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DRUŠTVO GRAĐEVINSKIH INŽENJERA NOVOG SADA

Iva DESPOTOVIĆ[1]

UTICAJ RAZLIČITIH MINERALNIH DODATAKA NA SVOJSTVA SAMOUGRAĐUJUĆEG BETONA

INFLUENCE OF DIFFERENT MINERAL ADDITIONS ON THE PROPERTIES OF SELF-COMPACTING CONCRETE

Rezime: *Razvijen tokom poslednje decenije dvadesetog veka u Japanu, samougrađujući beton se danas primenjuje u čitavom svetu. Po svojoj prirodi samougrađujući beton (Self-Compacting Concrete-SCC) je takav beton koji nakon unošenja u oplatu ne zahteva vibriranje. Ugrađivanje ovog betona se u svakom delu, ili u svakom uglu oplate, uključujući i njene teško pristupne delove, ostvaruje bez ikakvih spoljnih sila, osim sile gravitacije, tj. njegove sopstvene težine. Ovakva svojstva se postižu dodavanjem betonu hemijskih dodataka superplastifikatora, najčešće u kombinaciji sa 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 nus – produkt (poput letećeg pepela) ima višestruke ekološke koristi.*

Koncept održivog razvoja, koji pored socioloških i ekonomskih aspekata, obuhvata uštedu energije, zaštitu okoline i očuvanje neobnovljivih prirodnih resursa, nameće upotrebu recikliranog agregata kao rešenje dva značajna problema u građevinarstvu. Sa jedne strane postoji nedostatak prirodnog agregata u urbanim sredinama i sve veće rastojanje između nalazišta kvalitetnog prirodnog agregata i gradilišta, a sa druge strane, problem uklanjanja i deponovanja velikih količina betonskog otpada.

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

Ključne reči: *samougrađujući beton, mleveni krečnjak, leteći pepeo, silikatna prašina, reciklirani agregat.*

Abstract: *Developed during the last decade of the twentieth century in Japan, Self-Compacting Concrete-SCC is nowadays applied everywhere. Self-Compacting Concrete-SCC, by its nature, does not require concrete vibration after the pouring into the formwork.*

Placing of concrete in each section, i.e. in any corner of the formwork, including its difficult access areas, could be achieved without any external forces, apart from the gravitational force, i.e. its own weight.

These kinds of properties are obtained by the addition of chemical additions called super plasticizer into concrete, usually in combination with a new type of viscosity modifying admixture and / or by applying a certain amount of the fine mineral addition - powder. It is possible to use different mineral additions, with particular emphasis on usage of industrial by - product (such as fly ash), which has multiple environmental benefits.

The concept of sustainable development, which besides social and economic aspects includes energy-saving, environmental protection and the conservation of exhaustible natural resources, impose the use of recycled aggregates as a solution of two significant problems in the in civil engineering. There is a lack of natural aggregates in urban areas and increasing of the distance between the sources of natural aggregates and construction sites, as well as the problem of removal and disposal of large quantities of concrete waste.

The subject of this study is the analysis of the properties and technology of Self-Compacting Concrete-SCC with different mineral additions (lime, fly ash and silica fume), as well as with natural and recycled aggregate, represented by three-sized aggregate fracture mixtures without recycled aggregate, with third recycled fraction and also with second and the third fraction.

Key word: *Self-Compacting Concrete-SCC, lime, fly ash, silica fume and recycled aggregate.*

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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 je dostigla 10 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 CO_2, odgovornih za efekat staklene bašte. Ovi gasovi nastaju u toku miniranja stena i tokom transporta agregata do obično udaljenih gradskih sredina.

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

Jedno od rešenja navedenih problema je 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 se najviše koristi u putarstvu, za različite ispune i izradu nekonstruktivnih elemenata (ivičnjaka, ograda i sl.). Zbog neujednačenog kvaliteta, mogućnosti ostatka različitih primesa prilikom reciklaže, većeg upijanja vode i niže zapreminske mase u odnosu na prirodni agregat, reciklirani agregat zahteva niz ispitivanja i posebnu tehnologiju spravljanja betona.

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

2. SAMOUGRAĐUJUĆI BETON

Samougrađujući beton (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 oplate 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,

1. INTRODUCTION

The construction industry uses vast amounts of natural resources, simultaneously producing significant amounts of debris, which has a large impact on the environment. Annual production of concrete in the world has reached 10 billion tons, which classifying it as the most widely used construction material. Regards to the fact that about 70% of concrete is actually an aggregate, it is clear the how much of the quantities of natural and crushed aggregates is required. The uncontrolled exploitation of aggregates from rivers seriously disrupts aquatic ecosystems and habitats, while production of crushed natural aggregates increases emission of harmful gases, primarily CO_2, responsible for the greenhouse effect. These gases are produced during rock mining and also transportation of aggregates to the usually distant urban areas.

On the other hand, the amount of construction waste generated during construction and demolition process is growing rapidly, deepening problem of waste disposal, which is usually resolves by established (which are occupying large areas and waste disposal is expensive) or "wild" - illegal dumps.

One of the solutions of mentioned problems is recycling of deposited building, primarily concrete. This idea is not novelty for developed countries such as Japan, Netherlands, Belgium and Denmark, which achieve a high percentage of construction waste recycling. Recycled concrete aggregate is mainly used in road engineering, for fillings and making of unconstructive elements (curbs, fences, etc.). Recycled aggregate requires a series of tests and special technology of making concrete, by reason of: difference in quality, possibility of the rest of the various ingredients during recycling, increasing of water absorption and lower density compared to natural aggregate.

Self-Compacting Concrete-SCC, also an innovation in the field of concrete technology, contains a certain amount of powder material - filler. There are different possibilities of choosing these components. In case of use some of the industrial by - products, such as fly ash or silica fume, the problem of depositing these materials would be solved, and that type of concrete could be certainly named eco-friendly.

2. SELF-COMPACTING CONCRETE

Self-Compacting Concrete - SCC, according to many authors, as "the most revolutionary discovery in concrete industry of the twentieth century", does not require concrete vibration during placing and compacting. Under the effect of its own weight, concrete fully meets all parts of the formwork, even in case of dense reinforcement. Its benefits are: faster construction process, resmanjenje buke, odsustvo vibracija, i samim tim, zdravije radno okruženje.

Procena je da se prilikom upotrebe samougrađujućeg betona umesto vibriranog potrebe za radnom snagom smanjuju 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 su veća cena materijala, stroži zahtevi kvaliteta i veći pritisak na oplatu u odnosu na vibrirani beton [1].

Početak razvoja ovih betona se vezuje za Japan osamdesetih godina prošlog veka, mada podaci dostupni u svetskoj literaturi ukazuju da su „samoravnjajući" (self-levelling) betoni bez sklonosti ka segregaciji proučavani još 1975-76. godine u Italiji. Tvorac samougrađujućeg betona je profesor Hajime Okamura sa Univerziteta u Tokiju, a razvojnu studiju su, zajedno sa njim uradili Ozawa i Maekawa sa istog univerziteta. Prototip SCC-a je urađen 1988.g. od materijala kojih je tada bilo na tržištu, i po svojim osobinama kako u svežem, tako i u očvrslom stanju se izuzetno dobro pokazao. Zahvaljujući radu RILEMA (Međunarodno udruženje laboratorija i eksperata za materijale i konstrukcije) SCC je stigao u Evropu. Uvidevši potencijal samougrađujućeg betona RILEM je osnovao 1996.g. Tehnički Komitet za ispitivanje SCC-a. Članovi iz deset zemalja (4 kontinenta) su prionuli na posao koristeći japanske ideje, istraživanja i prve primene kao polaznu tačku. Iako su održani brojni međunarodni i nacionalni skupovi, koji su rezultovali različitim vodičima i preporukama, sve do 2007, samougrađujući beton nije pomenut ni u jednom CEN (The European Committee for Standardization) standardu, i upravo je nedostatak standarda otežao njegovu veću praktičnu implementaciju jer je učesnicima u gradnji bilo teško da se dogovore o kriterijumima kvaliteta prilikom proizvodnje i načinu kontrole na gradilištu. Najznačajniji vodič za samougrađujući beton su EFNARC – ove (Evropska Federacija Proizvođača Građevinske Hemije i Betonskih Sistema) preporuke iz 2002. godine „Specifikacija i vodič za samougrađujući beton", koje će postati osnov za donošenje evropskih normi EN 206-9 i EN 12350. Rad na implementaciji vodiča za samougrađujući beton u Evropsku normu EN 206 je trajao godinama. U tu svrhu je CEN formirao tehnički komitet TC 104/SC1/TG 16 „Odredbe za samougrađujući beton" koji je predložio nacrt standarda EN 206 – 9 (2007) : Beton, deo 9: Dopunska pravila za samougrađujući beton, zajedno sa serijom standarda EN 12350 : Ispitivanje svežeg betona. Svi ovi standardi su usvojeni 2010., 22 godine nakon što je napravljen prvi samougrađujući beton. Standarde koji se odnose na ispitivanje svežeg betona je Srbija usvojila 2012., a na ocenu ispitivanja 2014.g. – sve na engleskom jeziku, u

duction of the required workers, better final surfaces, easier placing, improved durability, bigger possibility for shaping of elements, noise reduction, absence of vibration, and thereby, healthier work environment.

It is estimated that in the usage of self-compacting concrete instead of vibrated decreased labor requirements for about 10%; in the application of precast construction elements, building time is shorter by about 5%, and the demand for workers decreased by about 20%; in the application of sandwich elements (steel - concrete) time saving is 20%, and labor requirements 50%. The main disadvantages of the self-compacting concrete usage are higher prices of material, stringent quality requirements and increasing pressure on the formwork in relation to vibrated concrete [1].

