granulometrijski i mineraloški sastav.

Tabela 1. *Hemijski sastav uzoraka letećeg pepela i portland cementa*

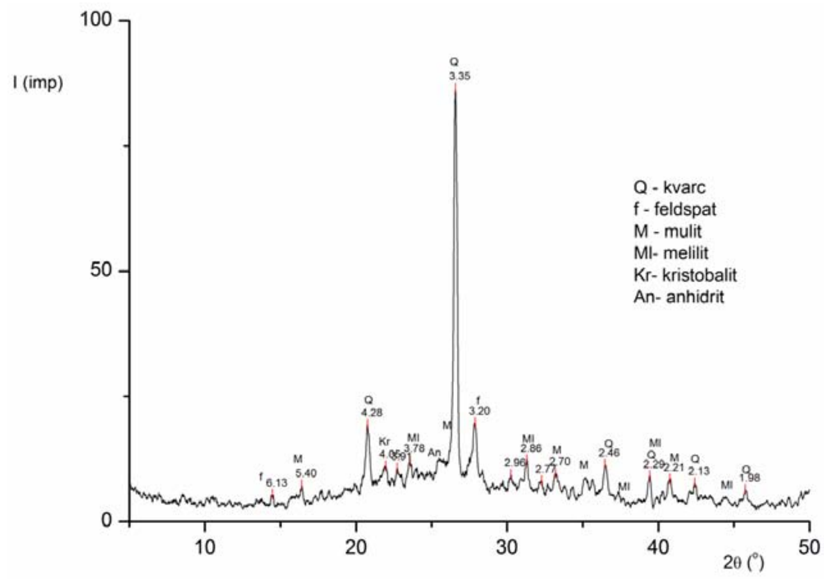
Komponenta	Sadržaj, %	
	Leteći pepeo	Portland cement
SiO_2	56,19	20.92
Al_2O_3	23,61	5.81
Fe_2O_3	5,37	3.55
CaO	6,42	63.07
MgO	2,11	1.86
SO_3	2,05	1,89
TiO_2	0,68	/
Na_2O	0,48	0,20
K_2O	0,87	0,74
MnO	/	0.09
Cl	/	0.003
CaO aktivni	0,29	/
SiO_2 aktivni	31,22	/
Gubitak žarenjem	2,04	0,96

__Tabela 2.__ Fizičko-mehaničke karakteristike portland cementa

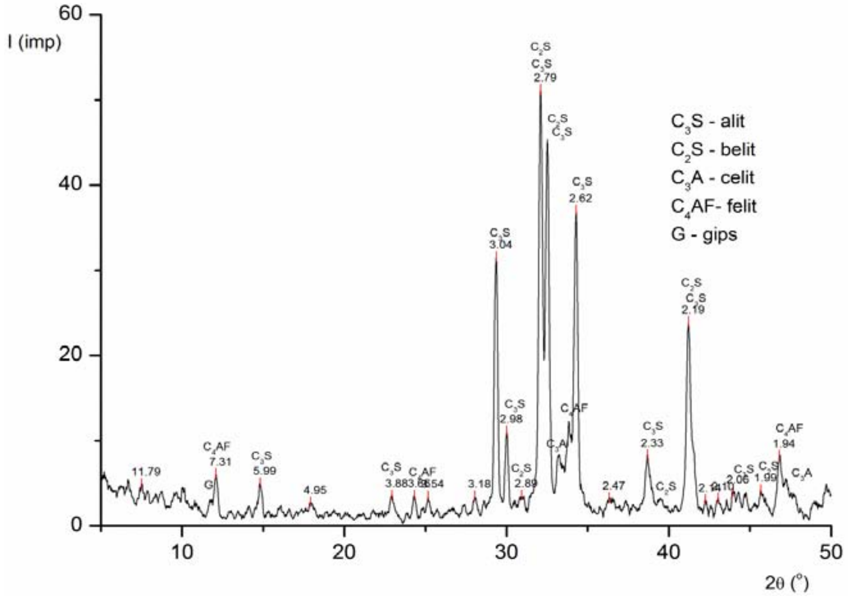
Čvrstoća na savijanje, MPa	2 dana		5,7
	7 dana		7,7
	28 dana		9,5
Čvrstoća na pritisak, MPa	2 dana		24,9
	7 dana		38,3
	28 dana		58,1
Vezivanje	Voda za standardnu konzis-tenciju, ml		25,8
	Početak, h : min		2:35
	Kraj, h : min		3:30
Stalnost zapremine	Kolačići	U vodi	Nema deformacija
		Na vazduhu	Nema deformacija
		Kuvano	Nema deformacija
	Prsten		Nema deformacija
Ostatak na situ otvora 90 µm, %			1,20
Gustina, g/cm^3			3,15
Specifična površina, cm^2/g			3850
Sadržaj vlage, %			0,43



Sl. 1. *Granulometrijski sastav letećeg pepela i portland cementa*



Sl. 2. *Mineraloški sastav letećeg pepela*



Sl. 3. *Mineraloški sastav portland cementa*

2.2. Priprema uzoraka letećeg pepela za potrebe ispitivanja

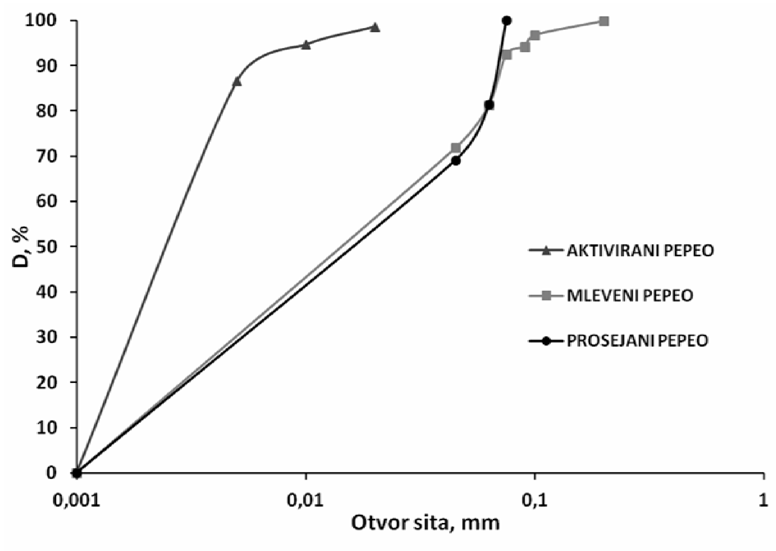
Za potrebe formiranja hidrauličnih veziva koja sadrže portland cement i leteći pepeo u različitim masenim odnosima, polazni uzorak letećeg pepela tretiran je različitim fizičkim postupcima. Na jednom delu uzorka izvršena je mehanička aktivacija u vibracionom mlinu sa prstenovima u trajanju od 35 minuta.

Drugi deo uzorka je mleven u laboratorijskom mlinu sa kuglama u trajanju od 22 minuta, kako bi se postigla odgovarajuća finoća pepela u skladu sa standardom ASTM C618 (minimum 66% klase -45 + 0 µm).

