

GRAĐEVINSKI MATERIJALI I KONSTRUKCIJE

BUILDING MATERIALS AND STRUCTURES

ČASOPIS ZA ISTRAŽIVANJA U OBLASTI MATERIJALA I KONSTRUKCIJA
JOURNAL FOR RESEARCH IN THE FIELD OF MATERIALS AND STRUCTURES

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Society for Materials and Structures Testing of Serbia, 11000 Belgrade, Kneza Milosa 9
Telephone: 381 11/3242-589; e-mail: dimk@ptt.rs, veb sajt: www.dimk.rs

REVIEWERS: All papers were reviewed

KORICE: Izgradnja podzemne etaže pijace Zeleni Venac u Beogradu (foto: prof. dr M. Maksimović)

COVER: "Zeleni Venac" Market in Belgrade - Construction of subsurface level dig (photo: prof. dr M. Maksimović)

Financial supports: Ministry of Scientific and Technological Development of the Republic of Serbia

DRUŠTVO ZA ISPITIVANJE I ISTRAŽIVANJE MATERIJALA I KONSTRUKCIJA SRBIJE
SOCIETY FOR MATERIALS AND STRUCTURES TESTING OF SERBIA

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CIP - Katalogizacija u publikaciji
Narodna biblioteka Srbije, Beograd

620.1

GRAĐEVINSKI materijali i konstrukcije :
časopis za istraživanja u oblasti materijala
i konstrukcija = Building Materials and
Structures : journal for research of
materials and structures / editor-in-chief
Radimir Polić. - God. 54, br. 1 (2011)-
- Beograd (Kneza Miloša 9) : Društvo za
ispitivanje i istraživanje materijala i
konstrukcija Srbije, 2011- (Novi Beograd :
Hektor print). - 30 cm

Tromesečno. - Je nastavak: Materijali i
konstrukcije = ISSN 0543-0798
ISSN 2217-8139 = Građevinski materijali i
konstrukcije
COBISS.SR-ID 188695820

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SVOJSTVA SAMOUGRAĐUJUĆEG BETONA SPRAVLJENOG S RECIKLIRANIM AGREGATOM I RAZLIČITIM MINERALNIM DODACIMA

PROPERTIES OF SELF-COMPACTING CONCRETE MADE OF RECYCLED AGGREGATES AND VARIOUS MINERAL ADDITIVES

Iva DESPOTOVIĆ

ORIGINALNI NAUČNI RAD
ORIGINAL SCIENTIFIC PAPER
UDK: 666.972.1
doi: 10.5937/grmk1504003D

1 UVOD

Građevinska industrija koristi ogromne količine prirodnih resursa, istovremeno proizvodeći značajne količine građevinskog otpada, tako da ima veliki uticaj na prirodnu sredinu. Godišnja proizvodnja betona u svetu dostigla je deset milijardi tona, svrstavajući beton u daleko najkorišćeniji građevinski materijal. Ako se ima u vidu činjenica da je oko 70% betona agregat, jasno je kolika je količina prirodnog i drobljenog agregata potrebna. Nekontrolisana eksploatacija agregata iz reka ozbiljno narušava vodene ekosisteme i staništa, dok proizvodnja drobljenog prirodnog agregata povećava emisiju štetnih gasova, prvenstveno CO₂, odgovornih za efekat staklene bašte. Ovi gasovi nastaju u toku miniranja stena i tokom transporta agregata do često udaljenih gradskih sredina.

S druge strane, količina građevinskog otpada koji nastaje tokom gradnje i rušenja objekata rapidno raste, produbljujući problem odlaganja ovog otpada, koji se najčešće rešava predviđenim deponijama (zauzimaju velike površine zemljišta, a odlaganje je skupo) ili „divljim“, nelegalnim deponijama.

Jedno od rešenja navedenih problema jeste recikliranje deponovanih građevinskih materijala, prvenstveno betona. Ova ideja nije nova i razvijene zemlje poput Japana, Holandije, Belgije i Danske ostvaruju visok procenat reciklaže građevinskog otpada. Reciklirani betonski agregat najviše se koristi u putarstvu, za različite ispune i izradu nekonstruktivnih elemenata (ivičnjaka, ograda i sličnog). Zbog neujednačenog kvaliteta, mogućnosti ostatka različitih primesa prilikom reciklaže,

1 INTRODUCTION

Construction industry uses vast amounts of natural resources, simultaneously producing significant amounts of construction waste, so that it has a great impact on the environment. Annual production of concrete in the world has reached 10 billion tons, classifying concrete in the most widely used building material. Having in mind the fact that 70 % of concrete is aggregate, it is clear what the quantity of natural and crushed aggregates requires. Uncontrolled exploitation of aggregates from rivers seriously disrupts aquatic ecosystems and habitats, while the production of crushed natural aggregates increases harmful gas emissions, primarily of CO₂, which are responsible for the greenhouse effect. These gases are formed during blasting rocks and during the transportation of aggregates to the usually distant urban areas.

On the other hand, the amount of construction waste generated during the construction and demolition of buildings is growing rapidly, deepening the problem of disposing this waste, which is usually solved by making planned landfills (which occupy large areas of land and disposal is costly) or illegal dumps.

One of the solutions of the mentioned problems is recycling deposited building materials, primarily concrete. This idea is not new and developed countries, like Japan, the Netherlands, Belgium and Denmark achieve a high percentage of recycling of construction waste. Recycled concrete aggregates are mostly used in road engineering, for different fillings and making non-structural elements (curbs, fences, etc). Because of the

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većeg upijanja vode i niže zapremine mase u odnosu na prirodni agregat, reciklirani agregat zahteva niz ispitivanja i posebnu tehnologiju spravljanja betona.

Samougrađujući beton, i sama inovacija u području tehnologije betona, sadrži određenu količinu praškastog materijala – filera. Postoje različite mogućnosti odabira ove komponente. Ukoliko bi se upotrebio neki od industrijskih nusproizvoda, poput letećeg pepela ili silikatne prašine, rešio bi se problem deponovanja ovih materijala, a ovako spravljen beton svakako bi se mogao uvrstiti u ekološke materijale.

Predmet istraživanja u ovom radu jesu svojstva i tehnologija samougrađujućeg betona koji je spravljen s različitim mineralnim dodacima: mlevenim krečnjakom, letećim pepelom i silikatnom prašinom, pri čemu su, kao agregat, korišćeni i prirodni i reciklirani agregat, dobijen rušenjem potpornog zida, čija je količina u betonu varirana.

2 SAMOUGRAĐUJUĆI BETON

Samougrađujući beton (engl. Self-Compacting Concrete - SCC), po mnogim autorima „najrevolucionarnije otkriće industrije betona XX veka“, ne zahteva vibriranje prilikom ugrađivanja i zbijanja. Pod dejstvom sopstvene težine u potpunosti ispunjava sve delove oplata čak i u prisustvu gusto postavljene armature. Njegove prednosti su: brža gradnja, smanjenje broja potrebnih radnika, bolje finalne površine, lakše ugrađivanje, poboljšana trajnost, veća sloboda oblikovanja elemenata, smanjenje buke, odsustvo vibracija, i samim tim, zdravije radno okruženje. Procena je da se prilikom upotrebe samougrađujućeg betona umesto vibriranog, potrebe za radnom snagom smanjuju za oko 10%; kod primene prefabrikovanih elemenata, vreme gradnje je kraće za oko 5%, a potreba za radnicima manja za oko 20%; prilikom primene sendvič-elemenata (čelik–beton) ušteda u vremenu je 20%, a u radnoj snazi 50%. Glavni nedostaci upotrebe samougrađujućeg betona jesu veća cena materijala, stroži zahtevi kvaliteta i veći pritisak na oplatu u odnosu na vibrirani beton [13].

Kod samougrađujućeg betona najvažnije su njegove karakteristike u svežem stanju. Prilikom projektovanja mešavine, akcenat se stavlja na sposobnost betona da se razliva samo pod dejstvom sopstvene težine i da u potpunosti ispunji oplatu ma kog oblika i dimenzija bez ostavljanja šupljina, da prođe kroz gusto postavljenu armaturu bez zaglavljivanja, da zadrži homogenu strukturu bez izdvajanja agregata iz paste ili vode od čvrste faze, kao i bez tendencije krupnog agregata da „propadne“ kroz betonsku masu pod dejstvom gravitacije (segregacija). Dakle, ključne karakteristike svežeg SCC-a jesu: sposobnost tečenja, viskoznost (izražena brzinom tečenja), sposobnost prolaza i otpornost na segregaciju [2]. Betonska mešavina će biti klasifikovana kao SCC jedino ako su sva navedena svojstva u potpunosti ostvarena, pri čemu se svako od njih može testirati na više načina.

Osnovne komponente mešavina kod vibriranog i samougrađujućeg betona jesu iste, ali se razlikuju odnosi mešanja i SCC sadrži više sitnog agregata i sitnih čestica, kao i aditive najnovije generacije (modifikatore viskoziteta i visoke sposobnosti redukcije vode) u odnosu na vibrirani beton. Propisno projektovan i ugrađen, SCC se odlikuje većom kompaktnošću i

uneven quality, the possibility of various impurities to rest during recycling, larger water absorption and lower bulk density, compared to natural aggregates, recycled aggregates require a series of tests and special technology of concrete making.

Self-compacting concrete, being innovation in the field of concrete technology, contains a certain amount of powdered materials – fillers. There are various possibilities of selecting this component. If we used any of the industrial by-products, such as fly ash or silica fume, we would solve the problem of depositing these materials, and thus made concrete ecological material.

The research subject presented in this paper are properties and technology of self-compacting concrete made with various mineral additives: lime, fly ash, and silica fume, wherein the aggregates used, are both natural and recycled aggregates, obtained by demolition of retaining wall, whose amount is varied in the concrete.

2 SELF - COMPACTING CONCRETE

Self - compacting concrete (SCC), according to many authors "the most revolutionary discovery of concrete industry of the 20th century", does not need vibrating when placing and compacting. Under the influence of its own weight, it completely fills all parts of the formwork, even in the presence of dense reinforcement. Its advantages are fast construction, a reduced number of required workers, better final surface, easier placement, and increased durability, greater freedom in designing elements, noise reduction, vibration absence, and therefore healthier work environment. It is estimated that when using self-compacting concrete instead of vibrated concrete, the need for workers is reduced by about 10%; when using prefabricated elements, construction time is shorter by about 5%, and demand for workers decreased by about 20%; when applying sandwich elements (steel - concrete) time saving is 20%, and savings in the labour force 50%. The main disadvantages of the use of self - compacting concrete are higher material prices, stricter quality requirements and increasing pressure on the formwork compared to vibrated concrete [13].

With self-compacting concrete, its most important characteristics are in its fresh state. When designing mixes, emphasis is placed on the ability of concrete to be levelled out only under the influence of its own weight and to fully fill the formwork of any shape and dimensions without leaving voids, to pass through dense reinforcement without blocking, to retain a homogenous structure without separating aggregate from paste or water from the solid phase, as well as without the tendency of coarse aggregates to "fall" through the concrete mass under the influence of gravity (segregation). Therefore, the key characteristics of fresh SCC are floating, viscosity (expressed by floating rate), passing ability and resistance to segregation [2]. Concrete mix will be classified as SCC only if all the above properties are fully achieved, wherein each of them can be tested in a number of ways.