The early development of this type of concrete is linked to Japan during the '80 of the twentieth century, although the data available in the world literature suggests that "self-leveling" concrete without segregation tendency are already studied since 1975-76 in Italy. Creator of self-compacting concrete is Professor Hajime Okamura from the University of Tokyo, who developed study, together with Ozawa and Maekawa from the same university. Prototype SCC was made in 1988 of material which were possible to be obtained on the market, and its characteristics, both in fresh and in the hardened state, were very well proved. Thanks to the work of RILEM (International Association of Laboratories and Experts in materials and structures) SCC has arrived in Europe.

Realizing the potential of Self-Compacting Concrete RILEM was founded in 1996 Technical Committee for testing SCC. Members from ten countries (4 continents) went to work using Japanese ideas, research, and the first application as a starting point. Although numerous international and national conferences were held, which have resulted in a variety of guides and recommendations, Self-Compacting Concrete was not mentioned in any of the CEN (the European Committee for Standardization) standard until 2007, and it was the lack of standards that has impeded its greater practical implementation. It was difficult for participants in the construction to reach an agreement on the criteria of quality during production and method of control on the construction site. The most important guide for Self-Compacting Concrete is EFNARC - the (European Federation of National Associations Representing producers and applicators of specialist building products for Concrete) recommendations from year 2002 "Specifications and instructions for Self-Compacting Concrete", which will become the basis for the establishment of the European standard EN 206-9 and EN 12350. Work on the implementation guide for Self-Compacting Concrete to the European norm EN 206 lasted for years. For this purpose, CEN formed a technical committee TC svom izvornom obliku [2].

2.1. Konstitutivni materijali i svojstva samougrađujućeg betona

Kod samougrađujućeg betona su najvažnije 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 ispuni 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). Ključne karakteristike svežeg SCC-a su: sposobnost tečenja, viskoznost (izražena brzinom tečenja), sposobnost prolaza između armaturnih šipki i otpornost na segregaciju [3]. 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.

Iako su osnovne komponente mešavina iste, razlikuju se odnosi mešanja, a 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. Svetska iskustva neosporno dokazuju da postoji mala razlika između svojstava očvrslog samougrađujućeg i vibriranog betona slične mešavine i istog vodocementnog faktora; pri čemu su neke osobine, poput prianjanja za armaturu ili vodonepropustljivosti, poboljšane kod SCC – a, što je posledica generalno bolje mikrostrukture.

U sastav samougrađujućeg betona ulaze:

- Cement - svi cementi u skladu sa EN 197-1 mogu da se koriste za SCC. Pravilan izbor tipa cementa je diktiran specifičnostima praktične upotrebe samougrađujućeg betona i samo od toga zavisi.
- Dodaci koji se često koriste u cilju postizanja potrebne kohezije i otpornosti na segregaciju se svrstavaju u dve grupe: prvu čine inertni ili poluinertni dodaci, dok su u drugoj pucolani i hidraulični dodaci (tabela 1).

Klasifikacija dodataka je izvršena prema njihovoj reaktivnosti sa vodom.

Mineralni filer (slika 1), svojim granulometrijskim sastavom, oblikom i upijanjem vode utiče na potrebnu količinu vode u betonu, što ga čini pogodnim za primenu kod samougrađujućeg betona. Najviše se koristi filer na bazi kalcijum karbonata (krečno brašno) koji obezbeđuje odlične reološke osobine i dobre finalne površine. Najveću prednost ima frakcija sitnija od 0.125 mm, pri čemu je poželjno da više od 70% prođe kroz sito 0.063 mm.

Leteći pepeo (slika 2) se pokazao kao koristan dodatak SCC-u obezbeđujući povećanje kohezije i manju osetljivost na promene sadržaja vode.

104 / SC1 / TG 16 "Provisions for Self-Compacting Concrete " which proposed draft standard EN 206 - 9 (2007): Concrete, Part 9: Additional rules for Self-Compacting Concrete, together with a series of standards EN 12350: Testing of fresh concrete. All these standards are established in 2010; 22 years after first Self-Compacting Concrete was made. Standards related to the testing of fresh concrete are adopted by Serbia in 2012 and in 2014 the assessment tests - all in English, in its original form [2].

2.1. Building materials and Self-Compacting Concrete properties

The most important characteristics for Self-Compacting Concrete are related to its fresh state. In designing of a concrete mixture, the emphasis on the ability of concrete to be spread out only under the effect of its own weight and to fully comply with formwork of any shape or dimension, without leaving voids, that pass through dense reinforcement without blocking, to maintain a homogeneous structure without separation of aggregates from paste or water from the solid phase, as well as to avoid coarse aggregate to segregate. Key characteristics of fresh SCC are: flowability, viscosity (measured by flow rate), the passing ability of the between the reinforcing bars and segregation resistance [3]. The concrete mixture would be classified as SCC only if all the above mentioned properties are fully implemented, whereby each of them can be tested in several ways.

Although the main components of a concrete mixture are the same, the difference is in mixing ratios, because SCC contains more of fine aggregate and particles, as well as admixture of the latest generation (viscosity modifiers and high water reduction capability) related to the vibrated concrete. World experience undeniably has proved that there is little difference between the properties of hardened Self-Compacting Concrete and vibrated one of the similar mixture and (the same) water-cement ratio; some properties, such as adhesion to the reinforcement or water impermeability, are enhanced with SCC - and, which is a consequence of the generally better microstructure.

The composition of Self-Compacting Concrete includes the following:

- Cement - all kinds of cement in accordance with EN 197-1 could be used for SCC. The correct/proper choice of the cement type is determine by the specifics of the practical use of Self-Compacting Concrete and only depends on it.
- Additions, which are often used in order to achieve the necessary cohesion and segregation resistance, are classified into two groups: the first group consists of inert or half-inert additions, and the other of pozzolana and hydraulic additions (Table 1). Classification of additions is based on their reactivity with water.

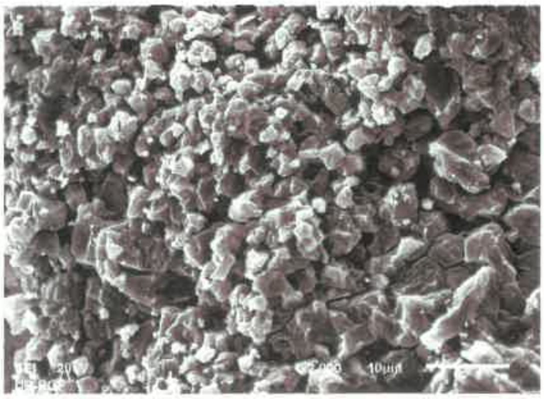
Tabela 1. Vrste dodataka
Table 1. Additions

Tip I / Type I	inertni ili poluinertni / inert or semi-inert	mineralni filer: krečno ili dolomitsko brašno / mineral filer: lime,dolomite; pigmenti / pigments)
Tip II / Type II	pucolani / pozzolanic	leteći pepeo prema EN 450 / fly ash conforming to EN450 silikatna prašina prema EN 13263 / silica fume conforming to EN 13263
	hidraulični / hydraulic	granulisana zgura visokih peći / ground granulated furnace slag

Međutim, visok sadržaj letećeg pepela može da stvori pastu toliko kohezivnu da uopšte ne može da teče pod dejstvom sopstvene težine što je u suprotnosti sa zahtevima za SCC. Čestice su sfernog oblika i doprinose fluidnosti betona optimizujući upakovanost.

Silikatna prašina - visok nivo prašinastih čestica i njihov praktično sferičan oblik kao rezultat daju dobru koheziju i povećanje otpornosti na segregaciju betona. Ipak, silikatna prašina redukuje ili eliminiše izdvajanje vode što može da izazove ubrzano površinsko očvršćavanje i pravi probleme ako ima prekida isporuke betona, otežavajući, pri tom, finiširanje površina.

Mlevena granulisana zgura visokih peći sadrži reaktivne prašinaste čestice niske toplote hidratacije. Ona je već prisutna u nekim cementima iz grupa CEM II ili CEM III, ali se takođe u pojedinim zemljama posebno dodaje u mikser. Visok udeo u betonskoj mešavini može da utiče negativno na njenu stabilnost u smislu da smanjuje čvrstoću i stvara probleme u kontroli konzistencije, dok sporije vezivanje povećava rizik od segregacije.



Slika 1. SEM slika mlevenog krečnjaka
Figure 1. SEM picture of the lime

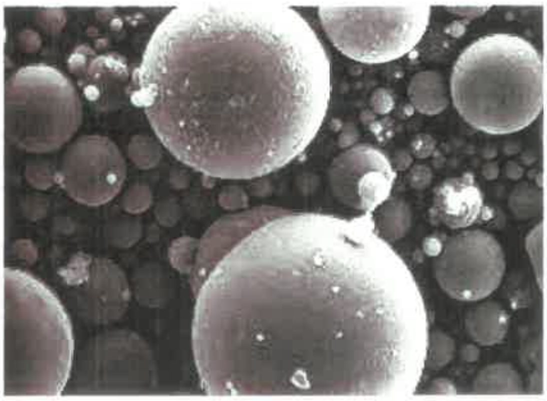
Agregat normalne težine treba da zadovolji EN 12620 i zahteve trajnosti po EN 206-1. Laki agregat treba da ispuni EN 13055-1. Agregat sitniji od 0,125 doprinosi sadržaju praškastih supstanci u SCC-u.

Sadržaj vlage, upijanje vode, granulacija i variranja prašinastih čestica u agregatu mora da se pažljivo i kontinuirano prate da bi se proizvodio samougrađujući beton konstantnog kvaliteta. Oblik i granulometrijski sastav agregata su veoma bitni i utiču na pakovanje zrna i sadržaj pora.

Mineral filler (Figure 1), with its grading size, shape and water absorption affects the required amount of water in the concrete, making it suitable for use in Self-Compacting Concrete. Most used filler based on calcium carbonate (lime flour), which provides excellent rheological properties and a good final surfaces.

Fly ash (Figure 2) proved to be a useful addition to SCC, ensuring increasing of cohesion and lower sensitivity to changes in water content. However, the high content of fly ash can create very cohesive paste, unable to flow under the effect of its own weight, which is inconsistent with the requirements of SCC. Fly ash particles are spherical in shape and contribute concrete fluidity by optimizing the placement of particles.