Analizom granulometrijskog sastava polaznog uzorka (slika 1) utvrđeno je da se prosejavanjem na situ otvora 75 µm postiže zadovoljavajuća finoća letećeg pepela (prema standardu), tako da je treći deo uzorka tretiran postupkom suvog sejanja na pomenutom situ. Granulometrijski sastavi svakog od uzoraka, dobijenih nakon odgovarajućeg tretmana prikazani su na slici 4, a njihova pucolanska aktivnost i specifična površina u tabeli 3.

Tabela 3. *Fizičke karakteristike letećeg pepela tretiranog različitim postupcima*

Vrsta pepela	Pucolanska aktivnost		Specifična površina po Blaine-u, cm^2/g
	Čvrstoća na savijanje, MPa	Čvrstoća na pritisak, MPa	
aktivirani	5,3	17,2	11770
mleveni	4,2	12,5	6940
prosejani	4,0	9,5	3810



Sl.4. *Granulometrijski sastav aktiviranog, mlevenog i prosejanog letećeg pepela*

3. EKSPERIMENTALNA ISPITIVANJA

Dalji eksperimentalni postupak odvijao se kroz tri serije opita. U prvoj seriji opita, portland cementu su dodavane različite količine aktiviranog letećeg pepela (10, 20, 30, 40, 50, 60 i 70%), a zatim su tako dobijene smeše homogenizirane radi ujednačavanja hemijskog sastava. U drugoj seriji opita portland cementu su dodavane analogne količine mlevenog letećeg pepela i nakon toga je takođe izvršena homogenizacija smeša. Isti postupak je ponovljen i u trećoj seriji opita, gde je kao supstituent za cement upotrebljen prosejani leteći pepeo. Od ovako dobijenih vezivnih materijala formiran je malter prema standardnom postupku. Na epruvetama od maltera je posle 2, 7, i 28 dana odležavanja u vodenoj sredini izvršeno ispitivanje čvrstoće na pritisak i savijanje (standardni postupak na presi marke "Toni Technik"). Ispitivanja su izvršena u fabrici cementa "Titan Cementara Kosjerić".

4. REZULTATI I DISKUSIJA

Rezultati eksperimentalnih ispitivanja su prikazani u tabelama 4 – 6 i na slikama 5 – 10.

Tabela 4. *Čvrstoće na pritisak i savijanje maltera koji sadrži aktivirani leteći pepeo*

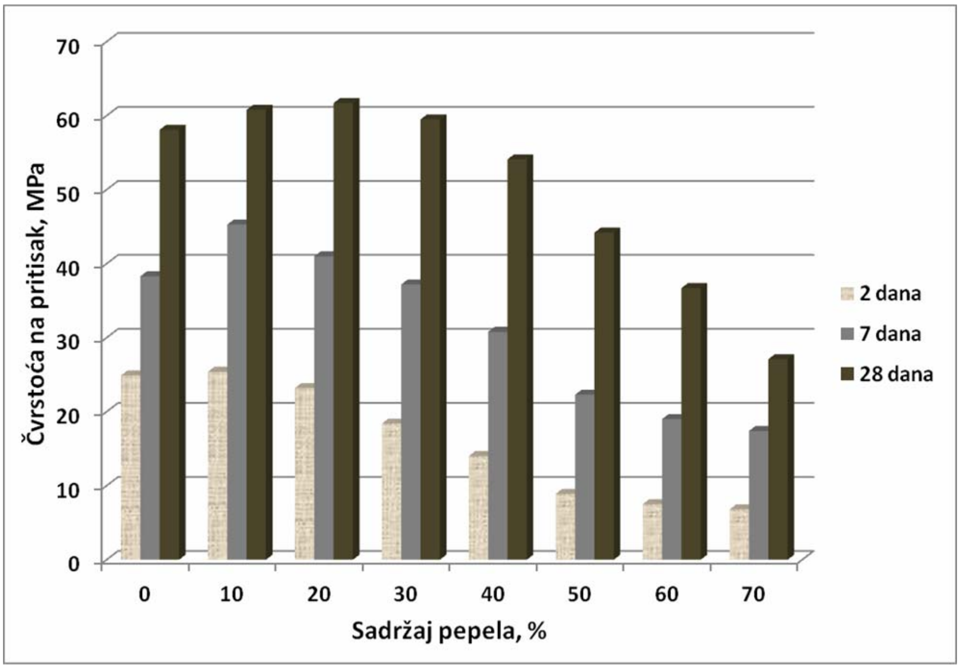
Količina pepela u uzorku, %	**Čvrstoća na savijanje, MPa**			**Čvrstoća na pritisak, MPa**		
	2 dana	**7 dana**	**28 dana**	**2 dana**	**7 dana**	**28 dana**
0	5,7	7,7	9,5	24,9	38,3	58,1
10	6,1	8,1	9,8	25,4	45,3	60,8
20	5,4	7,2	9,0	23,2	41	61,7
30	4,1	6,9	9,0	18,4	37,2	59,5
40	3,2	6,2	8,5	14,0	30,8	54,1
50	2,5	4,9	7,7	8,9	22,3	44,2
60	2,5	4,1	6,4	7,5	19	36,7
70	1,9	3,2	5,4	6,8	17,4	27,1

Tabela 5. *Čvrstoće na pritisak i savijanje maltera koji sadrže mleveni leteći pepeo*

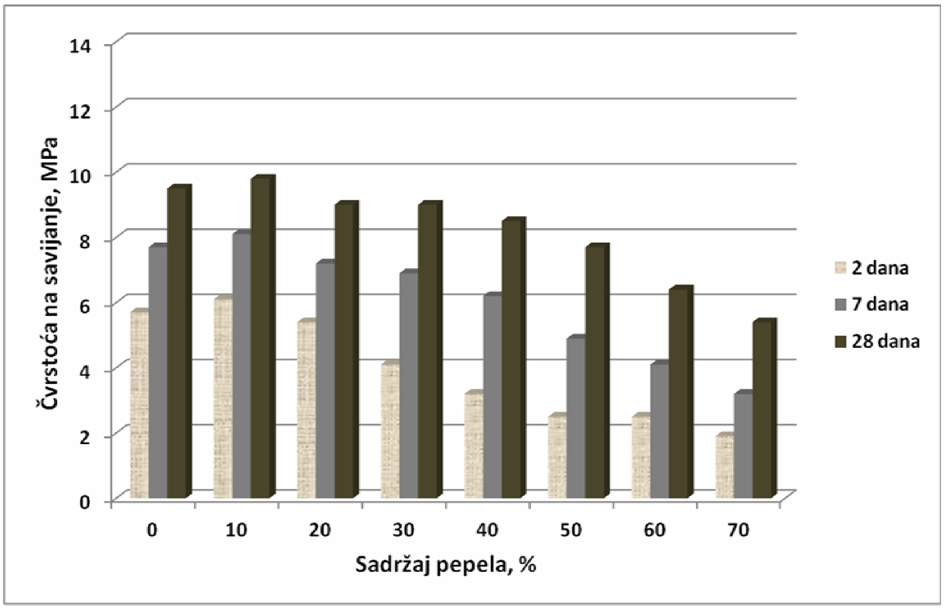
Količina pepela u uzorku, %	**Čvrstoća na savijanje, MPa**			**Čvrstoća na pritisak, MPa**		
	2 dana	**7 dana**	**28 dana**	**2 dana**	**7 dana**	**28 dana**
0	5,7	7,7	9,5	24,9	38,3	58,1
10	4,4	7,8	9,1	19,6	41,8	59,6
20	3,9	6,5	8,5	18,1	36,9	53,1
30	3,5	6	7,8	15,8	31,1	49,4
40	2,7	4,7	7,3	11,9	24,9	47,3
50	2,5	3,9	6,2	10,6	19,5	36,3
60	1,8	3	4,9	8,2	13,2	26,7
70	1,3	2,2	3,9	5,1	12,3	21,5