The basic components of the mixes in vibrated and self - compacting concrete are the same, but ratios differ, so that SCC contains more fine aggregate and fine particles, as well as additives of the latest generation (modifiers of viscosity and high capacity water

homogenošću u odnosu na vibrirani beton, pri čemu se svojstva očvrstlog samougrađujućeg betona ispituju na isti način kao odgovarajuća svojstva vibriranog betona.

3 MINERALNI DODACI

3.1 Leteći pepeo

Začetnici ideje o primeni letećeg pepela, dobijenog sagorevanjem uglja u betonu, bili su McMillan i Powers 1934. godine. Krajem 40-tih godina izvršena ispitivanja u Britaniji (Fulton i Marshall) dovela su do gradnje brana Lednock, Clatworthy i Lubreoch, s letećim pepelom kao cementnim dodatkom. Sve ove konstrukcije su i posle šezdeset godina u odličnom stanju [10].

Prilikom sagorevanja uglja u peći na temperaturi između 1250°C i 1600°C, nesagorive čestice se spajaju, formirajući sferične staklaste kapljice silikata (SiO_2), aluminata (Al_2O_3), oksida gvožđa (Fe_2O_3) i drugih, manje važnih konstituenata. Kada se leteći pepeo doda betonu, počinje pucolanska reakcija između silicijum-dioksida (SiO_2) i kalcijum-hidroksida ($\text{Ca}(\text{OH})_2$) ili kreča, koji je nusprodukt hidratacije Portland cementa. Nastali produkti hidratacije popunjavaju pore, smanjujući poroznost matrice. Ovi produkti se razlikuju od produkata nastalih u betonima, koji sadrže samo Portland cement. U reakcijama Portland cementa i vode nastaje najpre hidratisan kreč ($\text{Ca}(\text{OH})_2$), koji se zbog svoje ograničene rastvorljivosti formira u međuprostoru čestica. U prisustvu vode, kreč pucolanski reaguje s letećim pepelom, pri čemu nastaju novi produkti hidratacije fine strukture pora.

Čestice sitnije od 50µm uglavnom su sferične (slika 1) dok krupnije čestice mogu da budu nepravilnijeg oblika. Sferične čestice daju značajan doprinos fluidnosti betona u plastičnom stanju, optimizujući upakovanost čestica [1].

3.2 Silikatna prašina

Silikatna prašina (slika 2) veoma je fin prah sledećih osobina:

- 1) sadržaj silicijum-dioksida, SiO_2 , najmanje 85%;
- 2) prosečna veličina čestica između 0.1 i 0.2 mikrona;
- 3) minimalna specifična površina 15000 m^2/kg ;
- 4) sferni oblik čestica.

Silikatna prašina nastaje prilikom topljenja kvarca na visokoj temperaturi u peći sa električnim lukom, pri čemu nastaje silicijum ili ferossilicijum. Zbog ogromne količine potrebne električne energije, ove peći se nalaze u zemljama sa značajnim elektropotencijalom poput skandinavskih zemalja, Sjedinjenih Država, Kanade, Južne Afrike i Australije. Kvarc visoke čistoće zagreva se do 2000°C, gde se kao gorivo koriste ugalj, koks i drvena piljevina, a zatim uvodi električni luk da bi se izdvojili metali. Topljenjem kvarca oslobađa se silicijum-oksidi u gasovitom stanju, koji se meša s kiseonikom u višim delovima peći, gde oksidira, prelazeći u sićušne čestice amorfno silicijum-dioksida. Čestice se izvode iz

redukcijom) compared to vibrated concrete. Properly designed and placed, SCC is characterized by a greater compactness and homogeneity compared with the vibrated concrete, wherein the properties of the hardened self-compacting concrete are tested in the same way as the corresponding properties of the vibrated concrete.

3 MINERAL ADDITIVES

3.1 Fly Ash

The initiators of the idea of applying fly ash, resulted from coal burning, in concrete were McMillan and Powers (1934). At the end of 40s the experiments carried out in the UK (Fulton and Marshall) led to the construction of dams Lednock, Clatworthy and Lubreoch, with fly ash as a cement additive. All these structures are after 60 years in excellent condition [10].

During the combustion of coal in a furnace at temperatures between 1250°C and 1600°C, non-combustible particles combine to form spherical glassy droplets of silicate (SiO_2), aluminate (Al_2O_3), iron oxide (Fe_2O_3) and other less important constituents. When fly ash is added to concrete, pozzollanic reaction starts between silicon dioxide (SiO_2) and calcium hydroxide ($\text{Ca}(\text{OH})_2$) or lime, which is a by-product of hydration of Portland cement. The resulting products of hydration fill pores reducing the porosity of the matrix. These products differ from the products formed in concrete containing only Portland cement. In the reactions of Portland cement and water, hydrated lime ($\text{Ca}(\text{OH})_2$) is formed first, in the space between particles, because of its limited solubility. In the presence of water, lime reacts pozzollanic with fly ash to form new hydration products with fine pore structures.

Particles smaller than 50-are generally spherical (Figure 1), while larger particles may be irregularly shaped. Spherical particles provide a significant contribution to the fluidity of concrete in the plastic state, optimizing the packing of particles [1].

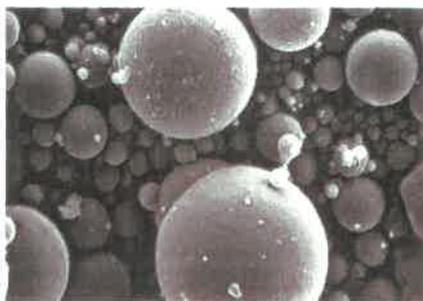
3.2 Silica Fume

Silica fume (Figure 2) is very fine powder with the following characteristics:

- 1) the silica, SiO_2 , content of at least 85%
- 2) average particle size between 0.1 and 0.2 microns
- 3) minimum specific area 15 000 m^2/kg
- 4) spherical shape of particles.

Silica fume is formed during melting quartz at high temperature in an electric arc furnace, wherein silicon or ferrosilicon occurs. Because of the huge amount of electricity needed, these furnaces are located in the countries with significant electrical potential, such as Scandinavian countries, USA, Canada, South Africa and Australia. High purity quartz is heated to 2000°C using coal, coke or wood chips as fuel and then electric arc is introduced in order to remove metals. By melting quartz, silicon oxide is released in gaseous state, and it is mixed with oxygen in the upper parts of the furnace, where it oxidizes turning into tiny particles of amorphous silicon dioxide. Particles are carried out from the furnace

peći kroz kolektor i obrtni deo u kojima se odstranjuju nesagoreli delovi uglja, a onda „uduvavaju“ u posebne filter- vreće.



Slika 1. Čestica letećeg pepela (SEM slika) [10]
Figure 1. Fly ash particle (SEM picture) [10]

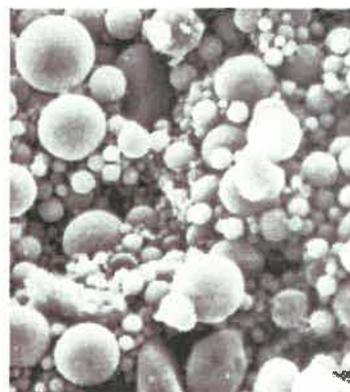
Zahvaljujući svojoj prirodi, i mali dodatak silikatne prašine znatno menja fizičko- hemijske osobine betona. Uobičajeno doziranje od 8 do 10% težine cementa znači između 50000 i 100000 mikrosfera prašine po zrnu cementa, što direktno povećava koheziju betona. Ukoliko se koristi silikatna prašina u praškastoj formi, javiće se potreba za većom količinom vode da bi se omogućili mešanje i ugradnja, pa je nužna primena plastifikatora ili superplastifikatora.

Iz aspekta ugradljivosti, treba pomenuti da svež beton sa silikatnom prašinom zbog veće kohezije ima manje rasprostiranje (slump vrednosti). Veoma fine čestice prašine obezbediće znatno veću kontaktnu površinu svežeg betona i armature i na taj način stvoriti bolju vezu očvrstlog betona sa armaturom. Osim odsustva segregacije i popunjavanja glavnih šupljina, tipično za betone sa silikatnom prašinom jeste da nema izdvajanja vode. Zbog toga se odmah po ugrađivanju mora otpočeti sa odgovarajućom negom. Takođe se i završna obrada, poput perdašenja, radi znatno ranije nego kod običnih betona.

Bez obzira na manje rasprostiranje, odsustvo izdvojene vode i „želiranje“ (zgušnjavanje kada se ne meša) ne ukazuju na ubrzano očvršćavanje. Silikatna prašina je pucolan i za njeno aktiviranje neophodno je prisustvo kalcijum-hidroksida. On nastaje u procesu hidratacije cementa tako da silikatna prašina može da se aktivira tek kada cement počne da reaguje. Vreme vezivanja kod betona sa silikatnom prašinom isto je kao i kod običnih betona. Kako beton počinje da vezuje i očvršćava, pucolanska aktivnost silikatne prašine postaje dominantna reakcija. Silikatna prašina reaguje sa slobodnim kalcijum-hidroksidom, gradeći kalcijum-silikat i hidrate aluminijuma. Ova jedinjenja povećavaju čvrstoću i smanjuju propusnost, progušujući cementnu matricu.

Zbog veće specifične površine i višeg sadržaja silicijum-dioksida, silikatna prašina je mnogo reaktivnija od letećeg pepela ili granulisane zgure. Ova pojačana reaktivnost prvobitno će znatno pojačati brzinu hidratacije C_3S minerala cementa, ali se nakon dva dana proces normalizuje.

through the collector and cyclone, where the unburned parts of coal are removed, and then “blown” into the special filter bags.



Slika 2. Silikatna prašina (SEM slika) [14]
Figure 2. Silica fume (SEM picture) [14]

Due to its nature, even a small addition of silica fume significantly changes physical and chemical properties of concrete. The customary dosage of 8- 10% by weight of cement means between 50 000 and 100 000 microspheres of dust per cement grain, which directly increases the cohesion of concrete. If silica fume is used in the powder form, there will be a need for a greater amount of water to allow mixing and placement of concrete so it is necessary to apply plasticizers and superplasticizers.

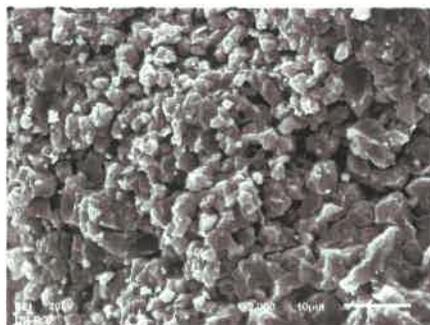
In terms of placeability, it should be noted that fresh concrete with silica fume has less spreading (slump values) because of greater cohesion. Very fine silica fume particles will provide considerably larger contact area of fresh concrete and reinforcement and thus make better bonding of hardened concrete with reinforcement. Besides the lack of segregation and filling the main cavities, in concrete with silica fume, there is no separation of water. That is why, immediately after placement, it is necessary to begin with appropriate curing. Finishing, such as pargeting, is also done much earlier than in ordinary concrete.

Regardless of less spreading, the absence of free water and “gelling” (jellification when not stirred) do not indicate rapid hardening. Silica fume is pozzolan and it requires the presence of calcium hydroxide to be activated. Calcium hydroxide is formed in the cement hydration process, so that silica fume can be activated only when the cement begins to react. Setting time of concrete with silica fume is the same as in plain concrete. As concrete begins to set and harden, pozzolanic activity of silica fume becomes dominant reaction. Silica fume reacts with free calcium hydroxide, thus forming calcium silicate and hydrates of aluminium. These compounds increase the strength and reduce permeability, thickening the cement matrix.