Silica fume - high levels of powder and their nearly spherical shape result in a good cohesion and also increase of resistance to segregation of concrete. However, silica fume reduces or eliminates separation of water which could lead to rapid surface hardening. That could cause problems in case of interruption of concrete supply, which could complicate surface finishing.



Slika 2. SEM slika letećeg pepela
Figure 2. SEM picture of the fly ash

Ground granulated furnace slag contains reactive powder of low heat of hydration. It is already included in some of the cements groups such as CEM II or CEM III, but in some countries can be add into the mixer separately. A high proportion of ground granulated furnace slag in the concrete mixture can negatively affect its stability, by reducing the strength and creates problems in flow control, while slow binding increases the risk of segregation.

Aditivi – superplastifikatori ili reduktori vode visokog ranga su suštinski važne komponente SCC-a. Modifikatori viskoziteta se takođe koriste da bi se smanjila segregacija i osetljivost mešavine na promenljivost ostalih konstituenata, posebno sadržaja vlage. Drugi aditivi kao što su aeranti, ubrzivači ili retarderi mogu da se koriste na isti način kao i u vibriranom betonu, s tim što treba da postoje preporuke proizvođača o upotrebi u skladu sa EN 934-2. Izbor aditiva za optimalne performanse betona je uslovljen njegovim fizičkim i hemijskim osobinama.

Vlakna – u dosadašnjoj praksi korišćena su i čelična i polimerna vlakna kod samougrađujućeg betona, mada ona smanjuju sposobnost tečenja i sposobnost prolaza koroz armaturu. Stoga su neophodne prethodne probe da bi se odredili optimalni tip, dužina i količina za postizanje željenih osobina kako svežeg, tako i očvrslog betona. Polimerna vlakna mogu da poboljšaju stabilnost betonske mešavine u smislu da sprečavaju sleganje i pojavu prslina usled plastičnog skupljanja betona. Čelična ili duga polimerna vlakna se koriste za modifikaciju žilavosti očvrslog betona. Njihova dužina i broj se određuju prema maksimalnom zrnu agregata i strukturnim zahtevima.

2.2. Metode ispitivanja samougrađujućeg betona

Razvijeno je više različitih metoda ispitivanja konzistencije SCC-a, najčešće korišćene su navedene u tabeli 2 [4].

Ispitivanje samougrađujućeg betona u svežem stanju je propisano Evropskom normom EN 12350. Pri tom su definisani testovi za određivanje fluidnosti: Slump – flow test, viskoznosti: t500 ili V-funnel test, sposobnosti prolaza kroz armaturu: L-box ili J-ring test, otpornosti na segregaciju: Sieve segregation resistance test. Treba naglasiti da se i sve druge (u standardu nazvane alternativnim metodama) mogu koristiti ukoliko su u saglasnosti sa normom EN 206-1:2000.

Prema evropskoj normi EN 206-9 klasifikacija samougrađujućeg betona se obavlja na sledeći način (tabela 3).

Aggregate of normal weight should meet the requirements of EN 12620 and durability requirements of EN 206-1. Lightweight aggregate should meet requirements of EN 13055-1. Aggregate smaller than 0,125 contribute to the content of powder in the SCC.The moisture content, water absorption, granulation and variations of powder in the aggregate must be carefully and continuously monitored in order to produce self-compacting concrete with consistent quality. The shape and grading of aggregates are very important and influential on the packing of grains as well as pores content.

Admixtures - super plasticizers or water reducers of high rank are essential components of SCC. Viscosity modifiers are also used to reduce segregation and the sensitivity of the mixture on the variability of the other constituents, in particular on the moisture content. Other admixtures, such as air entraining admixtures, accelerators or retarders can be used at the same manner as in vibrated concrete, except that there should be the manufacturer's recommendations on usage of it, in accordance with EN 934-2. The choice of admixtures for optimal concrete performance is determined by its physical and chemical properties.

Fibers - in the practice to date, steel and polymer fibers were also used within self-compacting concrete, although they/it reduced flow ability and passing ability through reinforcement. Therefore, the necessary preliminary tests are needed in order to determine the optimum type, length and quantity for achievement of the preferred properties of both fresh and hardened concrete. Polymer fibers can improve stability of the concrete mixture, in the sense that they prevent concrete settlement and cracks in concrete due to the plastic shrinkage of concrete. Steel or long polymer fibers are used to modify the toughness of hardened concrete. Their length and number are determined according to the maximum grain aggregates and structural requirements.

2.2. Testing methods of SCC

Several different testing methods of SCC consistency have been developed, the most commonly used are listed in Table 2 [4].

Regulation for testing of Self-Compacting Concrete in the fresh concrete is established within the European norm EN 12350. It represents definition of tests for determination of flowability structure: Slump - flow test, viscosity: t500 or V-funnel test, the passing through ability through reinforcement: L-box or J-ring test, segregation resistance: Sieve segregation resistance test. It should be emphasized that all the other (in a standard called alternative methods) could be used, if they are in compliance with norm EN 206-1: 2000.

According to the European norm EN 206-9 Classification of Self-Compacting Concrete is classified as follows (Table 3).

Tabela 2. Metode ispitivanja samougrađujućih betona
Table 2. Test methods for Self – Compacting concrete

	Metod ispitivanja / Test method	Cilj ispitivanja / Test aim
1	Test konzistencije / Slump-flow	sposobnost tečenja / flowability
2	Test T50cm	viskoznost / viscosity
3	J-prsten / J-ring	sposobnost prolaza / passing ability
4	V-levak / V-funnel	viskoznost / viscosity
5	V – levak za 5 min / V-funnel for 5min	otpornost na segregaciju / segregation resistance
6	L-kutija / L-box	sposobnost prolaza / passing ability
7	U-kutija / U-box	sposobnost prolaza / passing ability
8	Kutija za punjenje / Fill-box	sposobnost prolaza / passing ability
9	Test na situ / Sieve stability test	otpornost na segregaciju / segregation resistance
10	Orimet test	sposobnost tečenja / flowability

Tabela 3. Kriterijumi za ocenu rezultata ispitivanja svežeg SCC-a
Table 3. Conformity criteria for the testing results of SCC in the fresh state

osobina / property	kriterijum / criteria
Klasa konzistencije / Slump-flow class SF1	550-650 mm
Klasa konzistencije / Slump-flow class SF2	660-750 mm
Klasa konzistencije / Slump-flow class SF3	760-850 mm
t500 klasa / t500 class VS1	VS1< 2s
t500 klasa / t500 class VS2	VS2 ≥ 2 s
V – levak klasa / V-funnel class VF1	≤ 9 s
V – levak klasa / V-funnel class VF2	9-25 s
L – kutija klasa / L-box class PA1	≥ 0,80 sa dve šipke / with two bars
L – kutija klasa / L-box class PA2	≥ 0,80, sa tri šipke / with three bars
otpornost na segregaciju, klasa SR1 / segregation resistance, class SR1	≤ 20 %
otpornost na segregaciju, klasa SR2 / segregation resistance, class SR2	≤ 15 %

3. RECIKLIRANI AGREGAT

3.1. Održivi razvoj i reciklaža u građevinarstvu

Sintagma „održivi razvoj“ je prvi put upotrebljena u izveštaju Komisije Ujedinjenih Nacija za zaštitu životne sredine i razvoj Naša bliska budućnost – poznat i kao Brundlandski izveštaj (Brundtland Report) iz 1987. Usledio je Svetski samit u Rio de Ženeiru (1992), usvajanje Agende 21 (dokumenta od 300 strana) i formiranje Komisije za održivi razvoj. Opšte prihvaćena definicija održivog razvoja potiče upravo iz ovog izveštaja:«Održivi razvoj je razvoj koji zadovoljava potrebe sadašnjih generacija, bez ugrožavanja prava budućih generacija da zadovolje svoje potrebe».Cilj održivosti je da ostavi budućim generacijama onoliko mogućnosti koliko smo ih imali i mi, a jedno od ključnih pitanja jeste svesnost da su prirodni i materijalni resursi na našoj planeti ograničeni. Ovaj koncept ne obuhvata samo ekološke, već i sociološke i ekonomske interese poput zdravlja, bezbednosti, brige za životno okruženje, prosperitet, dovoljno posla i pravednu raspodelu resursa. Da bi se održivi razvoj zaista ostvario, ovi interesi moraju da budu kombinovani

3. RECYCLED AGGREGATE

3.1. The sustainable development and recycling in construction industry

The phrase “Sustainable development” was first used in the report of the World Commission on Environment Our immediate future - also known as Brundtland Report in 1987. This was followed by the World Summit in Rio de Janeiro (1992), the adoption of Agenda 21 (300 pages document) and the establishement of United Nations Commission for Sustainable Development. The generally accepted definition of sustainable development is coming exactly from this report: “Sustainable development is development that meets the needs of present generations without compromising the rights of future generations to meet their own needs”. The goal of sustainability is to leave to the future generations as many options as we have had for ourselves. One of the key issues is the awareness of limitation of natural and material resources on our planet. This concept includes not only environmental, but also social and economic interests such as health, safety, concern for the environment, prosperity, plenty of na svim nivoima. Održiva konstrukcija može da se predstavi kao način projektovanja i gradnje koji je u saglasnosti sa čovekovim zdravljem (fizičkim, psihološkim i socijalnim) i u harmoniji sa živom i neživom prirodom. Predložen je i model „20 faktora" gde je reč o određivanju uticaja na okruženje u odnosu na ostvareni napredak koji se umanjuje za navedene faktore [6].

Projektovanje i građenje objekata zadovoljavajuće trajnosti u okviru planiranog životnog veka, kao i primena obnovljivih prirodnih resursa i alternativnih materijala za građenje su opredeljenje savremenog graditeljstva. Jedan od osnovnih problema predstavlja neizbežno rušenje starih i dotrajalih objekata i njihova zamena novim objektima u velikim urbanim sredinama i u okviru saobraćajne infrastrukture. Razlozi rušenja objekata su promena njihove namene, starenje - dotrajalost objekata, preuređivanje delova gradova, proširenje putnih pravaca i povećanje saobraćajnog opterećenja, prirodne nepogode (zemljotresi, požari, poplave) [13].