Tabela 6. *Čvrstoće na pritisak i savijanje maltera koji sadrže prosejani leteći pepeo*

Količina pepela u uzorku, %	**Čvrstoća na savijanje, MPa**			**Čvrstoća na pritisak, MPa**		
	2 dana	**7 dana**	**28 dana**	**2 dana**	**7 dana**	**28 dana**
0	5,7	7,7	9,5	24,9	38,3	58,1
10	4,3	6,8	8,8	19,3	37,9	56,6
20	3,8	6,6	8,5	16,9	35,2	53,2
30	3,3	5,6	7,6	15,6	29,1	45,8
40	2,9	5	7,1	13,7	24,8	39,1
50	2,4	3,8	5,9	9,8	18,1	33,3
60	1,5	3,1	5,2	7,3	11,4	24,2
70	1,2	1,8	3,3	4,9	9	19,4



Sl. 5. *Čvrstoća na pritisak maltera koji sadrže aktivirani leteći pepeo*



Sl. 6. *Čvrstoća na savijanje maltera koji sadrže aktivirani leteći pepeo*

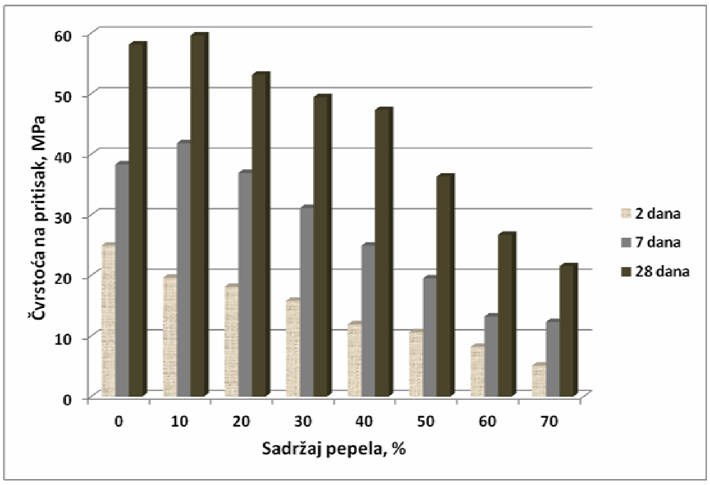
Iz tabele 4 i sa slika 5 i 6 se može uočiti da supstitucija cementa aktiviranim letećim pepelom do određene količine može uticati na povećanje čvrstoće maltera. Tako malteri koji sadrže hidraulična veziva sa 10, 20 i 30% aktiviranog letećeg pepela postižu čak veću čvrstoću na pritisak nakon 28 dana nego malter koji kao vezivo sadrži samo portland cement. Pri tome, u zavisnosti od sadržaja pepela, čvrstoće maltera na pritisak posle 2 dana (početna čvrstoća) i čvrstoće na pritisak posle 28 dana (tzv. marka cementa), ove smeše se mogu svrstati u određeni tip cementa (SRPS B.C1.011) i to:

- smeše sa 10 i 20% aktiviranog pepela pripadaju tipu portland cemenata sa dodatkom silikatnog letećeg pepela u količini do 20%, daju normalnu početnu čvrstoću, a nakon 28 dana postižu čvrstoću na pritisak veću od 50 MPa. Ovi cementi prema standardu nose oznaku PC 20V 52,5N
- smeša koja sadrži 30% mlevenog pepela pripada tipu portland cementa sa dodatkom slilikatnog letećeg pepela u količini 20 – 35%, daje normalnu početnu čvrstoću, a nakon 28 dana takođe postiže čvrstoću na pritisak veću od 50 MPa. Ovaj cement nosi oznaku PC 35V 52,5N.

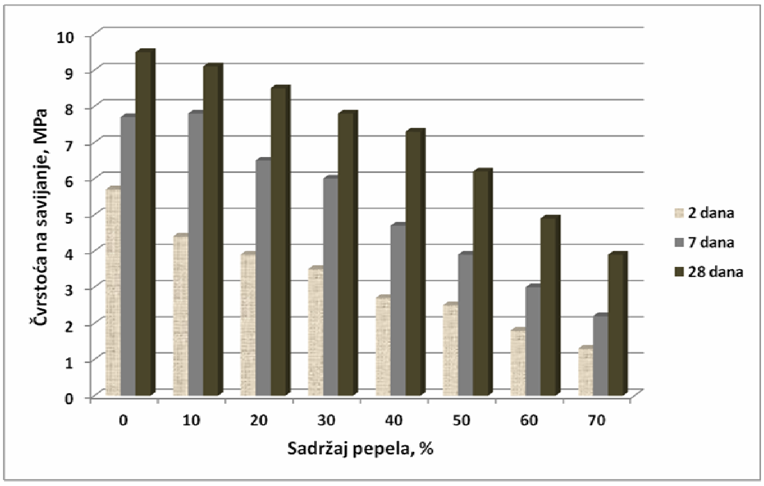
Neke od smeša koje sadrže veći procenat aktiviranog letećeg pepela (preko 35%) mogu se svrstati u pucolanske cemente:

- smeše koje sadrže 40 i 50% aktiviranog letećeg pepela pripadaju tipu pucolanskih cemenata sa dodatkom aditiva u količini 11 – 55%, nakon 28 dana dostižu čvrstoću na pritisak veću od 40 MPa i nose oznaku P55 42,5N. Treba istaći da bi se smeša koja sadrži 40% aktiviranog pepela, prema čvrstoći na pritisak koju dostiže nakon 28 dana, mogla svrstati u višu klasu cemenata, među tim, to nije moguće zbog relativno niske početne čvrstoće od 14,0 MPa.