Because of higher specific area and higher content of silicon dioxide, silica fume is much more reactive than fly ash or granulated slag. This increased reactivity initially increases hydration rate of C_3S cement mineral, but after two days the process becomes normal.

3.3 Mleveni krečnjak

Mleveni krečnjak (slika 3) više se koristi kao dodatak cementu nego betonu. Evropska norma EN197 – 1 predviđa dve klase Portland cementa s krečnjakom čije su oznake CEM II/A-L (ili L-L umesto A-L) i CEM II/B-L (ili L-L umesto B-L). Prvi sadrži između 6 i 20% krečnjaka, a drugi 21–35%.



Slika 3. Mleveni krečnjak (SEM slika)
Figure 3. Lime (SEM picture)

Zahtevi koje krečnjak za cement treba da ispuni jesu sledeći: sadržaj CaCO_3 mora da bude veći od 75%, sadržaj gline određen metilenskim plavim testom ne sme da pređe 1.20g /100 g, ukupni sadržaj organskog ugljenika ne sme da pređe 0.20% za LL krečnjak i 0.50% za L krečnjak.

Prisustvo krečnjaka izaziva ubrzanje hidratacionog procesa i hidratacionog skupljanja betona već u prvih nekoliko sati, zbog toga što čestice krečnjaka služe kao dodatna jezgra za hidrataciju.

4 RECIKLIRANI AGREGAT

Kao održivo rešenje za probleme građevinskog otpada i iscrpljivanje nalazišta prirodnih agregata, nametnuo se postupak recikliranja deponovanih građevinskih materijala, u prvom redu betona. Recikliranje i očuvanje prirodnih resursa bezrezervno su prihvaćeni od strane građevinske industrije, ali pozitivni efekti takvog pristupa donekle su ograničeni, zato što nisu obezbeđeni svi uslovi za primenu. To se prvenstveno odnosi na nedostatak: prostora i opreme za sortiranje građevinskog šuta, iskustva u postupcima recikliranja otpadnih materijala, obučanih radnika i kontrolora, znanja o tržištu sekundarnih materijala, zakonske regulative u oblasti zaštite životne sredine, i tako dalje [7].

Upotreba recikliranog agregata u konstrukcijama još je relativno nova priča. Njen početak Bak (Buck, 1977) smešta u period neposredno nakon Drugog svetskog rata, kada je postojala ogromna potreba da se grade novi objekti i infrastruktura i istovremeno raščišćavaju postojeće ruševine. Nakon toga, reciklirani agregat prestaje da se upotrebljava, da bi tokom sedamdesetih godina, Sjedinjene Države počele ponovo da koriste reciklirani agregat u nekonstrukcijske svrhe, mahom kao materijal za ispunu i različita nasipanja u putarstvu [8]. Zbog razloga koji su napred navedeni, ispitivanje

3.3 Lime

Lime (Figure 3) is more widely used as a cement additive than a concrete additive. European norm EN197 - 1 provides two classes of Portland cement with lime whose labels are CEM II/L (or L-L instead of A-L) and CEM II/BL (or L-L instead of B-L). The former contains between 6 and 20% of lime and the latter 21- 35%.

Requirements that lime for cement should meet are the following: CaCO_3 content should be greater than 75%, clay content, determined by methylene blue test, must not exceed 1.20g/100g, the total content of organic carbon must not exceed 0.20% for LL lime and 0.50% for L lime.

The presence of lime causes the acceleration of the hydration process and hydration shrinkage of concrete in the first few hours, because the particles of lime are used as additional cores for hydration.

4 RECYCLED AGGREGATE

As a sustainable solution to the problems of construction waste and the depletion of natural aggregates sites, the recycling process of deposited building materials, primarily concrete, has been imposed. Recycling and preservation of natural resources are unreservedly accepted by the construction industry but positive effects of this approach are somewhat limited, since the conditions for their application are still concealed. This is primarily related to the lack of space equipment for sorting construction rubble, lack of experience in the procedures of recycling waste materials, shortage of skilled workers and supervisors, lack of knowledge of the secondary materials market, of legislation in the field of environmental protection, etc [7].

The use of recycled aggregates in structures is still relatively new. Buck (1977) defines its beginning in the period immediately after the Second World War, when there was a tremendous need for building new facilities and infrastructure and at the same time, clearing the existing ruins. After that, the use of recycled aggregates stopped but during 70s the US started to re-use recycled aggregates in non-construction purposes, mainly as fill material and different fillings in road engineering [8]. Due to the above mentioned reasons, testing of recycled

recikliranog agregata (ne samo betonskog) i njegova primena danas su aktuelniji no ikad, jer je potreba za agregatom na svetskom nivou dostigla 26.8 milijardi tona godišnje [15]. Primera radi, Sjedinjene Države godišnje recikliraju oko 140 miliona tona betonskog otpada. Prema podacima iz godišnjeg izveštaja Evropske asocijacije za agregat (2010), reciklirani agregat čini 5% ukupne proizvodnje agregata u Evropskoj uniji, gde je Nemačka najveći proizvođač (60 miliona tona), a slede Velika Britanija (49 miliona tona), Holandija (20 miliona tona) i Francuska (17 miliona tona). U Australiji se oko 50% betonskog otpada reciklira, dok se u Japanu impozantnih 98% betonskog otpada pretvara u reciklirani agregat [5].

Procenjuje se da u Republici Srbiji godišnje nastaje oko milion tona građevinskog otpada i otpada od rušenja. Ovaj otpad završava na deponijama komunalnog otpada, a koristi se i kao inertan materijal za prekrivanje otpada na deponiji. Reciklaža građevinskog otpada praktično ne postoji [12].

Tehnološki postupak proizvodnje recikliranog agregata podrazumeva drobljenje komada starog betona na zrna određene veličine i njihovo prosejavanje, čemu prethodi odvajanje metalnih delova magnetnim separatorom i ručno ili mašinsko uklanjanje stranih materija. Zrno recikliranog agregata dobijeno ovakvim postupkom recikliranja sastoji se od zrna (ili dela zrna) prirodnog agregata i cementnog maltera originalnog betona, koji ga delimično ili potpuno obavija. Prisustvo starog cementnog maltera, koji je manje zapreminske mase i veće poroznosti od zrna prirodnog agregata, značajno utiče na niz fizičko-mehaničkih svojstava, kako recikliranog agregata, tako i betona na bazi recikliranog agregata, odnosno uslovljava „lošija” svojstva recikliranog u odnosu na prirodni agregat. Zbog toga su se u svetu u poslednjih nekoliko godina razvila istraživanja u smislu unapređivanja tehnologije recikliranja i dobijanja recikliranog agregata koji bi po svojstvima, odnosno kvalitetu, bio praktično identičan prirodnom agregatu. Radi uklanjanja cementnog kamena sa zrna agregata razvijeno je nekoliko naprednih tehnologija recikliranja, pre svega u Japanu. Jedna od tih tehnologija jeste takozvana „metoda zagrevanja i struganja”. Na ovaj način, dobija se 35% do 45% čistog krupnog agregata, 30% do 35% čistog sitnog i 18% do 35% finog praša od cementnog maltera u zavisnosti od temperature zagrevanja (300-700°C).

Druga tehnologija je hemijski tretman klasično proizvedenog recikliranog agregata. Prethodnim potapanjem recikliranog agregata u blage rastvore hlorovodonične, sumporne ili fosforne kiseline moguće je odstraniti deo cementnog maltera i poboljšati svojstva agregata, bez značajnijeg povećanja sadržaja hlorida i sulfata u njemu. Pomenuta procedura sastoji se iz potapanja recikliranog agregata u kiselu sredinu u trajanju od 24h, pri temperaturi od oko 20°C, a zatim se vrši ispiranje destilovanom vodom kako bi se u najvećoj mogućoj meri uklonile primenjene kiseline. Pre samog spravljanja betona, agregat stoji u vodi 24 časa. Da se ne bi smanjio kvalitet agregata (pH vrednost), koncentracija kiseline u rastvoru treba da bude oko 0.1 mol. Ovim postupkom moguće je smanjiti upijanje vode kod recikliranog agregata za 7-12% [9,6]. Sve navedene napredne tehnologije recikliranja, odnosno poboljšanja kvaliteta, iako omogućavaju proizvodnju kvalitetnog

aggregates (not just concrete) and their application are more relevant today than ever, because the need for aggregates globally reached 26.8 billion tons per year [15]. For example, the US annually recycles about 149 million tons of concrete waste. According to the data from the annual report of the European Association for aggregates (2010), recycled aggregates make 5% of the total production of aggregates in the European Union, where Germany is the largest producer, followed by Great Britain (49 million tons), the Netherlands (20 million tons) and France (17 million tons). In Australia, around 50% of the concrete waste is recycled, while in Japan, the impressive 98% of concrete waste is turned into recycled aggregate [5].

It is estimated that in the Republic of Serbia, about 1 million tons of construction waste and demolition waste is annually produced. This waste ends up in landfills of municipal waste, and is also used as inert material for coverage of waste at landfills. Recycling construction waste actually does not exist [12].

Technological process for the production of recycled aggregates involves crushing pieces of old concrete to a certain grain size and their sieving, which is preceded by the separation of metal parts, using magnetic separator, and manual or mechanical removal of foreign substances. Grains of recycled aggregate, obtained by this recycling process, consist of grains (or grain parts) of natural aggregates and cement mortar of original concrete which partially or completely wraps them. The presence of old cement mortar, which is of less density and higher porosity than grains of natural aggregates, significantly affects a number of physical and mechanical properties, of both recycled aggregate and concrete with recycled aggregate, i.e. causes “worse” properties of recycled aggregate compared to natural aggregate. Therefore, numerous researches have been carried out worldwide with the aim of improving recycling technologies and obtaining recycled aggregates that would be practically identical to natural aggregate in their properties or quality. In order to remove cement stone from an aggregate grain, a number of advanced recycling technologies have been developed, primarily in Japan. One of these technologies is called “the method of heating and abrasion”. Thus, they obtain 35% to 45% of pure coarse aggregate, 30% to 35% of pure small aggregate, and 18 % to 35% of fine powder of cement mortar, depending on the heating temperature (300 – 700°C).

Other technology is chemical treatment of classically produced recycled aggregate. By previous submerging of recycled aggregate in a mild solution of hydrochloric, phosphoric and sulphuric acid, it is possible to remove a part of cement mortar and improve aggregate properties without a significant increase of the content of chloride and sulphate in it. The mentioned procedure consists of immersing recycled aggregate in an acidic environment for 24 hours at a temperature of about 20°C, and then the applied acids are removed to the maximum extent possible, by washing with distilled water. Before making concrete, aggregate is left in water for 24 hours. In order to sustain the quality of the aggregate (ph value), concentration of acid in solution should be about 0.1mol. This method can reduce the absorption of water in recycled aggregate for 7-12% [9,6]. All of these advanced recycling technologies, although enable the

recikliranog agregata potpuno ekvivalentnog prirodnom, nemaju za sada širu primenu, jer su znatno skuplje od tradicionalnih tehnologija. Metode s termičkim tretmanom agregata su i energetske zahtevnije, što dovodi u pitanje korist od recikliranja i povoljan uticaj na zaštitu životne sredine [11].