Građevinski otpad (slika 3), koji se javlja kao posledica građenja novih i rušenja postojećih objekata je jedan od najvećih ekoloških problema u zemljama Evropske unije, kao i u mnogim razvijenim zemljama sveta. Procenjeno je, da oko 40% otpada nastalog rušenjem čini beton, 30% keramika, 10% drvo, 5% plastika, 5% metal i 10% različiti ostaci [12].

Glavni građevinski otpad (materijali koji su dobijeni rušenjem zgrada i infrastrukturnih objekata) iznosi oko 180 miliona tona godišnje ili 480kg/ po osobi/godišnje u EU [10], što je svakako razlog za globalnu zabrinutost. Uobičajeni metod "upravljanja" građevinskim otpadom u bliskoj prošlosti bio je njegovo odlaganje na deponije. Na taj način stvorene su ogromne deponije građevinskog otpada, koje zauzimaju zemljište i predstavljaju ekološki problem, zato što su potencijalni zagađivači životne sredine. Beton je već deceni-

work and a fair distribution of resources. Sustainable construction can be presented as a way of design and construction which is in compliance with human health (physical, psychological and social) and in harmony with the animate and inanimate nature. Model "20 factors" is proposed as way to determine impact on the environment in relation to the achieved progress, which is reduced by these mentioned factors [6].

Design and construction of facilities with satisfying durability within the planned lifetime, as well as the use of renewable natural resources and alternative materials for the construction, are one of the main commitment of modern construction engineering. The main problem is the inevitable demolition of old and worn out facilities and their replacement with new facilities in large urban areas and within traffic infrastructure. Reasons for demolition are change of their purposes, aging - the deterioration of facilities, rearranging of cities parts, expansion of roads and increasing of traffic load, natural disasters (earthquakes, fires, floods) [13].

Construction waste (Figure 3), which occurs as a result of new construction processes and demolition of existing buildings is one of the biggest environmental problems in the European Union, as well as in many developed countries. It is estimated that about 40% of the waste generated due to demolition makes concrete, ceramics 30%, 10% wood, 5% polyester, 5% metal and 10% different residues [12].

The main construction waste (materials obtained due to demolition of buildings and infrastructure) represents around 180 million tons per year or 480kg / per person / per year in the EU [10], which is certainly a cause for global concern. The usual method of "management" regarding construction waste in the recent past was his disposal in stock pile depots. That caused a formation of huge stock pile depots of construction waste. Con-

Slika 3. Tipičan građevinski otpad [16]
Figure 3. Typical construction waste

jama najkorišćeniji materijal na svetu, posle vode, a interesantan je podatak da je godišnja proizvodnja betona u svetu dostigla vrednost, koja se može izraziti sa jednom tonom betona po stanovniku planete [14]. Iz ovih podataka je potpuno jasna neophodnost pronalaženja novih mogućnosti za dobijanje agregata, u čemu prednjači reciklaža deponovanih materijala, prvenstveno starog betona. Problemi se javljaju zbog nedostatka prostora i opreme za sortiranje građevinskog šuta, iskustva u postupcima recikliranja otpadnih materijala, obučenih radnika i kontrolora, znanja o tržištu sekundarnih materijala, zakonske regulative u oblasti zaštite životne sredine, itd [9].

3.2. Tehnologija proizvodnje i svojstva recikliranog agregata

Postrojenja za proizvodnju recikliranog agregata su praktično ista kao postrojenja za proizvodnju prirodnog drobljenog agregata. Obzirom da je potrebno od komada otpadnog betona drobljenjem proizvesti zrnasti materijal određenih veličina zrna, dve osnovne operacije su drobljenje i prosejavanje. U zavisnosti od kontaminiranosti otpadnog materijala i namene agregata koji se proizvodi, tehnološki proces se još sastoji od odvajanja metalnog materijala magnetnim separatorom, ručnog ili mehaničkog uklanjanja stranih materija i pranja ili vazdušnog produvavanja finalnog proizvoda.

Reciklažna postojenja mogu biti stacionarna i mobilna. Na slici 4 je prikazano savremeno mobilno postrojenje koje se koristi u kamenolomu Ostrovica u blizini Niša, a na slici 5, staro stacionarno postrojenje za drobljenje kamena, iz istog kamenoloma.

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

crete is the world most widely used material for decades, after water; annual production of concrete in the world reached a value of a tone of concrete per inhabitant on the planet [14]. These data made absolutely clear the need for finding new possibilities for obtaining aggregates, where the recycling of deposited materials, primarily old concrete, is the primary option. Problems arise due to lack of space and equipment for sorting of construction waste, experience in the recycling procedures of waste materials, skilled workers and supervisors, knowledge of the secondary materials market, legal regulations in the field of environmental protection, etc. [9].

3.2. The production technology and properties of recycled aggregate

Plants for the production of recycled aggregates are practically the same as plants for the production of natural crushed aggregate. The process of obtaining recycled aggregates is actually crushing of scrap concrete pieces, which causes the creation of granular material of different sizes. Two basic operations required for this are crushing and sieving. Depending on the contamination of the waste material and purpose of the aggregates which is to be produced, further production technology includes separation of metal by a magnetic separator, manually or mechanically removing of stray materials and further washing and air purging or of the final product. Recycling facilities could be stationary and mobile. Figure 4 shows a modern mobile facility used in quarry Ostrovica near Nis, and in Figure 5, the old stationary crushing stone facility from the same quarry.

Recycled aggregate grain obtained by this recycling method consists of grain (or its part) of natural aggregate and cement mortar of the original concrete, which envelops it partially or completely. The presence of the old cement mortar, which has less density and larger porosity than a grain of natural aggregate, substantially affect a range of physical and mechanical properties of recycled

Slika 4. Mobilno reciklažno postrojenje
Figure 4. Mobile recycling plant

Slika 5. Staro stacionarnog postrojenja za drobljenje kamenja
Figure 5. Old stacionary stone crusher

agregata, tako i betona na bazi recikliranog agregata, odnosno uslovljava "lošija" svojstva recikliranog u odnosu na prirodni agregat.

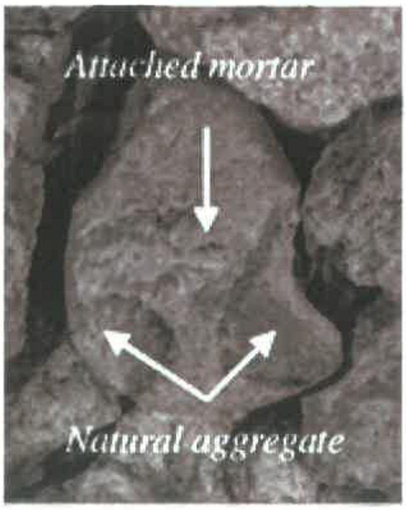
Radi uklanjanja cementnog kamena sa zrna agregata razvijeno je nekoliko naprednih tehnologija recikliranja pre svega u Japanu. Jedna od tih tehnologija je takozvana "metoda zagrevanja i struganja". Na ovaj način, dobija se 35% do 45 % čistog krupnog agregata, 30% do 35% čistog sitnog i 18% do 35% finog praha od cementnog maltera u zavisnosti od temperature zagrevanja (300-700°C) [13].

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 se sastoji 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 24h. Da se ne bi smanjio kvalitet agregata (pH vrednost) koncentracija kiseline u rastvoru treba da bude oko 0.1 mol. Ovim postupkom je moguće smanjiti upijanje vode kod recikliranog agregata za 7–12% [11,7].

Agregat od recikliranog betona (slika 6) se sastoji od originalnog agregata i sloja cementnog maltera preostalog od starog betona. Fizička i mehanička svojstva recikliranog agregata zavise kako od svojstava, tako i od količine preostalog maltera koja se kreće se od 25% do 65% (izraženo u zapreminskim procentima) i razlikuje se po pojedinim frakcijama – što je sitnija frakcija, veća je količina cementnog maltera, tako da pojedini autori ograničavaju upotrebu reciklirane prve

aggregate and concrete based on recycled aggregate as well, i.e. conditions "worse" properties of recycled compared to natural aggregate. In order to remove the hardened cement paste from aggregate grain, it has been developed several advanced recycling technology primarily in Japan, One of them is the so-called "method of heating and scraping." With this is possible to made 35% to 45% of pure coarse aggregate, 30% to 35% of pure and 18% to 35% of fine powder of the cement mortar, accordingly to the heating temperature (300-700°C) [13]. Another technology is chemical treatment of classically produced recycled aggregates. By previous soaking of recycled aggregate in a mild solutions of hydrochloric, sulfuric or phosphoric acids, it is possible to remove part of cement mortar and to improve the properties of aggregate, without a significant increase of chloride and sulfate in it. This procedure includes soaking of the recycled aggregate in an acidic environment for a period of 24 hours at a temperature of about 20 ° C, and further rinsing with distilled water in order to eliminate the maximum of possible applied acids. Prior to actual concrete mixing, aggregate should be in the water for 24 hours. In order not to reduce the quality of aggregate (pH value), the concentration of acid in the solution should be about 0.1 mol. This procedure enables reduction of the water absorption by recycled aggregate for 7-12% [11,7].

Recycled aggregate (Figure 6) consists of the original aggregate and cement mortar layer remaining of the old concrete. Physical and mechanical properties of recycled aggregate dependent on the properties, as well as on the quantity of remaining mortar, which range is from 25% to 65% (given in volume percentages) and varies by individual fractions - a smaller fraction, the greater the amount of cement mortar so that some authors restrict the use of recycled first fraction [13].



Slika 6. Agregat od recikliranog betona [17]
Figure 6. Recycled concrete aggregate [17]

frakcije [13].