- smeše koje sadrže više od 55% aktiviranog letećeg pepela ne mogu se svrstati u cemente bilo kog tipa prema pomenutom standardu.
- Na osnovu podataka iz tabele 5 i sa slika 7 i 8 može se konstatovati da sa povećanjem sadržaja mlevenog letećeg pepela u smešama, čvrstoća na savijanje i pritisak maltera generalno opada. Ipak, treba naglasiti da malter koji sadrži smešu sa 10% pepela postiže veću čvrstoću na pritisak nakon 7 i 28 dana od maltera sa čistim portland cementom. Analogno prvoj seriji opita, pojedine smeše pripadaju određenim tipovima cementa (SRPS B.C1.011):

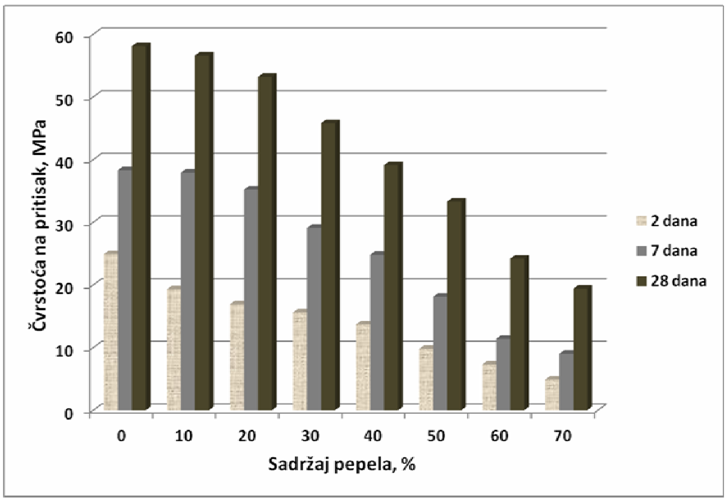


Sl. 7. *Čvrstoća na pritisak maltera koji sadrže mleveni leteći pepeo*

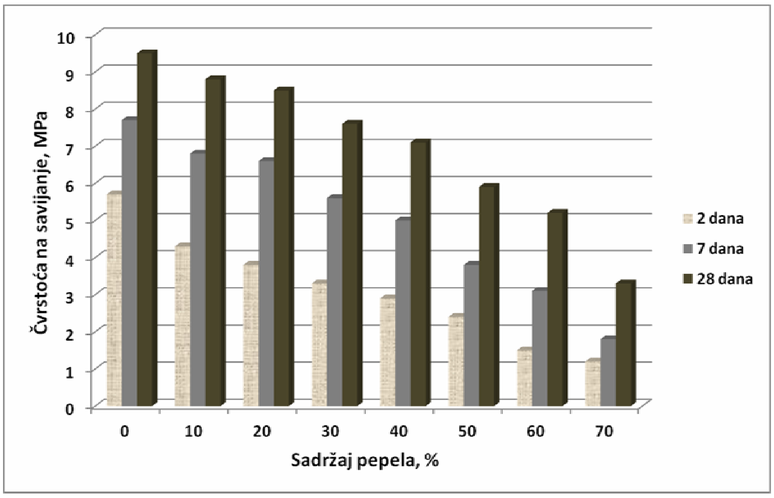


Sl. 8. *Čvrstoća na savijanje maltera koji sadrže mleveni leteći pepeo*

- smeše sa 10 i 20% mlevenog pepela pripadaju tipu portland cemenata sa dodatkom slilikatnog letećeg pepela u količini do 20% i prema standardu nose oznaku PC 20V 52,5N
- smeša koja sadrži 30% mlevenog pepela pripada tipu portland cementa sa dodatkom slilikatnog letećeg pepela u količini 20 – 35%. Ovaj cement nosi oznaku PC 35V 42,5N
- smeše koje sadrže 40 i 50% mlevenog letećeg pepela pripadaju tipu pucolanskih cemenata sa dodatkom aditiva u količini 11 – 55%, sa oznakama P55 42,5N i P55 32,5N, redom.



Sl. 9. *Čvrstoća na pritisak maltera koji sadrže prosejani leteći pepeo*



Sl. 10. *Čvrstoća na savijanje maltera koji sadrže prosejani leteći pepeo*

Kao što se može videti iz tabele 6 i sa slika 9 i 10, u trećoj seriji opita, sa povećanjem količine prosejanog letećeg pepela u smešama, ravnomerno opadaju njihova čvrstoća na savijanje i pritisak. Pored toga, analogno prvoj i drugoj seriji opita, cementi sa 10, 20 i 30% pepela mogu se svrstati u portland cemente sa dodatkom silikatnog letećeg pepela u količini do 20%, odnosno do 35% i prema čvrstoći na pritisak koju daju nakon 2 i 28 dana od spravljanja epruveta, nose oznake PC 20V 52,5N, PC 20V 42,5 N i PC 35V 42,5N. Smeše koje sadrže 40 i 50% prosejanog pepela pripadaju pucolanskim cementima iste oznake, tj. P55 32,5N.

5. ZAKLJUČAK

Mehaničke karakteristike maltera koji kao hidraulična veziva sadrže smeše portland cementa i letećeg pepela u velikoj meri zavise od količine pepela u smeši, kako je i očekivano. Međutim, supstitucija cementa aktiviranim letećim pepelom (prva serija opita) dala je znatno bolje rezultate u pogledu fizičko-mehaničkih karakteristika maltera, nego što je to postignuto u druge dve serije opita, kada je kao supstituent korišćen mleveni, odnosno prosejani leteći pepeo. Očigledno je da se mehaničkom aktivacijom može u znatnoj meri uticati na pucolanska svojstva letećeg pepela, a samim tim i na karakteristike mešavina portland cement – leteći pepeo. Kada se uporede prva i druga serija opita, zaključak je da nema velike razlike u tome da li je leteći pepeo samleven ili prosejan do adekvatne klase krupnoće (u ovom slučaju -75 +0 μm). Ipak, nešto bolji rezultati su postignuti prilikom upotrebe mlevenog letećeg pepela, posebno kod smeša koje sadrže 20 i 40% pepela. Tako, smeše iz druge serije opita koje sadrže 20 i 40% mlevenog letećeg pepela pripadaju višoj klasi cemenata u odnosu na pandane iz treće serije opita.

Prema srpskim standardima, maksimalna količina pucolana koja se može dodati cementu iznosi 55%, tako da se smeše sa 60 i 70% letećeg pepela ne mogu svrstati ni u jedan tip cemenata, bilo da se radi o aktiviranom, mlevenom ili pro-sejanom letećem pepelu. Ipak, ovakvi materijali svakako mogu naći primenu (u putogradnji, solidifikaciji zemljišta, itd.) jer je čvrstoća na pritisak koju oni daju nakon 28 dana odležavanja epruveta u vodi relativno visoka, posebno ako se uzme u obzir količina pepela koja zamenjuje cement u ovim hidrauličnim vezivima.

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MINING AND METALLURGY INSTITUTE BOR YU ISSN: 1451-0162
COMMITTEE OF UNDERGROUND EXPLOITATION OF THE MINERAL DEPOSITS UDK: 622

UDK: 691.53:662.613.11(045)=861 doi:10.5937/rudrad1204161J

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MECHANICAL CHARACTERISTICS OF MORTAR CONTAINING FLY ASH TREATED BY DIFFERENT PHYSICAL METHODS**

Abstract

This paper presents the results of laboratory tests with the aim to determine the effect of fly ash treated with various physical methods (mechanical activation, grinding and sieving) to the mechanical characteristics of mortar and its compressive and bending strength. Fly ash is used in this testing as a substituent for cement in hydraulic binders. Substitution of Portland cement with fly ash ranged from 10 to 70 % mass. The most favorable results were obtained in replacement the Portland cement with fly ash that was previously mechanically activated in a laboratory vibrating ring mill.
Keywords: *ash, cement, mortar, strength*

1. INTRODUCTION

Pozzolanic materials (pozzolana) are silicate or aluminosilicate materials which by themselves possess very little or no cementation properties. However, a very important characteristic of pozzolanic materials is their ability to react with lime or Portland cement in the presence of water. Namely, SiO_2 and Al_2O_3 that form a part of pozzolanic materials react with calcium hydroxide, $Ca(OH)_2$, to form the hydrated calcium silicate as well as hydrated calcium aluminate compounds. These compounds are not soluble in water.