5 SOPSTVENO EKSPERIMENTALNO ISPITIVANJE

5.1 Sastav betonskih mešavina

Za potrebe eksperimentalnog dela rada napravljeno je devet različitih trofrakcijskih betonskih mešavina. Korišćeni su cement PC 42.5R (Holcim Popovac); mineralni dodaci: mleveni krečnjak (proizvođač „Jelen Do“), elektrofilterski pepeo (iz Termoelektrane „Nikola Tesla“ B u Obrenovcu), i silikatna prašina (proizvod SikaFume, proizvođača građevinske hemije SIKA); prirodni agregat (Luka „Leget“ – Sremska Mitrovica), reciklirani agregat dobijen drobljenjem srušenog potpornog zida u kamenolomu Ostrovica kod Niša. Etaloni su spravljani sa svakim od dodataka i prirodnim agregatom; kod mešavina K50, P50 i S50, frakcija 8/16 mm zamenjena je recikliranim agregatom, a kod mešavina K100, P100 i S100, obe krupne frakcije (4/8 i 8/16 mm) zamenjene su recikliranim. U svim mešavinama korišćen je superplastifikator ViscoCrete 5380 (proizvođač SIKA), čije je doziranje izvršeno prema preporuci proizvođača. Kriterijum pri projektovanju mešavina bio je postizanje iste konzistencije betona, tj. slump - flow klase SF2, koja obuhvata uobičajenu primenu betona i podrazumeva rasprostiranje od 66 do 75 cm. Prilikom spravljanja betonskih mešavina, najpre je agregat mešan s polovinom potrebne vode u trajanju od oko 30 sekundi, a zatim su dodavane ostale komponente. Kada je korišćen reciklirani agregat, dodata je količina vode koju agregat upije za 30 minuta (II frakcija 2.22%, III frakcija 1.5%), mada ovaj princip nije mogao dosledno da se primeni.

Na svežem betonu urađena su ispitivanja: zapreminske mase, fluidnosti - slump flow test prema EN 12350-8, viskoznosti - T_{500} test prema EN 12350-8, sposobnosti prolaza između armature - L box test prema EN 12350-10, otpornosti na segregaciju - sieve segregation test prema EN 12350-11.

Na očvrslom betonu urađena su ispitivanja: zapreminske mase, čvrstoće pri pritisku, čvrstoće pri zatezanju savijanjem, skupljanja, vodonepropustljivosti, upijanja vode i SEM analize (skenirajuća elektronska mikroskopija).

Sastav betonskih mešavina prikazan je u tabeli 1.

production of high-quality recycled aggregates, fully equivalent to natural aggregates, have no wider application because they are significantly more expensive than traditional technologies. Methods of thermal treatment of aggregates are also more energy-demanding, which brings into question the benefits of recycling and its favourable impact on environmental protection.

5 MY OWN EXPERIMENTAL RESEARCH

5.1 Composition of Concrete Mixes

For the purposes of the experimental work, nine three-fraction concrete mixes have been made. Cement PC 42.5R (Holcim Popovac) has been used as well as mineral additives: lime (manufacturer "Jelen Do"), fly ash (from the power plant "Nikola Tesla B" in Obrenovac), and silica fume (product of SikaFume, a manufacturer of building chemicals SIKA); natural aggregate (Luka "Leget", Sremska Mitrovica), recycled aggregate obtained by crushing demolished retaining wall in the quarry Ostrovica, near Nis. Control concrete was made with each of the additives and a natural aggregate; in mixes K50, P50 and S50, fraction 8/16mm was replaced by the recycled aggregate, and in mixes K100, P100 and S100, both coarse fractions (4/8 and 8/16) were replaced by recycled fractions. In all the mixes, superplasticizer ViscoCrete 5380 (manufacturer SIKA) has been used, which was dosed according to the manufacturer. The criterion in the designing mixes was to achieve the same consistency of concrete, i.e. slump-flow class SF2, which includes the usual uses of concrete and involves spreading from 66 to 75cm. While making concrete mixes, the aggregate was first mixed with half of the required water for a period of about 30 seconds, and then other components were added. When used recycled aggregate, the amount of water which was absorbed by the aggregate in 30 minutes (II fraction 2.22%, III fraction 1.5%) was added, although this principle could not be consistently applied.

The fresh concrete tests were done for density, fluidity - slump flow test according to EN 12350-8, viscosity - T_{500} test according to EN 12350-8, the ability of the passage between the reinforcement - L box test according to EN 12350-10, segregation resistance - Sieve segregation test according to EN 12350-11.

The hardened concrete tests were done for density, compressive strength, tensile strength by bending, shrinkage, water impermeability, water absorption, and SEM analysis (Scanning Electron Microscopy).

Composition of concrete mixes is shown in Table 1.

Tabela 1. Sastav betonskih mešavina
Table 1. Concrete mixes

	cement (cement) (kg/m ³)	ml.krečnjak (lime) (kg/m ³)	el.pepeo (fly ash) (kg/m ³)	sil.prašina (silica fume) (kg/m ³)	0/4mm (kg/m ³)	4/8mm (kg/m ³)	8/16mm (kg/m ³)	voda (water) (kg/m ³)	VSC5380 (kg/m ³)
EK	400	120	0	0	770.86	306.28	532	170.8	4.94
EP	400	0	120	0	770.86	306.28	532	192.66	4.94
ES	400	0	0	52	770.86	306.28	532	185.71	4.94
K50	400	120	0	0	809.14	306.28	505.43	182.86	5.08
P50	400	0	120	0	809.14	306.28	505.43	214.28	5.08
S50	400	0	0	52	809.14	306.28	505.43	197.14	5.08
K100	400	120	0	0	809.14	306.28	505.43	189.5	5.08
P100	400	0	120	0	809.14	306.28	505.43	221	5.08
S100	400	0	0	52	809.14	306.28	505.43	208.6	5.08

5.2 Rezultati ispitivanja

Rezultati ispitivanja svežeg betona prikazani su u tabeli 2.

5.2 Test Results

The test results for concrete in the fresh state are shown in Table 2.

Tabela 2. Rezultati ispitivanja svežeg betona
Table 2. Test results for concrete in the fresh state

bet. mešavina (concrete mix)	zaprem. masa (density) kg/m ³	rasprostiranje (Slump-flow) cm	T500 s	L – kutija (L-box) H1/H2	test na situ, % (sieve segregation)
EK	2418	73	4	1	12.4
EP	2288	70	4	0.94	11
ES	2416	66	6	0.91	6.8
K50	2362	70	5	0.96	12
P50	2279	70	5	0.95	7.8
S50	2324	67	5	0.94	5.2
K100	2347	69	5	1	10
P100	2298	66	6	0.91	5.5
S100	2359	66	6	0.92	7.5

Rezultati ispitivanja zapremine mase betona u očvrslom stanju, prema SRPS EN 12390 – 7 : 2010, nakon dva, sedam i 28 dana, prikazani su u tabeli 3.

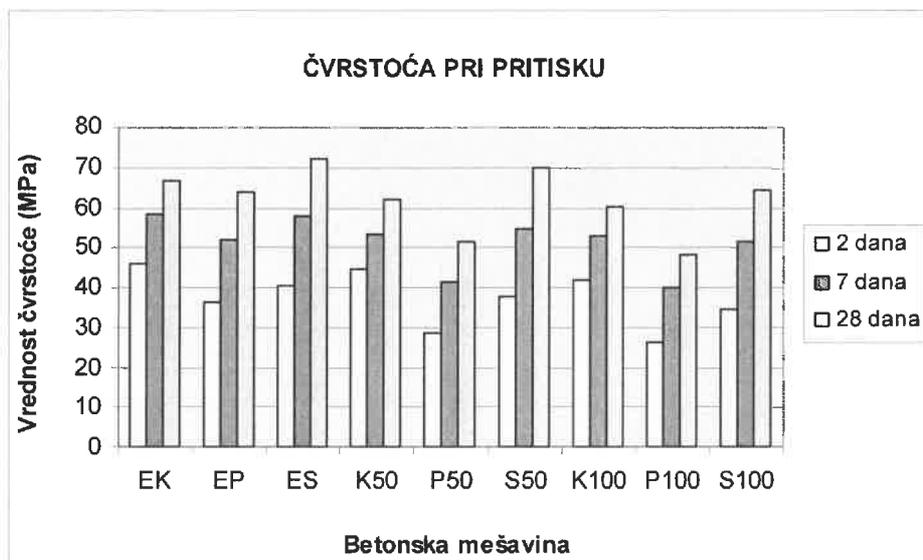
The test results for density of concrete in the hardened state, according to SRPS EN 12390 – 7:2010, after 2, 7 and 28 days are shown in Table 3.

Tabela 3. Rezultati ispitivanja zapremine mase betona (kg/m³)
Table 3. Test results for density (kg/m³)

	EK	EP	ES	K50	P50	S50	K100	P100	S100
2 dana	2396	2262.4	2366.4	2356.5	2313.5	2313	2363.5	2284.2	2312
7 dana	2469.2	2289.7	2361.8	2370	2315.5	2315.8	2352.9	2292.5	2338.6
28 dana	2426.7	2306.2	2376.3	2401.7	2314	2325	2357	2303.3	2333

Ispitivanje čvrstoće pri pritisku obavljeno je na kockama ivice 15 cm. Rezultati ispitivanja čvrstoće pri pritisku nakon dva, sedam i 28 dana, prikazani su na grafiku 1.

Testing compressive strength was carried out on the cubes with edges of 15cm. The test results for compressive strength after 2, 7 and 28 days are shown in Chart 1.



Grafik 1. Čvrstoća pri pritisku
Chart 1. Compressive strength

Ispitivanje čvrstoće na zatezanje savijanjem obavljeno je nakon 28 dana na uzorcima dimenzija 12x12x36 cm. Rezultati su prikazani na grafiku 2.

Testing tensile strength by bending was done after 28 days on the samples of dimensions 12x12x36cm. The results are shown on Chart 2.



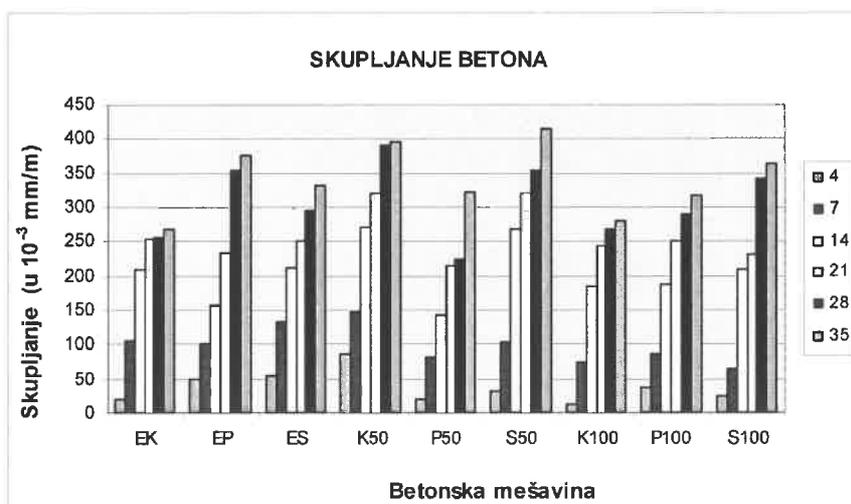
Grafik 2. Čvrstoća pri zatezanju savijanjem
Chart 2. Tensile strength by bending

Ispitivanje skupljanja izvršeno je na uzorcima dimenzija 12x12x36 cm, u svemu prema SRPS U.M1.029. Nakon 72 h od završetka izrade, uzorci se vade iz vode i izlažu kondicioniranim termohigrometrijskim uslovima. Izabrano je da to budu $70 \pm 5\%$ vlažnost vazduha i konstantna temperatura od $20 \pm 4\text{ }^\circ\text{C}$, što je standardom propisano za konstrukcije i elemente koji će biti u slobodnom prostoru. Prvo merenje se vrši nakon 72 ± 0.5 h nakon završetka izrade uzoraka, a zatim posle četiri i sedam dana. Nakon ovoga, dalja

Shrinkage test was done on the samples of dimensions 12x12x36cm, all in accordance with SRPS UM1.029. 72 hours after the samples are made they are taken out from the water and exposed to thermo hygrometric conditions. We chose it to be $70 \pm 5\%$ air humidity and a constant temperature of $20 \pm 4\text{ }^\circ\text{C}$, which is the standard prescribed for structures and elements located in free space. First measurement was done 72 ± 0.5 h hours after the samples were made, and then after 4 and 7 days. After this, further measurements were

merjenja rade se nakon svakih narednih sedam dana, dok se proces ne stabilizuje. Rezultati ispitivanja skupljanja betona nakon četiri, sedam, 14, 21, 28 i 35 dana prikazani su na grafiku 3.