Bez obzira na određene manje razlike u pogledu svojstava agregata od recikliranog betona, generalno reciklirani agregat u odnosu na prirodni agregat ima sledeća svojstva: veće upijanje vode, manju zapreminsku masu, veće habanje, veću drobljivost, veću količinu prašinastih čestica, veći sadržaj organskih materija i moguć sadržaj hemijski škodljivih materija, tako da su neophodna detaljna prethodna ispitivanja.

3.3. Specifičnosti spravljanja betona na bazi recikliranog agregata

Uobičajen postupak mešanja betona jeste doziranje u mešalicu svih potrebnih komponenti: krupnog i sitnog agregata, cementa i vode, pri čemu čitav proces mešanja traje oko 2 minuta. Kako se zrno recikliranog agregata sastoji iz prirodnog agregata i manje ili više poroznog starog maltera koji upija vodu, sam postupak mešanja betona koji sadrži ovaj agregat izgleda nešto drugačije. Različiti autori predlažu različita rešenja, ali je najčešće korišćen tzv. metod mešanja „iz dve faze" (Two stage Mixing Approach – TSMA). U okviru ovog postupka se prvo dozira krupan i sitan agregat koji se meša oko 1 minut, a zatim dodaje otprilike polovina potrebne količine vode i mešanje nastavlja još 1 minut. Sledi doziranje cementa i mešanje 30 sekundi, da bi se na kraju dodala preostala količina vode i proces spravljanja betona završio dvominutnim mešanjem. Prilikom prve faze mešanja, kada se doda polovina potrebne količine vode a zatim i cement, donekle se ovlaže zrna recikliranog agregata i na njima se formira tanak sloj cementne paste koja može da prodre u stari malter i popuni postojeće pukotine i šupljine. Druga polovina vode je dovoljna za proces hidratacije. SEM analize (elektronska mikroskopija) pokazuju da na ovaj način prelazna zona postaje mnogo gušća, a šupljine popunjenije nego u slučaju „običnog" mešanja betona.

Kako je glavni problem kod primene recikliranog agregata povećana poroznost stare prelazne zone,jedan od načina njenog poboljšanja je upotreba silikatne prašine. Nešto izmenjen TSMA (označen kao TSMAs) metod se sastoji u mešanju recikliranog agregata sa silikatnom prašinom (dodaje se kao zamena nekog procenta cementa, obično 2-3%) u trajanju od 1 minut, nakon čega se dodaju prirodan agregat, cement i voda, pa sve meša naredna 2 minuta. Postoji i varijanta postupka označena kao TSMAsc gde se u prvoj fazi mešaju reciklirani agregat, silikatna prašina i deo cementa. Dodatak silikatne prašine poboljšava performanse betona, a u ovom postupku predstavlja filer koji ispunjava prostor unutar zrna agregata, dok u slučaju primene zajedno sa cementom stvara debelu opnu oko zrna agregata. Primena TSMA postupka u odnosu na uobičajeno mešanje betona može poboljšati čvrstoće pri pritisku, savijanju, za-

Regardless of the certain minor differences in respect of recycled concrete aggregate properties, recycled aggregate has generally, in relation to the natural aggregate, the following properties: higher water absorption, lower density, higher abrasion, higher crushing, a greater amount of powder percentage, higher content of organic substances and possible content of harmful chemical substances, which imply previous detailed testing.

3.3. Specificities of recycled aggregate concrete mixing

The usual procedure of mixing concrete is mixer dosing of all the required components: coarse and fine aggregate, cement and water, wherein the entire mixing process takes about 2 minutes. As the grain of recycled aggregates consist of natural aggregates and more or less porous old plaster that absorbs water, the procedure of mixing concrete containing this aggregate looks a bit different. Different authors propose different solutions, but is most often used method is so-called "Two stage Mixing Approach – TSMA". During this process, the first dosing goes with coarse and fine aggregate mixed for about 1 minute, then follows addition of about half the required amount of water and mixing continued for 1 minute. The dosage of cement follows and further mixing for 30 seconds, and at the end addition of the remaining amount of water and the process of making concrete finished two-minute mixing. During the first stage of mixing, when the half of the required amount of water is added and after that cement, recycled aggregates grains became wet to some extent which reduces a thin layer of cement paste. It can penetrate into the old mortar and fill existing cracks and voids. The second half of the water is enough for the hydration process. SEM analyses show that through this method a transition zone becomes much denser. Since the main problem in the application of recycled aggregates increased porosity of old transitional zone, one of the ways of its improvement is the use of silica fume. Someway changed TSMA (labeled as TSMAs) method consists in mixing of the recycled aggregates with silica fume (added as a replacement of some cement percentage, usually 2-3%) for 1 min, followed by addition of natural aggregate, cement and water, and all should be mixed for the next 2 minutes. There is also a variant designated as TSMAsc, which includes in the first stage mixing of recycled aggregate, silica fume and part cement. Addition of silica fume improves the concrete properties, but in this procedure represents a filler of the space within the aggregate, while in the case of application with cement produces a thick membrane around the aggregate grain. Application of TSMA proceedings in relation to the usual concrete mixing can improve the compressive strength, flexural, tensile strength by bending and static modulus of elasticity of 10 -

tezanju cepanjem i statički modul elastičnosti od 10 – 30%, a primena TSMAs i TSMAsc postupka za 20 – 30% [15,8].

Postoje predlozi da se najpre napravi smesa vode i cementa (ili pucolanski aktivnog dodatka ako se koristi) a zatim da se dodaje agregat kako bi se nakon produženog mešanja došlo do pomenutog efekta oblaganja zrna [7]. Vlažnost recikliranog agregata je takođe faktor o kome posebno treba voditi računa prilikom njegove upotrebe. U slučaju betona sa recikliranim agregatom može se govoriti o ukupnom vodocementnom faktoru – odnos ukupne količine vode i cementa u betonu, i o slobodnom vodocementnom faktoru – odnos vode koja je stvarno na raspolaganju cementu za hidrataciju i ukupne količine cementa. Na osnovu svega navedenog problem većeg upijanja vode kod recikliranog agregata se može rešiti trojako: zasićenjem recikliranog agregata, povećavanjem količine potrebne vode za spravljanje betona na osnovu merenja upijanja vode recikliranog agregata u trajanju od 30 minuta ili dodavanjem vode na gradilištu do postizanja tražene konzistencije[7].

4. SOPSTVENO EKSPERIMENTALNO ISPITIVANJE

Za potrebe eksperimentalnog dela rada je napravljeno devet različitih trofrakcijskih betonskih mešavina, pri čemu su kao mineralni dodaci korišćeni mleveni krečnjak, leteći pepeo i silikatna prašina; etaloni su spravljeni sa svakim od dodataka i rečnim agregatom; kod mešavina K50, P50 i S50 je frakcija 8/16 mm zamenjena recikliranim agregatom, a kod mešavina K100, P100 i S100 su obe krupne frakcije (4/8 i 8/16 mm) zamenjene recikliranim. U svim mešavinama je korišćen superplastifikator ViscoCrete 5380 čije je doziranje izvršeno prema preporuci proizvođača. Kriterijum pri projektovanju mešavina je bio 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 je najpre agregat mešan sa 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. Sastavi betonskih mešavina su prikazani u tabeli 4.Na svežem betonu su urađena ispitivanja: zapreminske mase, fluidnosti – Slump flow test prema EN 12350-8, viskoznosti – T500 test prema EN 12350-8, sposobnosti prolaza između armaturnih šipki – L box test prema EN 12350-10, otpornosti na segregaciju – Sieve segregation test prema EN 12350-11. Na očvrslom betonu su urađena ispitivanja: zapreminske mase, čvrstoće pri pritisku, čvrstoće pri zatezanju savijanjem, skupljanja, vodonepropustljivosti, upijanja vode i SEM analize.

30%, and the application of TSMAs and TSMAsc procedure for 20 - 30% [15.8].

There are proposals for making mixture of water and cement first (or pozzolana active addition - if is to be used) and then addition of the aggregate in order to gain the mentioned effect of coating grains, after prolonged mixing [7]. Humidity of recycled aggregate is also a factor which should be paid the particular care during its usage. In the case of concrete with recycled aggregate, there are total water-cement ratio - the ratio of the total amount of water and cement in concrete and free water-cement ratio - the ratio of water that is actually available for cement hydration and the total amount of cement. The problem of a higher water absorption at recycled aggregate can be solved in three ways: by saturation of recycled aggregate, increasing the amount of water required for concrete making based on the measurement of water absorption at recycled aggregate in 30 min or by addition of water on the site to achieve the required consistency [7].

4. PROPER EXPERIMENTAL TESTING

For the purpose of the experimental part of the work, it was made nine different three-sized fracture concrete mixtures, with the mineral additions such as ground limestone, fly ash and silica fume; control concrete are made with all of the extras and river aggregate; by mixtures of K50, P50 and S50 is the fraction 8/16 mm replaced by recycled aggregate, and in a mixture of K100, P100 and S100 are both coarse fraction (4/8 and 8/16 mm) replaced with recycled. In all mixtures is used super plasticizer ViscoCrete 5380 which is dosed according to the manufacturer's recommendations. The criteria in the mixture design was achieving of the same concrete consistency, i.e. slump - flow class SF2, which includes the usual application of concrete and involves diffusion from 66 to 75 cm. By preparing of concrete mixture is the aggregate mixed with half the required water for about 30 seconds first, and then the other components were added. By case of recycled aggregate usage, it was added the amount of water absorbed by the unit in 30 minutes (fraction II 22.2%, fraction III of 1.5%), although this principle could not be applied consistently. The compositions of concrete mixtures are shown in Table 4. The fresh concrete tests were conducted on the following: density, flowability - Slump flow test according to EN 12350-8, viscosity - T500 test according to EN 12350-8, the passage ability between reinforcing bars - L box test according to EN 12350-10, segregation resistance - Sieve segregation test according to EN 12350-11. On hardened concrete tests were conducted on the following: density, compressive strength, tensile strength by bending, shrinkage, waterproofing, water absorption and SEM analysis.