Pozzolanic materials are divided into natural (volcanic ash, pumice, diatomaceous earth) and artificial (fly ash, microsilica, metakaolin, etc.). A great attention is paid in the world literature to the properties of pozzolanic materials and their impact on characteristics of different building materials [1-6].

Fly ash is a finely dispersed product of coal combustion from thermal power plants, separated from flue gases, whose grain size ranges from 0 to 1 mm. It is a heterogeneous material composed of particles of different

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** *This work is the result of the Project No. 34006: "Mechanochemical Treatment of Insufficient Quality Mineral Resources" and Project No. 37001 "The Effect of Mine Waste from RTB Bor on Pollution of Watercourses with a Proposal of Measures and Procedures to Reduce the Adverse Effects on Environment" funded by the Ministry of Education, Science and Technological Development of the Republic of Serbia.*

physical, chemical, mineralogical and morphological properties, which depends coal quality and combustion conditions and technology. According to the literature, the annual production of fly ash in Serbia amounts to more than 5 000 000 tons [7].

Thanks to the pozzolanic properties of fly ash, the material can be applied in the production of hydraulic binders and concrete (especially in the production of Portland cement clinker, as an active component that can partially replace the cement, or as an aggregate in concrete).

In order to replace partially cement, the fly ash has to meet the certain requirements of the standard in terms of chemical and physico-mechanical properties.

Fly ash that are produced in the territory of the Republic of Serbia are of such quality that they can be successfully applied as building materials (not only in the cement and concrete industry, but also for the construction of roads, soil solidification, etc.). Despite this, the largest amounts of fly ash are still not found their application and they are located within the ash dump. Taking into account this fact, it is necessary to take the certain measures in order to discuss and provide any possibility of its use.

In addition to using the fly ash for commercial purposes reduces its negative impact on the environment; this directly contributes to the conservation of natural mineral resources, reducing the costs to their exploitation and disposal, as well as the costs related to the disposal of ash. Accordingly, it should be noted that during construction of the fly ash dump, the all required statutory provisions have to be complied [8], what may also have an impact on the costs of disposal.

2. CHARACTERIZATION AND PREPARATION OF STARTING SAMPLES

2.1. Characterization of starting samples

The starting sample of fly ash, used in this testing, was taken from the thermal power plant "Nikola Tesla" - Obrenovac. According to its chemical composition (as shown in Table 1), this ash has high content of chemically active SiO_2 and high content of acidic oxides (SiO_2 + Al_2O_3 + Fe_2O_3) and low content of base oxides (CaO, MgO). Based on this, and according to the Standard SRPS B.C1.018, this ash can be placed in the artificial pozzolana - siliceous fly ash. Grain size distribution and mineralogical composition of this sample are shown in Figures 1 and 2.

A sample of Portland cement was taken from a cement factory "Titan Cement Plant Kosjerić" for the purposes of these tests. Cement is a high quality, mark PC 52.5 N (SRPS B.C1.011), and it was obtained by grinding the Portland cement clinker with addition of calcium sulfate up to 5%. In terms of chemical, physical and mechanical properties, this cement has fully complied the requirements prescribed by the Standard. Tables 1 and 2 show its chemical composition, physic-mechanical properties, and Figures 1 and 3 show its grain size distribution and mineralogical composition.

Table 1. *Chemical composition of fly ash and Portland cement samples*

Component	**Content, %**	
	Fly ash	**Portland cement**
SiO_2	56.19	20.92
Al_2O_3	23.61	5.81
Fe_2O_3	5.37	3.55
CaO	6.42	63.07
MgO	2.11	1.86
SO_3	2.05	1.89
TiO_2	0.68	/
Na_2O	0.48	0.20
K_2O	0.87	0.74
MnO	/	0.09
Cl	/	0.003
CaO active	0.29	/
SiO_2 active	31.22	/
Loss of ignition	2.04	0.96

Table 2. *Physico-mechanical characteristics of the Portland cement sample*

Flexural strength, MPa	2 days		4.9
	7 days		7.6
	28 days		8.7
Compressive strength, MPa	2 days		20.7
	7 days		44.5
	28 days		61.4
Binding	Water requirement for standard consistency, ml		25.8
	Initial, h : min		2:35
	Final, h : min		3:30
Volume constancy	Cement specimens	In water	Without deformations
		In the air	Without deformations
		Boiled	Without deformations
	Ring		Without deformations
Residue on sieve opening size 90 μm, %			1.20
Density, g/cm^3			3.15
Specific surface area, cm^2/g			3850
Wet, %			0.43