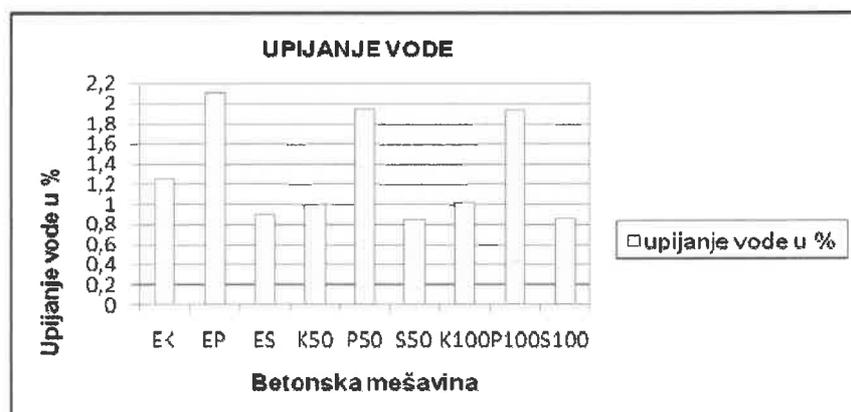
done after every seven days, until the process stabilized. The results of shrinkage tests after 4, 7, 14, 21, 28, and 35 days, are shown in Chart 3.



Grafik 3. Skupljanje betona
Chart 3. Shrinkage

Ispitivanje upijanja vode urađeno je na uzorcima dimenzija 12x12x36 cm, metodom postupnog potapanja. Rezultati ispitivanja upijanja vode nakon 28 dana prikazani su na grafiku 4.

Water absorption test was done on the samples of dimensions 12x12x36cm, by the method of gradual immersion. The test results for water absorption after 28 days are shown in Chart 4.



Grafik 4. Upijanje vode
Chart 4. Water absorption

Ispitivanje vodonepropustljivosti rađeno je na uzorcima dimenzija 200x200x150 mm, pri starosti betona od 28 dana, u svemu prema SRPS U.M1.015:1998. Uzorci su 24 časa izloženi dejstvu vode pod pritiskom od 1 bara, sledećih 48 časova pritisku od 3 bara, i na kraju poslednja 24 časa ispitivanja, pritisku od 7 bara. Nakon ovoga se polome i meri se dubina prodora vode. Kod uzoraka s krečnjakom i silikatnom prašinom, zabeležen je prodor vode od oko 2 cm, dok je kod uzoraka s pepelom prodor vode iznosio 8-10 cm.

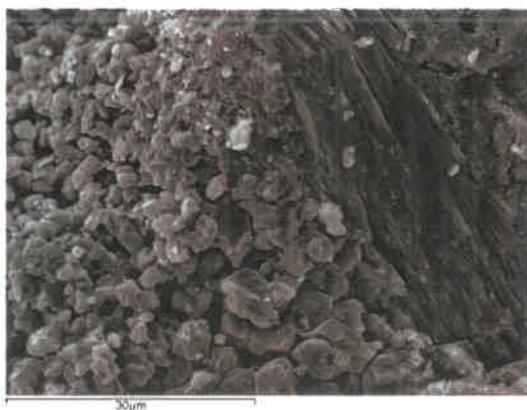
Water permeability testing was done on the samples of dimensions 200x200x150mm, in concrete at an age of 28 days, all in accordance with SRPS U.M1.015:1998. The samples were exposed to water under pressure of 1 bar for 24 hours; then the following 48 hours of 3 bars and finally, the last 24 hours of testing, under pressure of 7 bars. After this, they were broken and the depth of water ingress is measured. With the samples with lime and silica fume, ingress of water of about 2cm was recorded, while with the samples with fly ash, ingress of water was 8-10 cm.



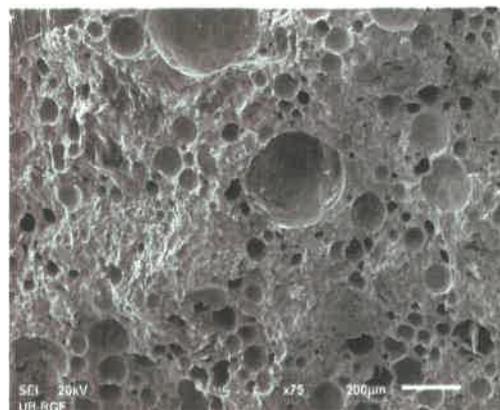
Slika 4. Ispitivanje vodonepropustljivosti
Figure 4. Water permeability testing

Skenirajuća elektronska mikroskopija (SEM analiza) omogućava da se „zaviri“ u strukturu spravljenih betona i bolje objasne rezultati koji su dobijeni ispitivanjima (slike 5-7).

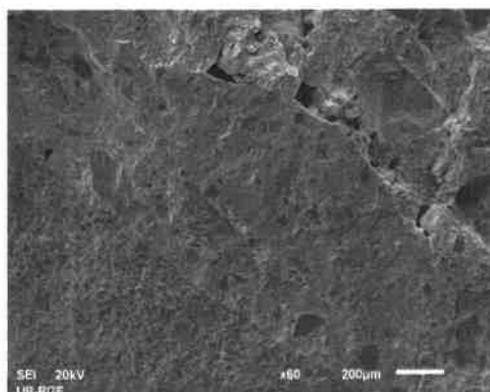
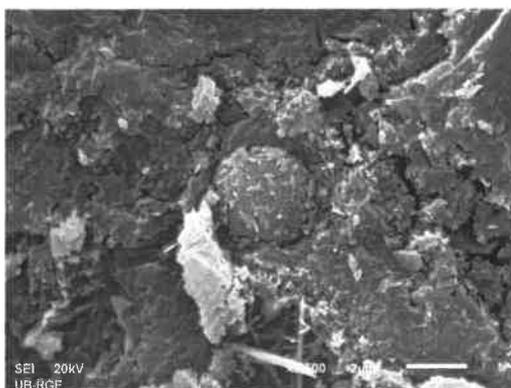
Scanning electron microscopy (SEM analysis) enables to “look into” the structure of concrete made and to better explain the results obtained by testing (Figures 5-7).



Slika 5. Mikrostruktura betona s mlevenim krečnjakom
Figure 5. Microstructure of the concrete with lime



Slika 6. Mikrostruktura betona sa elektrofilterskim pepelom
Figure 6. Microstructure of the concrete with fly ash



Slika 7. Mikrostruktura betona sa silikatnom prašinom
Figure 7. Microstructure of the concrete with silica fume

6 ANALIZA REZULTATA

Rasprostiranje svežeg betona iznosilo je od 66 do 73 cm, što sve projektovane mešavine svrstava u klasu SF2, koja odgovara najčešćoj primeni betona u građevinarstvu. Najmanju pokretljivost imale su betonske mešavine sa silikatnom prašinom, kao i mešavine s recikliranim agregatom, jer je oštrovično zrno ovog agregata teže „pomeriti” prilikom razlivanja betona. Najveće rasprostiranje izmereno je kod etalona s krečnjakom - 73 cm, a najmanje kod etalona sa silikatnom prašinom, mešavine sa silikatnom prašinom i krupnim recikliranim agregatom i mešavine s pepelom i krupnim recikliranim agregatom - 66 cm.

T_{500} je vreme za koje beton dostigne 500 mm, a meri se prilikom izvođenja slump-flow testa. Predstavlja proveru viskoznosti mešavine; za klasu SF2 preporučuje se interval od 3.5 do 6.0 s, u koji se sve mešavine „uklapaju”. Rezultati su u opsegu od 4 do 6 s, pri čemu su najsporije bile betonske mešavine sa silikatnom prašinom. Vreme duže od 2 s svrstava ih u klasu viskoznosti VS2.

Sve mešavine zadovoljavaju kriterijum da odnos visina betona na krajevima L-boxa bude najmanje 0.8, a kako je ispitivanje rađeno s tri armaturne šipke (što je i zahtev za gušće armirane konstrukcije), njihova klasa je PA2 (engl. passing ability = sposobnost prolaza). Rezultati testa kreću se u opsegu 0.91 – 1.0, pri čemu su najbolje rezultate (najbliže 1.0) postigle mešavine s krečnjakom. Najveća razlika na krajevima L box-a izmerena je kod mešavina sa silikatnom prašinom, što je i logična posledica njihovog najmanjeg rasprostiranja. Ni u jednom slučaju nije zabeleženo zaglavljivanje zrna agregata između šipki armature.

Test na situ pokazao je da su sve mešavine otporne na segregaciju i pripadaju klasi SR2 (<15%), pri čemu veće rasprostiranje znači manju otpornost na segregaciju.

Najveću zapreminsku masu u svežem stanju imao je etalon s krečnjakom 2418 kg/m^3 , gotovo istu kao i etalon sa silikatnom prašinom (2416 kg/m^3 , tj. za 0.08% manju), dok je najmanja zapreminska masa određena kod mešavine P50 (pepeo i reciklirana III frakcija) 2279 kg/m^3 za 5.7% manja. Uopšte, mešavine s pepelom imale su najmanje zapreminske mase, oko 70 kg/m^3

6 THE RESULTS ANALYSIS

Fresh concrete was spread from 66 to 73cm which designed mixes of class SF2 which fits in most common use of concrete in construction. Mixes with silica fume had the slightest mobility, as well as mixes with recycled aggregate, because grains with sharp edges were more difficult to “move” while levelling concrete. The largest spreading was recorded in control concrete with lime - 73cm, and the smallest in control concrete with silica fume, in mixes with silica fume and coarse recycled aggregate, and in mixes with fly ash and coarse recycled aggregate - 66.

T_{500} is the time that concrete reaches 500mm, and it is measured when doing slump-flow test. It represents a check of viscosity of the mix; the recommended interval for class SF2 is from 3.5 to 6.0s, and all mixes “fit” into it. The results are in the range of 4 – 6s, wherein concrete mixes with silica fume were the slowest. Time longer than 2s puts them in viscosity class VS2.