Tabela 4. Sastav betonskih mešavina
Table 4. Concrete mixes

	Cement (kg/m³)	ml.krečnjak lime (kg/m³)	el.pepeo fly ash (kg/m³)	sil.prašina silica fume (kg/m³)	0/4mm (kg/m³)	4/8mm (kg/m³)	8/16mm (kg/m³)	Voda (water) (kg/m³)	VSC5380 (kg/m³)
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. REZULTATI ISPITIVANJA

5.1. Rezultati ispitivanja svežeg betona

Rezultati ispitivanja svežeg betona su prikazani u tabeli 5.

5. TESTING RESULTS

5.1. Testing results of fresh concrete

Testing results of fresh concrete are given in Table 5.

Tabela 5. Rezultati ispitivanja svežeg betona
Table 5. Test results for concrete in the fresh state

bet. mešavina concrete mix	zaprem. masa / density kg/m³	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

5.2. Rezultati ispitivanja očvrslog betona

Rezultati ispitivanja zapreminske mase betona u očvrslom stanju, prema SRPS EN 12390 – 7 : 2010, nakon 2, 7 i 28 dana su prikazani u tabeli 6.

Ispitivanje čvrstoće pri pritisku je obavljeno na kockama ivice 15 cm. Rezultati ispitivanja čvrstoće pri pritisku nakon 2, 7 i 28 dana su prikazani u tabeli 7.

Ispitivanje čvrstoće na zatezanje savijanjem je obavljeno nakon 28 dana na uzorcima dimenzija 12x12x36 cm. Rezultati su prikazani na slici 7.

5.2. Testing results of hardened concrete

Testing results of hardened concrete density, according to SRPS EN 12390 – 7, after 2, 7 and 28 days are given in Table 6.

Testing of compressive strenght is done on concrete cubes with edge of 15cm. Testing results of compressive strenght by pressure after 2, 7 and 28 days are given in Table 7.

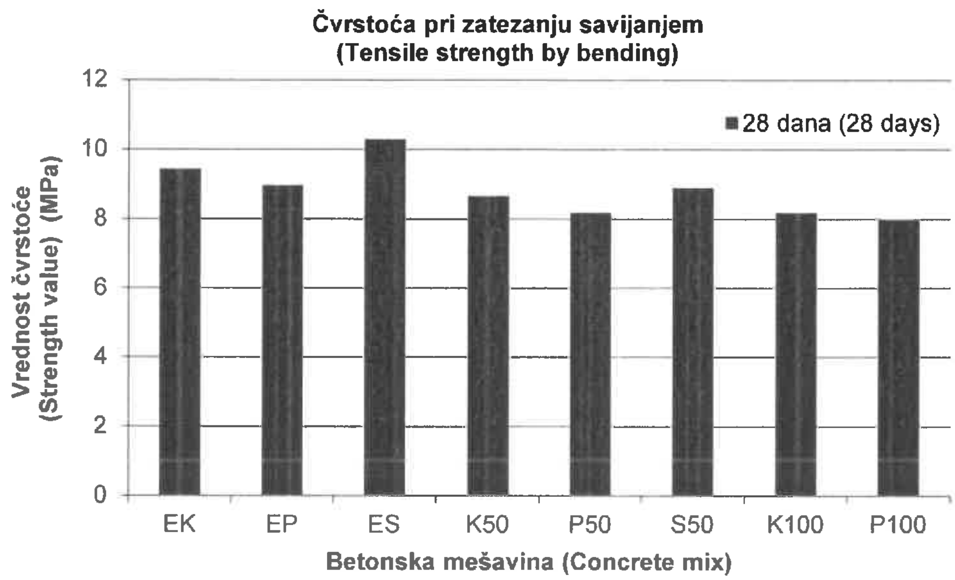
Testing of tensile strength by bending is done after 28 days at 12x12x36 cm samples. Testing results are given in Figure 7.

Tabela 6. Rezultati ispitivanja zapreminske mase betona (u kg/m³)
Table 6. Test results for density, in u 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

Tabela 7. Rezultati ispitivanja čvrstoće pri pritisku (u MPa)
Table 7. Test results for compressive strength, in MPa

	EK	EP	ES	K50	P50	S50	K100	P100	S100
2 dana	46	36.3	40.4	44.8	28.7	37.7	41.9	26.2	34.4
7 dana	58.2	52.2	58.	53.1	41.2	54.7	52.9	40.2	51.6
28 dana	66.7	64	72.3	62.2	51.7	69.7	60.3	47.2	64.5



Slika 7. Čvrstoće pri zatezanju savijanjem
Figure 7. Tensile strength by bending

Ispitivanje skupljanja je izvršeno 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 ± 5 % vlažnost vazduha i konstantna temperatura od 20 ± 4 °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 4 i 7 dana. Nakon ovoga, dalja merenja se vrše nakon svakih narednih 7 dana, dok se proces ne stabilizuje. Rezultati ispitivanja skupljanja betona nakon 4, 7, 14, 21, 28 i 35 dana su prikazani u tabeli 8.

Testing of shrinkage is done on 12x12x36 cm samples, all i n accordance SRPS U.M1.029. The samples are removed from the water 72 hours after their completion and are exposed to conditioned thermo-hygrometric conditions. It was chosen humidity of 70 ± 5% and a constant temperature of 20 ± 4 ° C, which is the prescribed standard for the structures and elements foreseen to be in free space. The first measurement has to be done 72 ± 0.5 hours after the sample completion, and then after 4 and 7 days. After this, further measurements are to be made after every next 7 days, until the stabilization of the process. Testing results of shrinkage after 4, 7, 14, 21, 28 and 35 days are given in Table 8.

Tabela 8. Rezultati ispitivanja skupljanja betona u mm/m
Table 8. Test results for shrinkage in mm/m

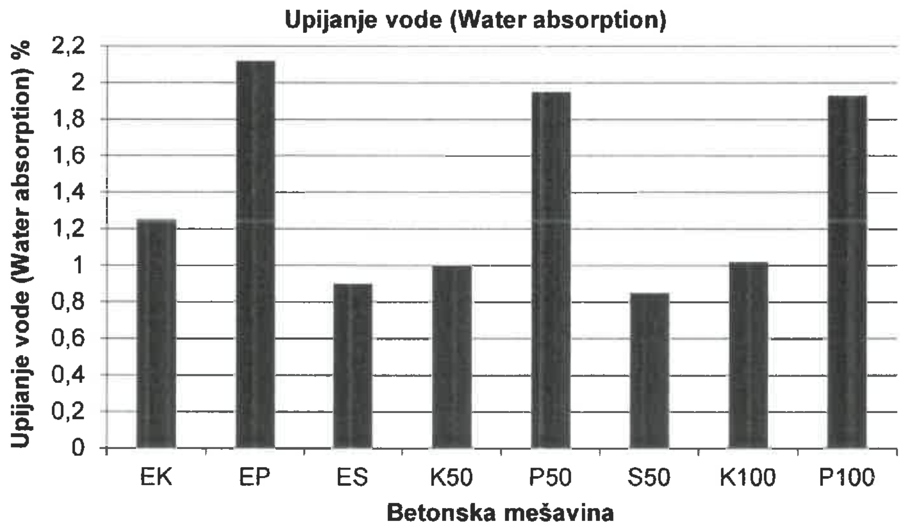
	EK	EP	ES	K50	P50	S50	K100	P100	S100
4	19	50	53	85	20	31	13	36	24
7	105	100	133	148	80	104	73	85	65
14	209	157	211	271	143	267	184	188	209
21	253	234	252	319	213	320	243	252	231
28	256	355	296	392	224	355	268	291	343
35	267	376	332	396	321	416	281	316	364

Ispitivanje upijanja vode je urađeno na uzorcima dimenzija 12x12x36 cm, metodom postupnog potapanja. Rezultati ispitivanja upijanja vode nakon 28 dana su prikazani na slici 8.

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

Water absorption testing was done on 12x12x36 cm samples, by the gradual sinking/soaking method. Testing results of water absorption after 28 days are given in Figure 8.

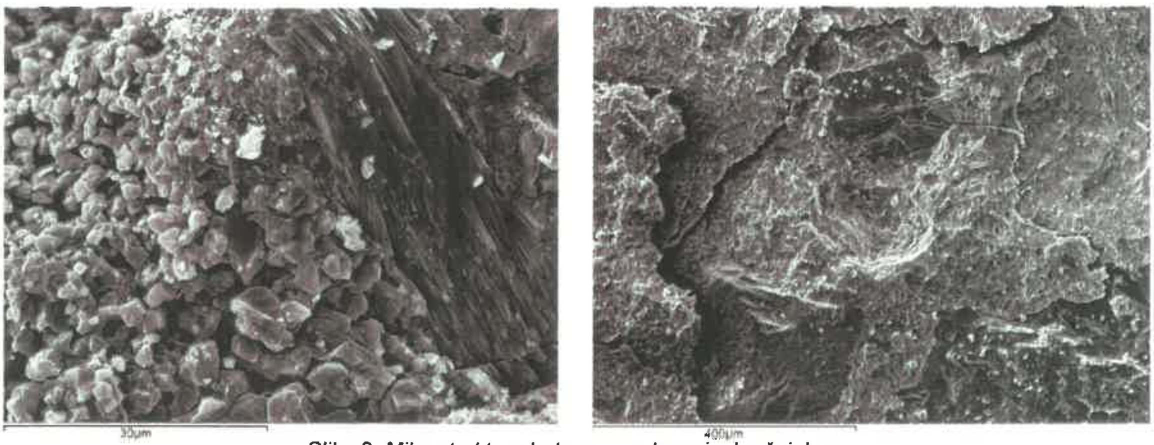
Testing of waterproofing is done on 200x200x150 mm samples, with 28 days concrete, all in accordance with SRPS U.M1.015:1998. The samples were exposed water to in 24 hours at a pressure of 1 bar, for the next 48 hours at a pressure of 3 bar, and at the end the last 24 hours of testing, a pressure of 7 bar. After that follows their breaking and measurement of water penetration depth. For samples with limestone and silica fume it was recorded water penetration of about 2cm, while the samples with fly ash were with water penetration stood at 8 - 10 cm.