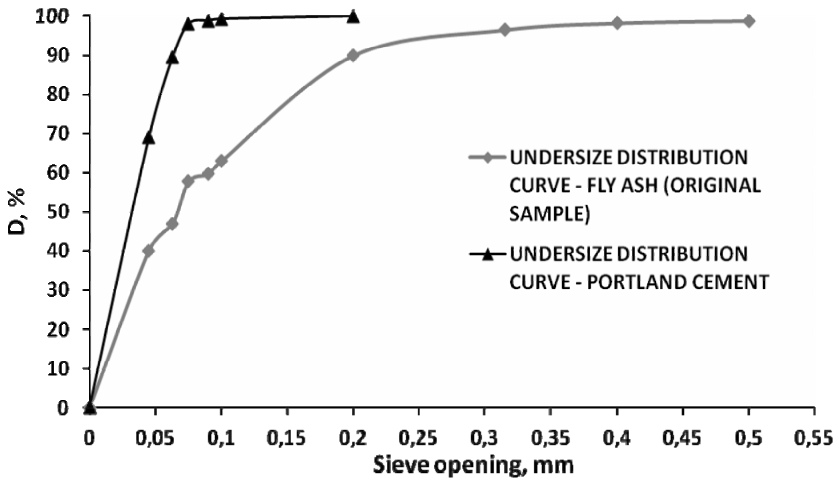

Fig. 1. *Grain size distribution of fly ash and Portland cement*

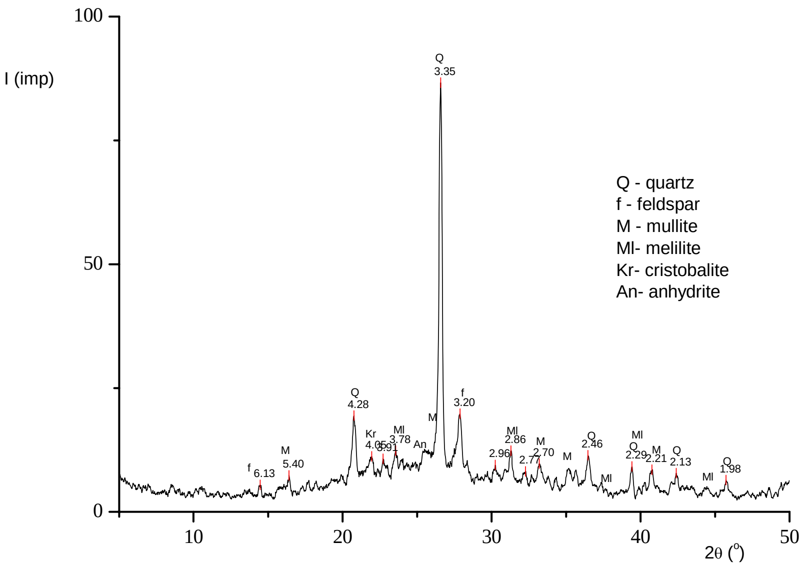

Fig. 2. *Mineralogical composition of fly ash*

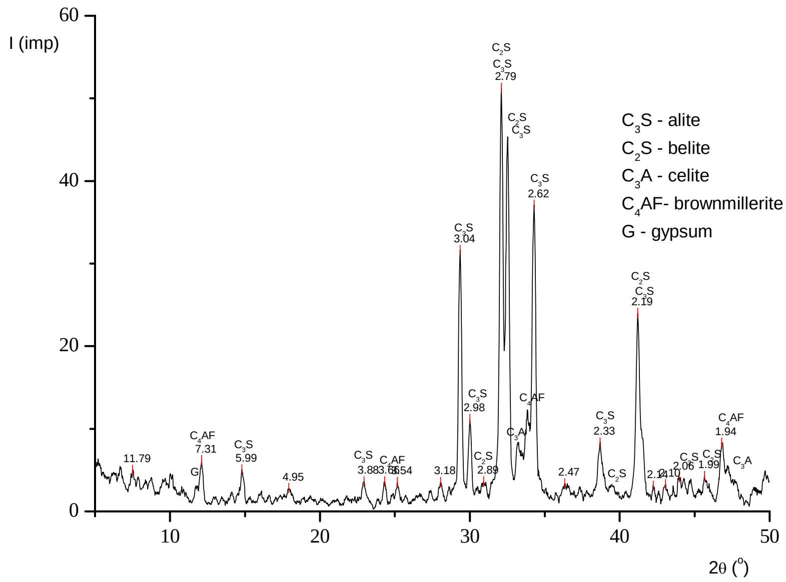

Fig. 3. *Mineralogical composition of Portland cement*

2.2. Preparation the samples of fly ash for the needs of testing

For the needs of formation the hydraulic binders containing the Portland cement and fly ash in different mass ratios, the starting sample of fly ash was treated by different physical methods. A mechanical activation in a vibrating ring mill for the period of 35 minutes was performed on one part of sample.

The second part of sample was ground in a laboratory ball mill for the period of 22 minutes, in order to achieve the appropriate fineness of ash in accordance with the Standard ASTM C618 (minimum 66%, class -45 + 0 µm).

The analysis of grain size distribution of the starting sample (Figure 1) has showed that screening on a sieve of 75 µm resulted into satisfactory fineness of fly ash (according to the Standard), so that the third part of sample was treated by the method of dry screening on the given sieve. Grain size distributions of each sample, obtained after appropriate treatment, are shown in Figure 4, and their pozzolanic activity and specific surface area in Table 3.

Table 3. *Physical characteristics of fly ash treated by different methods*

Type of fly ash	Pozzolanic activity		Specific area per Blaine, cm^2/g
	Flexular strength, MPa	Compressive strength, MPa	
activated	5.3	17.2	11770
ground	4.2	12.5	6940
sieved	4.0	9.5	3810

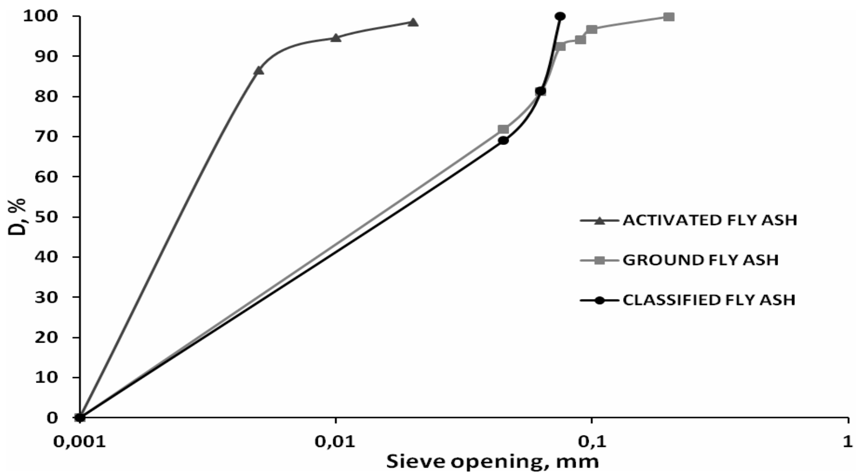

Fig. 4. *Grain size distribution of activated, ground and sieved fly ash*

3. EXPERIMENTAL TESTING

Further experimental procedure was carried out through three series of experiments. In the first series of experiments, varying amounts of activated fly ash (10, 20, 30, 40, 50, 60 and 70%) were added to the Portland cement, and then the resulting mixtures were homogenized for equalization the chemical composition. In the second series of experiments, the analogue ground amounts of fly ash were added to the Portland cement and then a homogenization of mixtures was also made. The same procedure was repeated in the third series of experiments, where the sieved fly ash was used as a substituent for cement. From such obtained binding materials, a mortar was formed according to the Standard method. On specimens of mortar, after 2, 7, and 28 days of aging in aqueous media, the compressive strength and bending strength (standard method on the press "Toni Technik") were tested. The tests were performed in the cement plant "Titan Cement Plant Kosjerić".

4. RESULST AND DISCUSSION

The results of experimental testing are present in Tables 4 – 6 and Figures 5 – 10.

Table 4. *Flexural and compressive strengths of mortar containing the activated fly ash*

Amount of ash in sample, %	Flexural strength, MPa			Compressive strength, MPa		
	2 days	7 days	28 days	2 days	7 days	28 days
0	5.7	7.7	9.5	24.9	38.3	58.1
10	6.1	8.1	9.8	25.4	45.3	60.8
20	5.4	7.2	9.0	23.2	41	61.7
30	4.1	6.9	9.0	18.4	37.2	59.5
40	3.2	6.2	8.5	14.0	30.8	54.1
50	2.5	4.9	7.7	8.9	22.3	44.2
60	2.5	4.1	6.4	7.5	19	36.7
70	1.9	3.2	5.4	6.8	17.4	27.1

Table 5. *Flexural and compressive strengths of mortar containing the ground fly ash*

Amount of ash in sample, %	Flexural strength, MPa			Compressive strength, MPa		
	2 days	7 days	28 days	2 days	7 days	28 days
0	5.7	7.7	9.5	24.9	38.3	58.1
10	4.4	7.8	9.1	19.6	41.8	59.6
20	3.9	6.5	8.5	18.1	36.9	53.1
30	3.5	6	7.8	15.8	31.1	49.4
40	2.7	4.7	7.3	11.9	24.9	47.3
50	2.5	3.9	6.2	10.6	19.5	36.3
60	1.8	3	4.9	8.2	13.2	26.7
70	1.3	2.2	3.9	5.1	12.3	21.5

Table 6. *Flexural and compressive strengths of mortar containing the sieved fly ash*