All mixes meet the criterion that height ratio of concrete at the ends of L-box is at least 0.8 and their class is PA2 as the testing was done with three reinforcement rods which is a requirement for thicker reinforced construction. The test scores are in the range of 0.91 – 1.0, wherein mixes with lime achieved the best results (nearest to 1.0). The biggest difference at the ends of L box was measured in mixes with silica fume, which is a logical consequence of its minimum spreading. Blocking of aggregate grains between reinforcement rods was not recorded in any case.

Sieve test shows that all mixes are resistant to segregation and they belong to class SR2 (<15%), while larger spreading means lower resistance to segregation.

Control concrete with lime had the highest density in the fresh state, 2418 kg/m^3 , nearly the same as the control concrete with silica fume (2416 kg/m^3 , i.e. 0.08 lower), while minimum density was found in the mix P50 (fly ash and recycled III fraction) 2279 kg/m^3 , 5.7% lower. Generally speaking, mixes with fly ash had the lowest density, about 70 kg/m^3 lower, compared to the corresponding mixes with lime and silica fume.

While designing concrete mixes, in order to obtain the same consistency because of the use of recycled

manje u odnosu na odgovarajuće mešavine s krečnjakom i silikatnom prašinom.

Prilikom projektovanja sastava betonskih mešavina, a da bi se postigla ista konzistencija, zbog primene recikliranog agregata bilo je neophodno intervenisati u dva pravca: povećati količinu vode i smanjiti količinu III frakcije za 5%, istovremeno povećavajući količinu peska za 5%. Bez ovih intervencija u sastavu, nije bilo moguće postići samougradljivost mešavine, zbog oštrovičnog oblika zrna recikliranog agregata i samog granulometrijskog sastava (reciklirani agregat je imao 7% nadmerenih zrna). Najveća promena vodocementnog faktora bila je kod betonskih mešavina sa elektrofilterskim pepelom, pri istoj količini mineralnog dodatka (i svim ostalim komponentama), u etalon s pepelom je dodato 21.86 kg (12.8%) vode u odnosu na etalon s krečnjakom; u mešavinu sa III recikliranom frakcijom 31.42 kg (17.2%) u odnosu na odgovarajuću mešavinu s krečnjakom, a u mešavinu s recikliranom II i III frakcijom 31.5 kg (16.6%). Silikatna prašina ima mnogo sitnije čestice od krečnjaka i pepela, tako da je njeno doziranje bilo 52 kg/m³ betona, tj. 13% mase cementa (uobičajena doza za je 10–15%). U etalon sa silikatnom prašinom dodato je 14.91 kg (8.7%) vode u odnosu na etalon s krečnjakom, i po 14.28 kg (7.8%) i 19.1 kg (10.1%) u odnosu na mešavine s krečnjakom i recikliranim agregatom. Zahtevana klasa konzistencije postignuta je pri najmanjem vodocementnom faktoru kod mešavina s krečnjakom, dok je najviše vode bilo potrebno kod mešavina s pepelom. Najmanji vodocementni faktor zabeležen je kod etalona s krečnjakom – 0.43 (ujedno i najmanji vodopraškasti faktor – 0.33), a najveći kod mešavine s pepelom i obe krupne reciklirane frakcije – 0.55. Najveći vodopraškasti faktor imala je mešavina sa silikatnom prašinom i obe krupne reciklirane frakcije – 0.46. Treba napomenuti da su betonske mešavine s krečnjakom pri najmanjem sadržaju vode u odnosu na ostale mešavine imale najveće prečnike rasprostiranja i najbolja svojstva samougradljivosti.

Najveću zapreminsku masu u očvrslom stanju nakon dva dana imala je betonska mešavina etalon s krečnjakom, a najmanju etalon s pepelom (razlika 133.6 kg/m³ tj. 5.6%). Ovaj trend se održao i nakon sedam dana s tim što je razlika iznosila 179.5 kg/m³ (7.3%). Nakon 28 dana, etalon s krečnjakom imao je najveću zapreminsku masu, 2426.7 kg/m³, za 123.4 kg/m³ (5.1%) veću od mešavine s pepelom i obe krupne reciklirane frakcije, i za 120.5 kg/m³ (5%) veću od etalona s pepelom. Zapreminska masa u očvrslom stanju kod mešavina sa silikatnom prašinom kretala se od 2312 kg/m³ (S100, dva dana) do 2366.4 kg/m³ (ES, 28 dana); to su vrednosti „između“ odgovarajućih kod krečnjaka i pepela. Treba imati u vidu da je za spravljanje betonskih mešavina korišćeno 52 kg silikatne prašine i po 120 kg mlevenog krečnjaka i pepela.

Najveću vrednost čvrstoće pri pritisku, nakon dva dana imao je etalon s krečnjakom, a najmanju mešavina s pepelom i obe krupne reciklirane frakcije – P100. Razlika je iznosila 19.8 MPa (43%). Nakon sedam dana, etaloni s krečnjakom i silikatnom prašinom imali su gotovo iste čvrstoće (58 MPa), dok je mešavina P100 dostigla 40.18 MPa (razlika 17.82 MPa, tj. 30.7%). Nakon 28 dana, najveću vrednost čvrstoće dostigao je etalon sa silikatnom prašinom, 72.31 MPa, a najmanju mešavina P100, 47.2 MPa (razlika 25.11 MPa, tj.

aggregate, it was necessary to intervene in two directions: to increase the amount of water and to reduce the amount of III fraction by 5%, simultaneously increasing the amount of sand by 5%. Without these interventions in the composition, it was impossible to achieve self-compacting of mixes because of the sharp-edged grain shape of recycled aggregates and granulometric composition itself (recycled aggregate had 7% of oversized grains). The greatest change of the water-cement ratio was found in concrete mixes with fly ash; at the same amount of mineral additive (and all other components), 21.86 kg (12.8%) of water was added into the control concrete with fly ash compared to the control concrete with lime; in the mix with III recycled fraction 31.42 kg (17.2%) compared to the appropriate mix with lime and in the mix with I and III fraction 31.5 kg (16.6%). Silica fume has much smaller particles than lime and fly ash, so that its dosage was 52 kg/m³ of concrete, i.e. 13% by the mass of cement (the usual dosage is 10 – 15%). We added 14.91 kg (8.7%) of water into the control concrete with silica fume compared to the control concrete with lime and 14.28 kg (7.8%) and 19.1 kg (10.11%) compared to mixes with lime and recycled aggregate. The required class of consistency was obtained at the lowest water-cement ratio in mixes with lime, while the highest amount of water was needed in mixes with fly ash. The lowest water-cement ratio was recorded in the control concrete with lime – 0.43 (at the same time the lowest water-cement ratio - 0.33), and the highest in mixes with fly ash and both two coarse recycled fractions – 0.46. It is necessary to point out that concrete mixes with lime, at the lowest content of water compared to other mixes, had the largest diameters of spreading and the best properties of self-compacting.

The highest density in the hardened state after two days was recorded in the control concrete with lime, and the lowest in the control concrete with fly ash (the difference 133.6 kg/m³ i.e.5.6%). This trend was held even after 7 days excepting that the difference amounted 179.5 kg/m³ (7.3%). After 28 days, control concrete with lime had the highest density, 2426.7 kg/m³, 123.4 kg/m³ (5.1%) higher than the mix with fly ash and both two coarse recycled fractions, and 120.5 kg/m³ (5%) higher than control concrete with fly ash. Density in the hardened state in mixes with silica fume ranged from 2312 kg/m³ (S100, 2days) to 2366.4 kg/m³ (ES, 28days); those are the values “between” the corresponding values in lime and fly ash. It should be borne in mind that, for making concrete mixes, we used 52 kg of silica fume and 120 kg of lime and 120 kg of fly ash.

The highest value of the compressive strength after 2 days was recorded in the control concrete with lime, and the lowest in the mix with fly ash and both two coarse recycled fractions – P100. The difference was 19.8 MPa (43%). After 7 days, control concrete with lime and control concrete with silica fume had nearly the same compressive strength (58MPa), while the mix P100 reached 40.18 MPa (the difference 17.82 MPa, i.e.30.7%). After 28 days, the highest value of strength was found in the control concrete with silica fume, 72.31 MP, and the lowest in the mix P100, 47.2 MPa (the difference 25.11 MPa, i.e. 34.7%). Considering mixes with lime, it can be concluded that the differences in the obtained strength, when using natural and recycled

34.7%). Posmatrajuci mešavine s krečnjakom, može se zaključiti da su razlike u dostignutoj čvrstoći pri upotrebi prirodnog i recikliranog agregata relativno male, iznose 4.51 MPa (6.8%) i 6.38 MPa (9.6%) – poređenje etalona s mešavinama kod kojih je zamenjena jedna, odnosno obe krupne frakcije. Kod mešavina s pepelom razlika je 12.3 MPa (19.2%) i 16.8 MPa (26.2%). Veća razlika u čvrstoćama u okviru mešavina s pepelom može da se objasni neujednačenim kvalitetom recikliranog agregata, koji predstavlja glavni problem njegove primene. U grupi mešavina sa silikatnom prašinom, razlika između etalona i druge dve mešavine iznosila je 2.61 MPa (3.6%) i 7.81 MPa (10.8%). Najbrži priraštaj čvrstoće imale su mešavine sa silikatnom prašinom. Kod svih betonskih mešavina s rečnim agregatom zabeležen je lom po cementnoj pasti, dok je kod mešavina s recikliranim agregatom zabeležen lom po agregatu, bez obzira na vrstu mineralnog dodatka.

Razlike u rezultatima čvrstoće pri zatezanju savijanjem nisu velike. Vrednosti čvrstoće pri zatezanju u opsegu su od 7.97 MPa (P100) do 10.31 MPa (ES). Razlika između ovih vrednosti je 2.34 MPa (22.7%).

Dostupni podaci iz literature kao i lična prethodna istraživanja [2] pokazuju da je nezahvalno predviđati ili nalaziti neku zakonitost kada je skupljanje betona u pitanju. Obavljena merenja pokazuju da je najveće skupljanje imala betonska mešavina sa silikatnom prašinom i III recikliranom frakcijom, S50, a najmanje etalon s krečnjakom EK, pri čemu je razlika 56%. Ne može se izvući nikakva pravilnost u ovim rezultatima: mešavine sa III recikliranom frakcijom imale su veće skupljanje od mešavina sa II i III recikliranom frakcijom, pri čemu su razlike kod krečnjaka i silikatne prašine bile izraženije nego kod betona s pepelom. Ako se klasifikacija betona vrši prema mineralnom dodatku, najveće skupljanje imale su mešavine sa silikatnom prašinom; ukoliko je kriterijum agregat, među etalonima najveće skupljanje imao je etalon s pepelom (29% više od etalona s krečnjakom i 11.7% više od etalona sa silikatnom prašinom), među mešavinama sa III recikliranom frakcijom S50 (4.8% više od mešavina s krečnjakom i 22.8 % više od mešavina s pepelom), a među mešavinama sa II i III recikliranom frakcijom S100 (22.8% više od mešavina s krečnjakom i 13.2% više od mešavina s pepelom).

Upijanje vode kreće se u opsegu 0.85% (mešavina S50) do 2.12% (mešavina EP). Najveće upijanje vode imale su mešavine s pepelom, a najmanje mešavine sa silikatnom prašinom, što je potpuno u skladu sa ostvarenom strukturom betona, koja je, kako su SEM analize pokazale, bila najporoznija kod betonskih mešavina s pepelom. Prosečno upijanje vode kod mešavina sa silikatnom prašinom iznosilo je 0.9%, kod mešavina s mlevenim krečnjakom 1% , a kod mešavina s pepelom 2%.