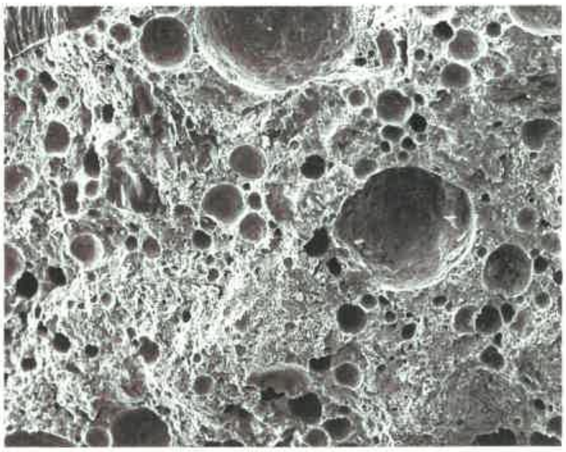
Slika 8. Upijanje vode
Figure 8. Water absorption

Skenirajuća elektronska mikroskopija (SEM analiza) omogućava da se „zaviri" u strukturu spravljenih betona i bolje objasne rezultati koji su dobijeni ispitivanjima (slike 9 – 11).

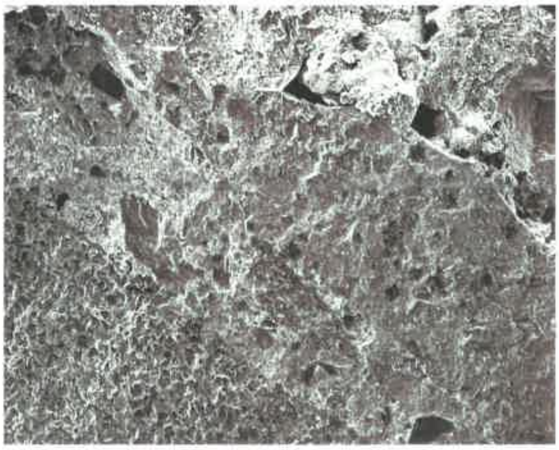
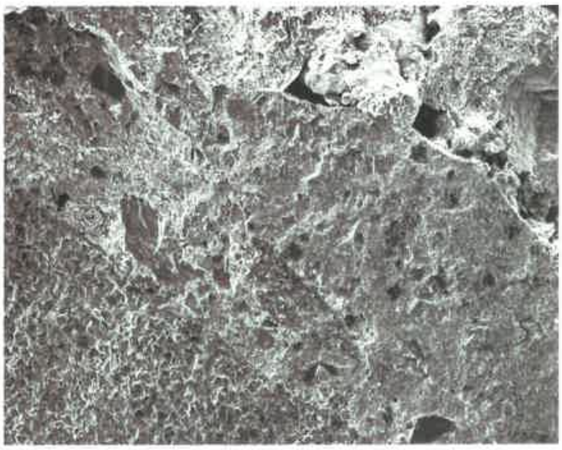
Scanning electronic microscopy (SEM analysis) allows "peeking" into the structure of made concrete and better explanation of the results obtained from tests (Figure 9 - 11).



Slika 9. Mikrostruktura betona sa mlevenim krečnjakom
Figure 9. Microstructure of the concrete with lime

Slika 10. Mikrostruktura betona sa elektrofilterskim pepelom
Figure 10. Microstructure of the concrete with fly ash

Slika 11. Mikrostruktura betona sa silikatnom prašinom
Figure 11. Microstructure of the concrete with silica fume

6. ANALIZA REZULTATA

6.1. Analiza rezultata dobijenih ispitivanjem svežeg betona

Slump-flow testom je proveravana prva od četiri ključne osobine SCC-a: pokretljivost, tj. fluidnost. Rasprostiranje je iznosilo od 66 do 73 cm što sve projektovane mešavine svrstava u klasu SF2 koja odgovara najčešćoj primeni betona u građevinarstvu. Najmanju pokretljivost su imale betonske mešavine sa silikatnom prašinom, kao i mešavine sa recikliranim agregatom, jer je oštroivično zrno ovog agregata teže „pomeriti" prilikom razlivanja betona. Najveće rasprostiranje je izmereno kod etalona sa krečnjakom - 73 cm, a najmanje kod etalona sa silikatnom prašinom, mešavine sa silikatnom prašinom i krupnim recikliranim agregatom i mešavine sa pepelom i krupnim recikliranim agregatom - 66 cm.

T500 je vreme za koje beton dostigne 500 mm a meri se prilikom izvođenja slump-flow testa. Predstavlja proveru viskoznosti mešavine; za klasu SF2 se preporučuje interval od 3.5-6.0 s, u koji se sve mešavine „uklapaju". Rezultati su u

6. RESULTS ANALYSIS

6.1. Result analysis obtained by testing of fresh concrete

By Slump-flow test is checked first of the four key characteristics of SCC: flowability. Spreading was between 66 to 73 cm, and it ranked all the projected mixtures in class SF2, corresponding to the most common use of concrete in construction. The lowest mobility was by concrete mixtures with silica fume, as well as mixtures with recycled aggregate, because this kind of sharp edged grain is harder to "move" during concrete pouring. The largest spreading is measured at control concrete with limestone - 73 cm, but a minimum of control by silica fume, its mixtures and coarse recycled aggregate and mixture of ash and coarse recycled aggregate - 66 cm.

T500 is the time needed for the concrete to reach 500 mm and is measured during the execution of slump-flow test. It represents checking of the mixture viscosity; for class SF2 is recommended interval of 3.5-6.0 s, in which all mixtures "fit". The results are in the range of 4 - 6s, wherein the slow-opsegu od 4 - 6s, pri čemu su najsporije bile betonske mešavine sa silikatnom prašinom. Vreme duže od 2 s ih svrstava u klasu viskoznosti VS2. Nije uočena segregacija, niti izdvajanje vode.

L-box testom (slika 12) je proveravana treća ključna osobina: sposobnost prolaza samougrađujućeg betona između armaturnih šipki bez zaglavljivanja. Sve mešavine zadovoljavaju kriterijum da odnos visina betona na krajevima L-boxa bude najmanje 0.8, a kako je ispitivanje rađeno sa tri armaturne šipke (što je i zahtev za gušće armirane konstrukcije) njihova klasa je PA2. Rezultati testa se kreću u opsegu 0.91 – 1.0, pri čemu su najbolje rezultate (najbliže 1.0) postigle mešavine sa krečnjakom. Najveća razlika na krajevima L box-a je izmerena 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.

Otpornost na segregaciju kao četvrta karakteristika svežeg SCC-a je testirana na situ (slika 13). Rezultati pokazuju da su sve mešavine otporne na segregaciju i pripadaju klasi SR2 (<15%). Najveći procenat prolaska paste kroz sito je izmeren kod etalona sa krečnjakom – 12.4% (i kod svih mešavina sa krečnjakom), a najmanji kod mešavine S50 sa silikatnom prašinom i III recikliranom frakcijom agregata (i kod svih mešavina sa silikatnom prašinom) – 5.2%.

Najveću zapreminsku masu u svežem stanju stanju je imao etalon sa krečnjakom 2418 kg/m3, gotovo istu kao i etalon sa silikatnom prašinom (2416 kg/m3, 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 sa pepelom su imale najmanje zapreminske mase, oko 70 kg/m^3 manje u odnosu na odgovarajuće mešavine sa

est were the concrete mixtures with the silica fume. Time period longer than 2 seconds puts them in a class of viscosity VS2. There was no segregation or separation of water noticed.

L-box test (Figure 12) is used for checking of the third key property: the passing ability of SCC between reinforcing bars without blocking. All mixtures meet the criterion for the relative height of the concrete at the ends of L-box is at least 0.8; and how the testing was done with three reinforcing bars (which is a requirement for densely reinforced structures) their class is PA2. The test results are in the range from 0.91 - 1.0, whereby the best results (the nearest to 1.0) was achieved with a mixture of limestone. The largest difference at the ends of L-box is measured with a mixture with silicafume, which is the logical consequence of its minimum spreading. In neither case was not noted blocking of the aggregate between reinforcing bars.

Resistance to segregation as a fourth property of fresh SCC has been tested in sieve paste (Figure 13). The results show that all blends/mixtures are resistant to segregation and belong to the class SR2 (<15%). The highest percentage of passing through the sieve paste was measured in standards with limestone - 12.4% (at all mixtures with limestone), and lowest in S50 mixtures with silica fume and III recycled aggregate fractions (at all mixtures with silica fume) - 5.2%.

The largest density in the fresh state was at control concrete with limestone 2418 kg/m^3, almost the same as control concrete with silica fume (2416 kg/m^3, i.e., 0.08% less), while the lowest density was determined with a mixture of P50 (ash and recycled fraction III) 2279 kg/m^3 to 5.7% smaller. In general, mixtures with fly ash had the density of lowest density, about 70 kg/m^3 less than the corresponding mixtures with limestone and silica fume.