Amount of ash in sample, %	**Flexural strength, MPa**			**Compressive strength, MPa**		
	2 days	**7 days**	**2 days**	**7 days**	**2 days**	**7 days**
0	5.7	7.7	9.5	24.9	38.3	58.1
10	4.3	6.8	8.8	19.3	37.9	56.6
20	3.8	6.6	8.5	16.9	35.2	53.2
30	3.3	5.6	7.6	15.6	29.1	45.8
40	2.9	5	7.1	13.7	24.8	39.1
50	2.4	3.8	5.9	9.8	18.1	33.3
60	1.5	3.1	5.2	7.3	11.4	24.2
70	1.2	1.8	3.3	4.9	9	19.4

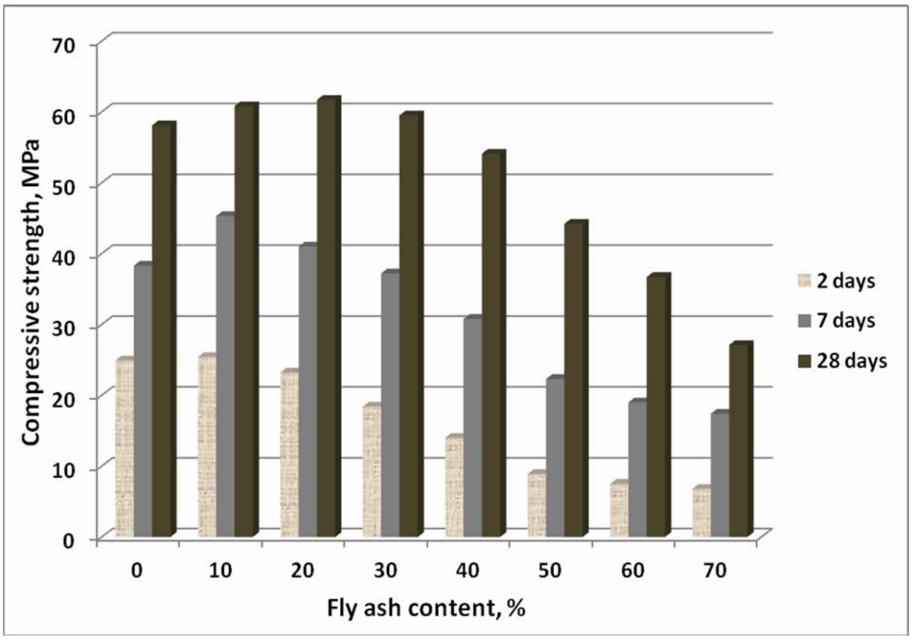

Fig. 5. *Compressive strength of mortar containing the activated fly ash*

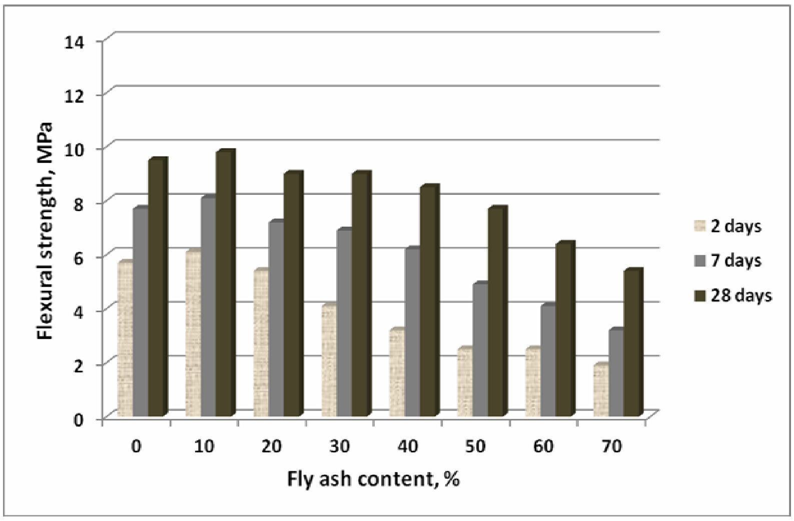

Fig. 6. *Flexural strength of mortar containing the activated fly ash*

It can be seen from Table 4 and Figures 5 and 6 that the substitution of cement with activated fly ash to the certain amounts can cause an increase in strength of mortar. So mortars containing hydraulic binders with 10, 20 and 30% activated fly ash achieve even higher compressive strength after 28 days than mortar as a binder containing only the Portland cement. In addition, depending on the ash content, the strength of mortar on pressure after 2 days (the initial strength) and compressive strength after 28 days (so called the brand of cement), these mixtures can be classified into a specific type of cement (SRPS B.C1.011) as follows:

- mixtures with 10 and 20% of activated ash, belonging to the type of Portland cement with addition of silica fly ash to the amount up to 20%, give normal early strength, and after 28 days achieve a compressive strengths higher than 50 MPa. These cements are marked according to the Standard PC 20V 52.5 N,
- mixture that contains 30% of the ground ash belong to the type of Portland cement with addition of silica fly ash to the amount 20 - 35%, giving a normal early strength, and after 28 days also achieves a compressive strength higher than 50 MPa. This cement is marked PC 35V 52.5 N.

Some of the mixtures containing higher percentage of activated fly ash (over 35%) can be classified in the pozzolanic cements:

- mixtures containing 40 and 50% of activated fly ash belong to the type of pozzolanic with additives in the amount of 11-55%; after 28 days they reach the compressive strength higher than 40 MPa and they are marked with P55 42.5 N. It should be noted that a mixture, containing 40% activated ash, regarding to the compressive strength that is reached after 28 days, could be classified into higher class of cements, however, this is not possible due to the relatively low initial strength of 14.0 MPa,
- mixtures, containing more than 55% of activated fly ash, cannot be classified into any type of cement according to this Standard,

- based on data from Table 5 and Figures 7 and 8, it can be concluded that with the increase of ground fly ash content in mixtures, the bending and compressive strength of mortar generally decreases. However, it should be noted that the mortar, containing a mixture with 10% fly ash, achieves higher compressive strength after 7 and 28 days than the mortar with pure Portland cement. Analogous to the first series of experiments, some of the mixtures belong to the certain types of cement (SRPS B.C1.011):