Kod ispitivanja vodonepropustljivosti, prodor vode u beton s krečnjakom i silikatnom prašinom bio je veoma mali, oko 2 cm, tako da su ove mešavine praktično bile nepropustljive, dok je kod mešavina s pepelom zabeležen veći prodor vode, oko 10 cm, što je posledica povećane poroznosti ovih betona. Prema kriterijumu da prodor vode ne sme biti veći od 4 cm [4] betoni s letećim pepelom smatrali bi se propustljivim.

aggregate, are relatively small, 4.51 MPa (6.8%) and 6.38 MPa (9.6) – comparison of control concrete with mixes in which one or both coarse fractions are replaced. In mixes with fly ash, the difference is 12.3 MPa (19.2%) and 16.8 MPa (26.2%). Greater difference in strength among mixes with fly ash can be explained by the uneven quality of recycled aggregate, which represents a major problem of their application. In the group of mixes with silica fume, the difference between the control concrete mix and other two mixes was 2.61 MPa (3.6%) and 7.81 MPa (10.8%). The fastest increment of strength was found in mixes with silica fume. In all concrete mixes with natural aggregate, a failure was recorded through cement paste, while in mixes with recycled aggregate, the failure was found through aggregate, no matter which mineral additive was used.

Differences in the results of tensile strength by bending are not great. The values of strength by bending are in the range of 7.97 MPa (P100) to 10.31 MPa (ES). The difference between these values is 2.34 MPa (22.7).

Available data from the literature, like my own previous researches [2] show that it is difficult to predict or find regularities when shrinkage of concrete is in question. The measurements done show that the largest shrinkage was found in the concrete mix with silica fume and III recycled fraction, S50, and the smallest in the control concrete with lime EK, wherein the difference is 56%. No regularities can be drawn from these results: mixes with III recycled fraction had greater shrinkage than mixes with II and III recycled fraction, wherein differences in lime and silica fume were more pronounced than in concrete with fly ash. If classification of concrete is done according to the mineral additive, the largest shrinkage was found in mixes with silica fume; if the criterion is aggregate, the largest shrinkage among control concrete mixes, was found in the control concrete with fly ash (29% more than in the control concrete with lime and 11.7% more than in the control concrete with silica fume); among mixes with III recycled fraction S50 (4.8% more than in mixes with lime and 22.8% more than in mixes with fly ash), and among mixes with II and III recycled fraction S100 (22.8% more than in mixes with lime and 13.2% more than in mixes with fly ash).

Water absorption is in the range of 0.85% (mix S50) to 2.12% (mix EP). The highest water absorption was recorded in the mixes with fly ash, and the lowest in the mixes with silica fume, which is absolutely in accordance with the achieved concrete structure, which was, according to SEM analyses, the most porous in concrete mixes with fly ash. Average water absorption in mixes with silica fume was 0.9%, in mixes with lime 1%, and in mixes with fly ash 2%.

When testing water impermeability, the ingress of water into the concrete with lime and silica fume, was very small, about 2cm, so as these mixes were practically impermeable, while in the mixes with fly ash, larger ingress of water was noted, about 10cm, which is the consequence of the increasing porosity of these concretes and, according to the criterion, that penetration of water must not be larger than 4cm [4], concretes with fly ash can be considered permeable.

7 ZAKLJUČCI

Na osobine svežeg samougrađujućeg betona utiču i vrsta mineralnog dodatka i vrsta primenjenog agregata. Najbolja svojstva samougradljivosti postižu se upotrebom mlevenog krečnjaka. Ovi betoni su imali najbolju fluidnost, viskoznost, nakon prolaska kroz armaturu bili su potpuno horizontalni, ali se zbog najvećeg rasprostiranja kod njih javila najmanja otpornost na segregaciju. Mešavine s pepelom imale su najbolji odnos prečnika rasprostiranja (fluidnosti) i otpornosti na segregaciju. Zbog toga što su veoma sitne (oko 100 puta sitnije od zrna cementa ili pepela) s jako velikom površinom zrna (15000–20000 m²/kg), čestice silikatne prašine značajno povećavaju koheziju betona i nepovoljno utiču na samougradljivost svežeg betona. Mešavine sa silikatnom prašinom bile su teško pokretne, imale najmanje prečnike rasprostiranja, ali i najveću otpornost na segregaciju. Primena recikliranog agregata, zbog oštroičnog oblika zrna koji povećava trenje, takođe nepovoljno utiče na svojstva samougradljivosti betona, te je bilo neophodno intervenisati u smislu smanjenja III odnosno povećanja I frakcije za 5%, kako bi se postigla željena konzistencija.

Uticaj silikatne prašine na čvrstoću betona pri pritisku: silikatna prašina je pucolan i za njeno aktiviranje neophodno je prisustvo kalcijum-hidroksida. On nastaje u procesu hidratacije cementa tako da silikatna prašina može da se aktivira tek kada cement počne da reaguje. Kako beton počinje da vezuje i očvršćava, pucolanska aktivnost silikatne prašine postaje dominantna reakcija. Zbog veće specifične površine i višeg sadržaja silicijum-dioksida, silikatna prašina je mnogo reaktivnija od letećeg pepela. Ova pojačana reaktivnost prvobitno će znatno pojačati brzinu hidratacije C₃S frakcije cementa, ali se nakon dva dana proces normalizuje. Kako silikatna prašina reaguje i stvara hidrate kalcijum-silikata, šupljine i pore u betonu se popunjavaju, pri čemu nastali kristali povezuju prostor između čestica cementa i zrna agregata. Ako se ovom efektu doda i samo fizičko prisustvo silikatne prašine u mešavini, jasno je da će betonska matrica biti veoma homogena i gusta, a rezultat će biti poboljšana čvrstoća i nepropusnost, što se i jasno vidi na SEM slikama. Pored ovoga, zbog svoje veličine, čestice silikatne površine mogu da izazovu i „mikrofiler“ efekat, dodatno popunjavajuću tranzitnu zonu u betonu.

Uticaj letećeg pepela na čvrstoću betona pri pritisku: kada se leteći pepeo doda betonu, počinje pucolanska reakcija između silicijum-dioksida (SiO₂) i kalcijum-hidroksida (Ca(OH)₂) ili kreča, koji je nusprodukt hidratacije Portland cementa. Slaba pucolanska reakcija odvija se tokom prvih 24 sata na 20°C. Zbog toga se za datu količinu cementa, s povećanjem sadržaja letećeg pepela postižu niže rane čvrstoće. Prisustvo letećeg pepela usporava reakciju alita u okviru Portland cementa u ranom stadijumu. Međutim, produkcija alita kasnije se ubrzava zahvaljujući stvaranju jezgara hidratacije na površini čestica letećeg pepela. Kalcijum- hidroksid utiskuje se na površinu staklastih čestica, reagujući sa SiO₂ ili Al₂O₃-SiO₂ rešetkom. Sporiji priraštaj čvrstoće betona s letećim pepelom onemogućava njegovu primenu tamo gde se očekuju velike rane čvrstoće, što se može rešiti primenom akceleratora. Dostupna literatura zbog ovog razloga upućuje na projektovanje i

7 CONCLUSIONS

Properties of self-compacting concrete are affected both by a kind of mineral additive and a kind of the applied aggregate. Best properties of self-compacting are achieved by using lime. These concrete mixes had the best fluidity and viscosity, after passing through reinforcement they were absolutely horizontal, but because of the largest spreading, they had minimum segregation resistance. Mixes with fly ash had the best ratio of diameter of spreading (fluidity) and segregation resistance. Since they are very small (about 100 times smaller than cement or ash grains), and have very large area of grain (15 000 to 20 000 m²/kg), particles of silica fume significantly increase concrete cohesion and adversely affect the fresh concrete self-compacting. Use of recycled aggregates, due to a sharp-edged shape of grains which increases adhesion, also adversely affects the properties of self-compacting concrete, so it was necessary to intervene in the sense of reducing III or increasing I fraction by 5%, in order to achieve the desired consistency.

Effect of silica fume on the compressive strength of concrete: silica fume is pozzolan which is activated by calcium hydroxide. Calcium hydroxide is formed in the process of cement hydration so that silica fume can be activated only when cement begins to react. As concrete starts to bind and harden, pozzolanic activity of silica fume becomes the dominant reaction. Due to the high specific area and higher content of silicon dioxide, silica fume is much more reactive than fly ash. This increased reactivity will initially significantly intensify hydration rate of C₃S cement fraction, but after two days the process becomes normal. As silica fume reacts and forms calcium silicate hydrates, voids and pores in the concrete are filled, wherein crystals formed connect the space between cement particles and aggregate grains. If this effect is added by the physical presence of silica fume in the mix, it is clear that the concrete matrix will be very homogenous and dense, resulting in improved strength and impermeability, which is clearly seen in SEM pictures. Besides, owing to their size, silica fume particles can cause "micro filler" effect, additionally filling transit zone of concrete.

Effect of fly ash on the compressive strength of concrete: when fly ash is added to concrete, there is pozzolanic reaction between the silicon dioxide (SiO₂) and calcium hydroxide (Ca(OH)₂) or lime, which is a by-product of hydration of Portland cement. Weak pozzolanic reaction occurs during the first 24 hours at a temperature of 20°C. That is why, for a given amount of cement, with increasing fly ash content, lower early compressive strength is achieved. The presence of fly ash slows the reaction of alite in Portland cement at an early stage. Meanwhile, production of alite later accelerates thanks to the creation of cores of hydration on the surface of fly ash particles. Calcium hydroxide is pressed in the surface of the glassy particles, reacting with SiO₂ or Al₂O₃-SiO₂ grid. Slower early strengths of concrete with fly ash prevent its application where high early strength is expected, which can be solved by using accelerator. Therefore, the available literature refers to the design and monitoring of the 90 day compressive strength of concrete. SEM analyses evidently show extremely spongy, i.e. porous structure of the concrete

praćenje 90-dnevne čvrstoće betona. SEM analize jasno pokazuju izuzetno sunderastu, tj. poroznu strukturu betona s letećim pepelom bez obzira na vrstu primenjenog agregata.

Uticaj mlevenog krečnjaka na čvrstoću betona pri pritisku: SEM analize ukazuju na postojanje čestica krečnjaka u betonu i nakon 28 dana, a s druge strane, priraštaj dvodnevne čvrstoće potvrđuje da ove čestice predstavljaju jezgro za hidrataciju C_3S i C_2S , te tako ubrzavaju reakcije hidratacije, što ide u prilog tezi da je mleveni krečnjak hemijski inertan.

Razlike u čvrstoći pri pritisku između betona sa silikatnom prašinom i krečnjakom ne prelaze 10% pri istoj količini cementa, pri čemu je beton s krečnjakom imao bolje performanse u svežem stanju, što treba imati u vidu, posebno ako se uključiti i ekonomski faktor.

Razlike u čvrstoći pri pritisku između betona s pepelom i betona sa silikatnom prašinom kreću se od 13% (kod etalona) do 37% kod betona s krupnim recikliranim agregatom, pri čemu betoni s pepelom imaju veću ekološku vrednost, jer rešavaju problem deponovanja ogromnih količina letećeg pepela.

Rezultati ispitivanja čvrstoće pri zatezanju savijanjem ujednačeni su i pokazuju da vrsta mineralnog dodatka i agregata ne utiče na vrednost ove čvrstoće.