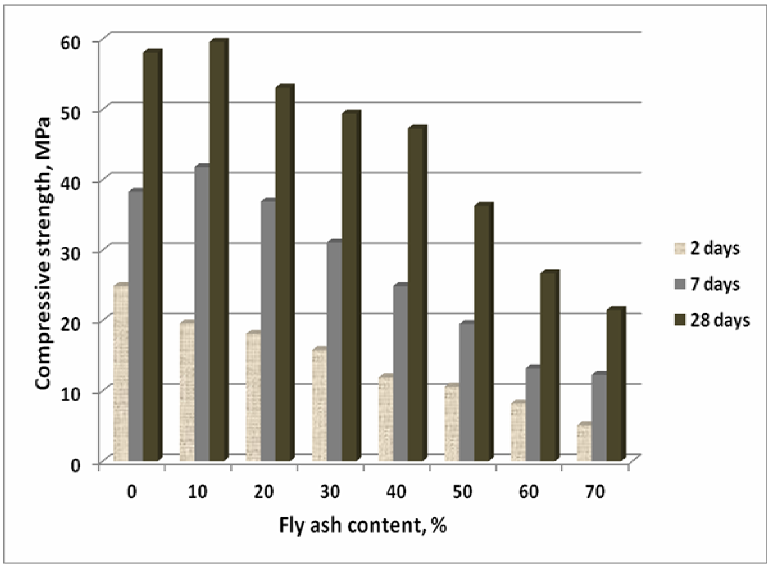

Fig. 7. *Compressive strength of mortar containing the ground fly ash*

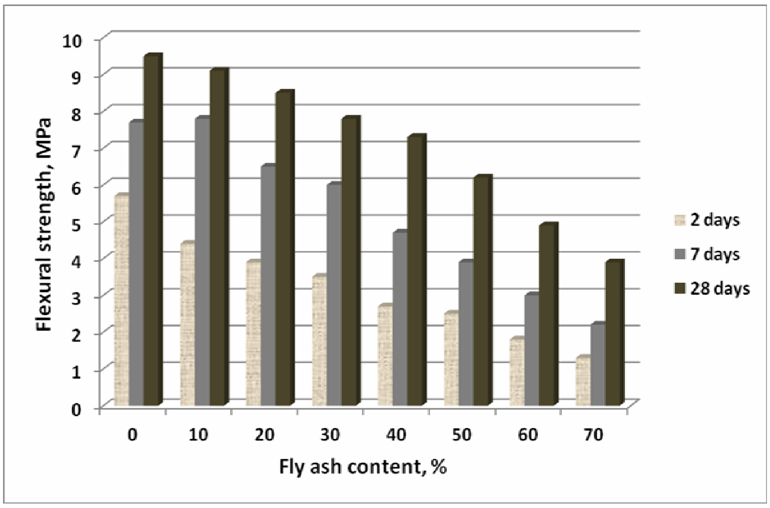

Fig. 8. *Flexural strength of mortar containing the ground fly ash*

- mixtures with 10 and 20% of ground ash belong to the type of Portland cement with silicate fly ash addition in the amount up to 20%, and according to the Standard they are marked with PC 20V 52.5 N,
- mixture, containing 30% of ground ash, belong to the type of Portland cement with addition of silicate fly ash in the amount of 20 - 35%. This cement is marked with PC 35V 42.5 N,
- mixtures, containing 40 and 50% of ground fly ash, belong to the type of pozzolanic cements with additive in the amount of 11-55%, with marks P55 and P55 42.5 N 32.5 N, respectively.

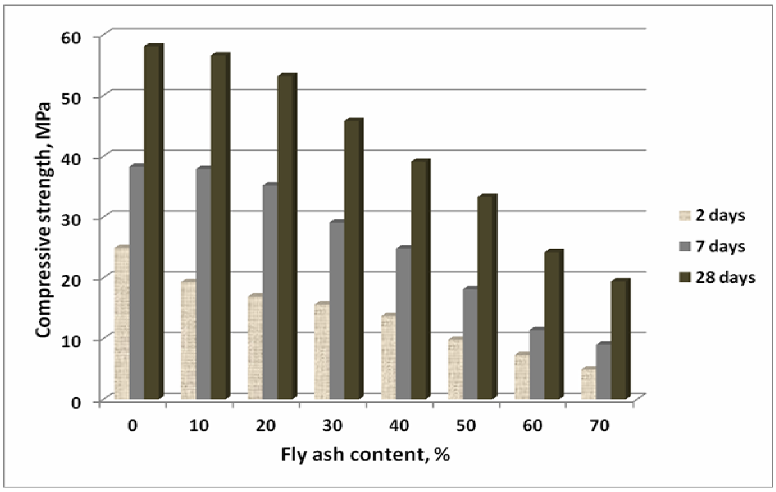

Fig. 9. *Compressive strength of mortar containing the sieved fly ash*

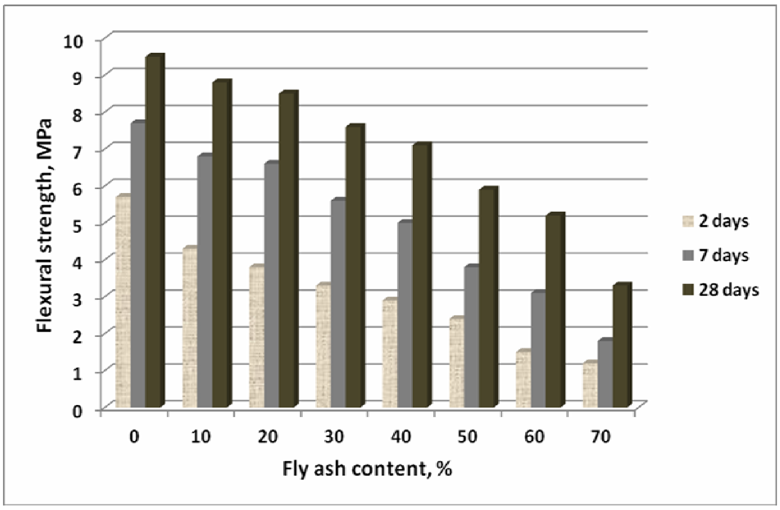

Fig. 10. *Flexural strength of mortar containing the sieved fly ash*

As it can be seen from Table 6 and Figure 9 and 10, in the third series of experiments, with increasing amount of sieved fly ash in mixtures, their banding and compressive strengths decrease uniformly. Furthermore, analogue to the first and second series of experiments, the cements with 10, 20 and 30% of fly ash can be classified into the Portland cements with silica fly ash addition in the amount up to 20%, i.e. up to 35% and according to their the compressive strength after 2 and 28 days of preparing the specimens, marked as PC 20V 52.5N, PC 20V 42.5 N and PC 35V 42.5N. Mixtures, containing 40 and 50% of sieved ash, belong to the pozzolanic cements of the same mark, P55 32.5 N.

5. CONCLUSION

Mechanical characteristics of mortar as a hydraulic binder containing the mixtures of Portland cement and fly ash are highly dependent on the amount of ash in the mixture, as it is expected. However, substitution of cement with activated fly ash (first series of experiments) gave significantly better results in terms of physico-mechanical characteristics of mortar than it is achieved in the other two series of experiments, when the ground and sieved fly ash was used as a substitute. It is obvious that the mechanical activation can significantly affect the pozzolanic properties of fly ash, and therefore the characteristics of mixtures of Portland cement - fly ash. When comparing the first and second series of experiments, the conclusion is that there is no a great difference in whether the fly ash is ground or sieved to the appropriate size class (in this case -75 +0 μm). However, slightly better results were achieved in using the ground fly ash, especially in mixtures containing 20 and 40% of ash. Thus, the mixtures from the second series of experiments, containing 20 and 40% of fly ash ground, belong to higher class of cements compared to the counterparts from the third series of experiments.

According to the Serbian Standards, maximum amount of pozzolan that can be added to cement is 55%, so that the mixtures of 60 and 70% fly ash cannot be classified into any type of cements, whether it is activated, ground or sieved fly ash. Nevertheless, such materials can certainly find application (in the road construction, soil solidification, etc.). because their compressive strength after 28 days of aging the specimens in water is relatively high, especially if it is taken into account the amount of ash that replaces cement in these hydraulic binders.

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