Skupljanje u cementnoj pasti povećano je kada se koristi silikatna prašina, o čemu treba posebno voditi računa, što je u skladu s dostupnim literaturnim podacima. Ne može se utvrditi zakonitost skupljanja, niti izvesti neki uopšten zaključak, već se skupljanje kod svakog od ovih betona mora posebno i pažljivo pratiti.

Najmanje upijanje vode zabeleženo je kod betonskih mešavina sa silikatnom prašinom, a najveće kod betona s pepelom. Ipak, ova razlika nije previše velika (oko 1%) s obzirom na sunderastu građu betona s pepelom, što se može objasniti manjim sadržajem otvorenih pora veličine 1–10 μm , kroz koje je najbrži transport vode, a što je opet u vezi s pucolanskom aktivnošću letećeg pepela da učestvuje u C-S-H formacijama i popunjava pore.

Svi betoni su imali dobru vodonepropustljivost osim mešavina s letećim pepelom, što je u skladu sa ostvarenom mikrostrukturom.

Velika eksploatacija prirodnog agregata ozbiljno je ugrozila rečne ekosisteme, tako da je na nekim mestima i zabranjena. Pored ovoga, sve veća udaljenost prirodnih nalazišta od mesta gradnje svakako utiče na cenu materijala. S druge strane, u urbanim sredinama postoje znatne količine betonskog otpada koji nastaje prilikom izgradnje ili rušenja starih objekata, te je izražen problem deponovanja ovakvog materijala. Razvijene, ekološki svesne zemlje, mnogo polažu na recikliranje sirovina i za odlaganje na deponije (koje oduzimaju korisno zemljište) naplaćuju novčane kazne. Drobljenjem betonskog otpada dobija se reciklirani agregat koji se može „vratiti“ u proizvodnju.

Glavni problem primene recikliranog agregata jeste povećana poroznost koja je posledica postojanja zaostale stare cementne paste na zrnima agregata. Postojanje stare cementne paste osnovni je uzročnik neujednačenosti kvaliteta agregata i dovodi do smanjenja čvrstoće pri pritisku betona. Postoje postupci „čišćenja“ agregata koji poskupljuju beton, ali treba imati u vidu ekološku korist njegove upotrebe.

with fly ash, no matter which aggregate is used.

The effect of lime on the compressive strength of concrete: SEM analyses show the presence of lime particles in concrete even after 28 days, and on the other hand, two day increment of strength confirms that these particles constitute the core for hydration C_3S and C_2S , so that they accelerate the reactions of hydration, which supports the thesis that lime is chemically inert.

Differences in compressive strength between concrete with silica fume and concrete with lime do not exceed 10% at the same quantities of cement, wherein concrete with lime had better performances in the fresh state, what should be borne in mind, particularly if the economic factor is included.

Differences in compressive strength between concrete with fly ash and concrete with silica fume are from 13% (in control concrete) to 37% in concrete with coarse recycled aggregate, wherein concrete mixes with fly ash have greater ecological value, because they solve the problem of depositing huge quantities of fly ash.

The test results of tensile strength by bending are uniform and show that type of mineral additive and aggregate fails to affect the value of this strength.

Shrinkage in the cement paste is increased when silica fume is used, which has to be taken into account, and it is in accordance with the data available from the literature. It is impossible to determine the legality of shrinkage or draw a general conclusion about it, but shrinkage of each of the concrete must be specifically and carefully monitored.

The lowest water absorption was recorded in concrete mixes with silica fume and the highest in mixes with fly ash. However, this difference is not too great (about 1%), due to the sponge-like composition of concrete with ash, which can be explained by the lower content of open pores of size 1 – 10 μm through which water transport is the fastest, and which is again related to the pozzolanic activity of fly ash to participate in C-S-H formations and to fill pores.

All concrete mixes had good water impermeability except mixes with fly ash, which is in accordance with the achieved microstructure.

Great exploitation of natural aggregates has seriously endangered river ecosystems, so that it is in some places forbidden. Besides, long distances of natural deposits from building sites surely affect the price of materials. On the other hand, in urban areas, there are significant amounts of concrete waste generated during construction or demolition of old buildings, so there is a problem of depositing such material. Developed, ecologically conscious countries, invest a lot in the recycling of raw materials and they charge penalties for the waste disposal at landfills (that take away useful land). When crushing concrete waste, recycled aggregate is obtained and it can be "returned" to production.

The main problem of using recycled aggregate is its increased porosity, caused by the remained old cement paste on aggregate grains. This is the main reason for uneven quality of aggregates and it causes a decrease in the compressive strength of concrete. There are "cleaning" procedures that raise the price of concrete, but the environmental benefits should be borne in mind.

While designing concrete mixes, it is of great use to

Prilikom projektovanja betonskih mešavina, veoma je korisno poznavati poreklo recikliranog agregata - što je prvobitni beton bio kvalitetniji, to će i novospavljeni imati bolje karakteristike. Poželjno je i da agregat bude spravljen od betona iste marke, kako bi mu kvalitet bio što je moguće ujednačeniji.

Količina upotrebljenog recikliranog agregata ne utiče značajnije na vrednosti čvrstoće pri zatezanju savijanjem.

Količina recikliranog agregata utiče na upijanje vode tako što s povećanjem količine recikliranog agregata raste i procenat upijanja vode kao posledica veće poroznosti.

Samougrađujući betoni s recikliranim agregatom mogu biti vodonepropustljivi. Na ovu osobinu utiču kapilarna poroznost starog cementnog kamena zaostalog na agregatu, kao i kapilarna poroznost cementnog kamena novog betona. Ukoliko je agregat dobijen drobljenjem betona male poroznosti, vodonepropustljivost novog betona zavisice od ostvarene strukture novog cementnog kamena.

Primenom sva tri ispitivana mineralna dodatka mogu se dobiti samougrađujući betoni visokih performansi. U tome prednjači silikatna prašina, ali ako se ima u vidu ekonomska i ekološka komponenta elektrofilterskog pepela, kao i relativno mala razlika u dobijenim rezultatima, pepeo neizostavno treba uzeti u obzir. Uz to, upotreba recikliranog agregata (uz pojačana ispitivanja) čini da ovakvi betoni s pravom ponesu naziv ekološki. Nedovoljna istraženost ovog područja otvara širok spektar mogućnosti za dalja ispitivanja u smislu varijacije količine cementa, kombinovanja različitih dodataka i sličnog.

ZAHVALNOST

U radu je prikazan deo istraživanja koje je pomoglo Ministarstvo za nauku i tehnološki razvoj Republike Srbije, u okviru tehnološkog projekta TR 36017 pod nazivom: Istraživanje mogućnosti primene otpadnih i recikliranih materijala u betonskim kompozitima, sa ocenom uticaja na životnu sredinu, u cilju promocije održivog građevinarstva u Srbiji.

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know the origin of a recycled aggregate – the more qualitative the original concrete was, the better characteristics the newly made concrete have. It is preferable that the aggregate is made of concrete of the same brand so that its quality will be as uniform as possible.

The values of tensile strength by bending are insignificantly affected by the amount of the recycled aggregate used.

The amount of recycled aggregate affects the absorption of water in the sense that with increasing the amounts of recycled aggregates, the percentage of water absorption is also increased, as a consequence of greater porosity.

Self-compacting concretes with recycled aggregates can be water impermeable. This property can be affected both by capillary porosity of the old cement stone remained on the aggregate, and capillary porosity of the cement stone of the new concrete. If the aggregate is obtained by crushing concrete of low porosity, water impermeability of the new concrete will depend on the achieved structure of the new cement stone.

Using all three tested mineral additives, high performance self-compacting concretes can be obtained. Silica fume is ahead, but having in mind economic and ecological component of fly ash, as well as relatively small difference in the obtained results, fly ash should necessarily be taken into account. Besides, the use of recycled aggregates (with increased testing) makes these concretes ecological rightly considered. Insufficient research in this area opens up a wide range of options for further testing, in terms of variations in the amount of cement, combining different additives, etc.

ACKNOWLEDGEMENTS

The work reported in this paper is a part of the investigation within the research project TR 36017 "Utilization of by-products and recycled waste materials in concrete composites in the scope of sustainable construction development in Serbia: investigation and environmental assessment of possible applications", supported by the Ministry for Science and Technology, Republic of Serbia. This support is gratefully acknowledged.

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REZIME

SVOJSTVA SAMOUGRAĐUJUĆEG BETONA SPRAVLJENOG S RECIKLIRANIM AGREGATOM I RAZLIČITIM MINERALNIM DODACIMA

Iva DESPOTOVIĆ

Po svojoj tehnologiji, samougrađujući beton nakon unošenja u oplatu ne zahteva vibriranje. Ugrađivanje ovog betona u svakom delu, ili u svakom uglu oplate, uključujući i njene teško pristupne delove, ostvaruje se bez ikakvih spoljnih sila, osim sile gravitacije, tj. njegove sopstvene težine. Ovakva svojstva postižu se dodavanjem betonu hemijskih dodataka superplastifikatora, najčešće u kombinaciji s novom vrstom aditiva za modifikaciju viskoziteta i/ili primenom određene količine finog mineralnog dodatka - praha. Moguće je koristiti različite mineralne dodatke, pri čemu upotreba onih koji predstavljaju industrijski nusprodukt (poput letećeg pepela) ima višestruke ekološke koristi.

Nedostatak prirodnog agregata u urbanim sredinama i sve veće rastojanje između nalazišta kvalitetnog prirodnog agregata i gradilišta, prisilili su graditelje da razmotre mogućnosti zamene prirodnog agregata recikliranim materijalima (građevinska keramika, zgura, beton i tako dalje). S druge strane, u urbanim sredinama često se javlja velika količina betonskog otpada čije uklanjanje i deponovanje predstavlja ekološki problem.

Predmet ovog rada je analiza svojstava i tehnologije samougrađujućeg betona s različitim mineralnim dodacima (mlevenim krečnjakom, letećim pepelom i silikatnom prašinom), prirodnim i recikliranim agregatom, pri čemu su pravljene mešavine bez recikliranog agregata, s trećom recikliranom frakcijom i s drugom i trećom recikliranom frakcijom.

Ključne reči: samougrađujući beton, mleveni krečnjak, leteći pepeo, silikatna prašina, reciklirani agregat, ekološki aspekt

SUMMARY

PROPERTIES OF SELF-COMPACTING CONCRETE MADE OF RECYCLED AGGREGATES AND VARIOUS MINERAL ADDITIVES

Iva DESPOTOVIC

By its technology, Self-Compacting Concrete does not need compaction by vibration. Compaction of this concrete, in every part, or in every corner of the formwork, including its hardly available parts, is done without any external forces except its own weight. These properties are achieved by adding superplasticizers, commonly with new Viscosity Modification Admixtures, or/and determined amount of powders. It is possible to use different mineral additions, where the use of those which are industrial by-products (like fly ash) has multiple environmental benefits.

Lack of natural aggregate in urban areas and increasing distance between deposits of high-quality natural aggregate and building sites, forced building contractors to analyze possibility of replacing of natural aggregate with recycled materials (masonry, slag, concrete, etc.). On the other hand, huge amount of old concrete exists in urban areas and its removal and deposition is a big ecological problem.

Aim of this paper is analysis of properties and technology of Self-Compacting Concrete with different mineral additions (lime, fly ash and silica fume), natural and recycled aggregate, considering mixes without recycled aggregate, with third recycled fraction, and with second and third recycled fractions.

Key words: Self-Compacting Concrete, lime, fly ash, silica fume, recycled aggregate, ecological aspect