By designing the concrete mix, and in order to

Slika 12. L – box test
Figure 12. L – box test

Slika 13. Test na situ
Figure 13. Sieve segregation test

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 oštroivičnog oblika zrna recikliranog agregata i samog granulometrijskog sastava (reciklirani agregat je imao 7% nadmerenih zrna). Najveće promene vodocementnog faktora je bilo kod betonskih mešavina sa elektrofilterskim pepelom, pri istoj količini mineralnog dodatka (i svim ostalim komponentama), u etalon sa pepelom je dodato 21.86 kg (12.8%) vode u odnosu na etalon sa krečnjakom; u mešavinu sa III recikliranom frakcijom 31.42 kg (17.2%) u odnosu na odgovarajuću mešavinu sa krečnjakom, a u mešavinu sa 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 dozaža je 10 – 15%). U etalon sa silikatnom prašinom je dodato 14.91 kg (8.7%) vode u odnosu na etalon sa krečnjakom, i po 14.28 kg (7.8%) i 19.1 kg (10.1%) u odnosu na mešavine sa krečnjakom i recikliranim agregatom. Zahtevana klasa konzistencije je postignuta pri najmanjem vodocementnom faktoru kod mešavina sa krečnjakom, dok je najviše vode bilo potrebno kod mešavina sa pepelom. Najmanji vodocementni faktor je zabeležen kod etalona sa krečnjakom – 0.43 (ujedno i najmanji vodopraškasti faktor – 0.33), a najveći kod mešavine sa pepelom i obe krupne reciklirane frakcije – 0.55. Najveći vodopraškasti faktor je imala mešavina sa silikatnom prašinom i obe krupne reciklirane frakcije – 0.46. Treba napomenuti da su betonske mešavine sa krečnjakom pri najmanjem sadržaju vode u odnosu na ostale mešavine imale najveće prečnike rasprostiranja i najbolja svojstva samougradljivosti.

6.2. Rezultati dobijeni ispitivanjem očvrslog betona

Najveću zapreminsku masu u očvrslom stanju je nakon 2 dana imala betonska mešavina etalon sa krečnjakom a najmanju etalon sa pepelom (razlika 133.6 kg/m3 tj. 5.6%). Ovaj trend se održao i nakon 7 dana s tim što je razlika iznosila 179.5 kg/m^3 (7.3%). Nakon 28 dana, etalon sa krečnjakom je imao najveću zapreminsku masu, 2426.7 kg/m^3, za 123.4 kg/m^3 (5.1%) veću od mešavine sa pepelom i obe krupne reciklirane frakcije, i za 120.5 kg/m^3 (5%) veću od etalona sa pepelom. Zapreminska masa u očvrslom stanju kod mešavina sa silikatnom prašinom se kretala od 2312 kg/m^3 (S100, 2 dana) do 2366.4 kg/m^3 (ES, 28 dana); to su vrednosti „između" odgovarajućih

achieve the same consistency, due to the application of recycled aggregates, it was necessary to intervene in two directions: to increase the amount of water and at the same time to reduce the amount of fraction III by 5% while increasing the amount of sand for 5%. Without these interventions in the composition, it was not possible to achieve self-compacting mixture; by reason of sharp edged form of recycled aggregate grain and its particle size distribution (recycled aggregate had a 7% of oversized grains). The biggest changes happen at the water-cement ratio in concrete mixtures with fly ash, using thereby the same amount of mineral addition (also at all other components); in ETALON with fly ash 21.86 kg (12.8%) of water is added compared to standard with limestone; in III recycled aggregate fractions mixture with the recycled fraction to 31.42 kg (17.2%) compared to the corresponding mixture with limestone, and in a mixture with the II and III recycled fraction to 31.5 kg (16.6%). Silica fume has much smaller powder of limestone and fly ash, so that its dosing was 52 kg / m3 of concrete, i.e. 13% of cement (normal dosage is from 10 to 15%). In the control concrete with the silica fume is added to 14.91 kg (8.7%) of water in relation to the etalon with the limestone, and to the 14.28 kg (7.8%) and 19.1 kg (10.1%) compared to a mixture with limestone and recycled aggregates. Required class of consistency is achieved at the lowest water-cement ratio with a mixture of limestone, while the highest water was required in a mixture with the fly ashes. The lowest water-cement ratio was noted for standards with limestone - 0.43 (also the smallest water - powder factor - 00:33), but the highest was in mixtures with fly ash and both major recycled factions - 00:55. The highest water - powder factor had a mixture of silica fume and both recycled coarse fractions - 0.46. It should be noted/underlined that the concrete mixture with limestone have had, at the lowest water content compared to other mixtures, the largest diameters of spreading and the best self-compacting.

6.2. Result analysis obtained by testing of hardened concrete

The highest density at hardened state, after two days, had concrete mixture control concrete with limestone, but the lowest control concrete with fly ashes (difference of 133.6 kg/m^3, i.e. 5.6%). This trend was maintained even after 7 days, with notification that the difference goes to 179.5 kg/m^3 (7.3%).

After 28 days, the etalon with the limestone had the highest density, 2426.7 kg/m^3, higher for 123.4 kg/m^3 (5.1%) higher than the mixture with fly ash and both major recycled factions, and for120.5 kg/m^3 (5%) higher than control concrete with the fly ashes. Density in the hardened state with a mixture with silicate dust ranged from 2312 kg/

Slika 14. Ispitivanje čvrstoće pri pritisku
Figure 14. Compressive strength testing

kod krečnjaka i pepela. Treba imati u vidu da je za spravljanje betonskih mešavina korišćeno 52 kg silikatne prašine i po 120 kg i po 120 kg mlevenog krečnjaka i pepela.

Najveću vrednost čvrstoće pri pritisku (slika 14) nakon 2 dana je imao etalon sa krečnjakom a najmanju mešavina sa pepelom i obe krupne reciklirane frakcije – P100. Razlika je iznosila 19.8 MPa (43%). Nakon 7 dana etaloni sa krečnjakom i silikatnom prašinom su imali 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 je dostigao etalon sa silikatnom prašinom, 72.31 MPa, a najmanju mešavina P100, 47.2 MPa (razlika 25.11 MPa, tj. 34.7%). Posmatrajući mešavine sa 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 sa mešavinama kod kojih je zamenjena jedna, odnosno obe krupne frakcije. Kod mešavina sa pepelom razlika je 12.3 MPa (19.2%) i 16.8 MPa (26.2%). Veća razlika u čvrstoćama u okviru mešavina sa pepelom može da se objasni neujednačenim kvalitetom recikliranog agregata, koji i predstavlja glavni problem njegove primene. U grupi mešavina sa silikatnom prašinom razlika između etalona i druge dve mešavine je iznosila 2.61 MPa (3.6%) i 7.81 MPa (10.8%). Najbrži priraštaj čvrstoće su imale mešavine sa silikatnom prašinom. Kod svih betonskih mešavina sa rečnim agregatom zabeležen je lom po cementnoj pasti, dok je kod mešavina sa recikliranim agregatom zabeležen lom po agregatu, bez obzira na vrstu mineralnog dodatka (slike 15,16)

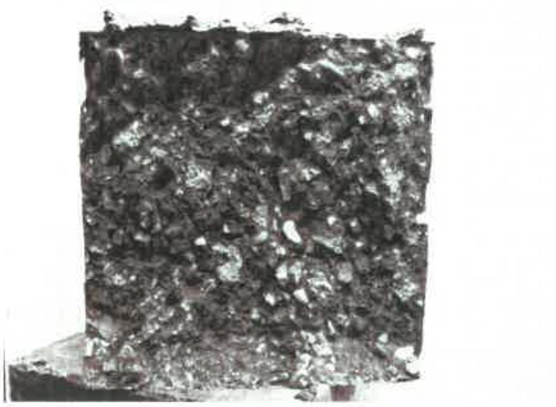
Razlike u rezultatima čvrstoće pri zatezanju savijanjem nisu velike. Vrednosti čvrstoće pri zatezanju su u opsegu od 7.97 MPa (P100) do 10.31 MPa (ES). Razlika između ovih vrednosti je 2.34 MPa (22.7%).

Dostupni podaci iz literature kao i sopstvena prethodna istraživanja [2] pokazuju da je nezah-

m³ (S100, 2 days) to 2366.4 kg/m³ (ES, 28 days); those values are something called "between" the appropriate by limestone and fly ash. It should be borne in mind that was used 52 kg of silica fume and up to 120 kg of ground limestone and fly ash for making of concrete mixtures. The highest value of compressive strength (Figure 14) after two days had control concrete with limestone and the lowest mixture with fly ash and recycled both coarse fractions - P100. The difference was 19.8 MPa (43%). After 7 days control concrete with limestone and silica fume had almost the same compressive strength (58 MPa) while the mixture of P100 reached 40.18 MPa (difference of 17.82 MPa, i.e. 30.7%). After 28 days, the maximum value of compressive strength is attained/was reached by/ with silica fume control concrete 72.31 MPa, while the lowest mixture of P100, 47.2 MPa (difference of 25.11 MPa, i.e. 34.7%). Observing mixtures with limestone, it can be concluded that the differences in achieved compressive strength with/by the use of natural and recycled aggregates are relatively small – 4.51 MPa (6.8%) and 6.38 MPa (9.6%) - comparison with standards mixtures with replaced one or both coarse fractions. By mixtures with fly ashes difference is 12.3 MPa (19.2%) and 16.8 MPa (26.2%). The bigger difference in compressive strength within the mixtures with the fly ashes can be explained by the uneven quality of recycled aggregates, which represents a major problem within its application. In the group of mixtures with silica fume difference between the control concrete and the other two mixtures goes to 2.61 MPa (3.6%) and 7.81 MPa (10.8%). Fastest increase of strength had mixtures with silica fume. In all concrete mixes with river aggregate it was recorded fracture at cement paste, while the mixture with recycled aggregate recorded after fracture at it (r. aggregate), regardless of the type of mineral addition (Figure 15-16).

The differences in the results of tensile strength by bending are not significant. The values of tensile strength by bending are in the range from7.97

Slika 15. Lom po cementnoj pasti
Figure 15. Fracture at cement paste



Slika 16. Lom po agregatu
Figure 16. Fracture at aggregate

valno 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 sa krečnjakom EK, pri čemu je razlika 56%. Ne može se izvući nikakva pravilnost u ovim rezultatima: mešavine sa III recikliranom frakcijom su imale veće skupljanje od mešavina sa II i III recikliranom frakcijom, pri čemu su razlike kod krečnjaka i silikatne prašine bile izraženije nego kod betona sa pepelom. Ako se klasifikacija betona vrši prema mineralnom dodatku, najveće skupljanje su imale mešavine sa silikatnom prašinom; ukoliko je kriterijum agregat, među etalonima najveće skupljanje je imao etalon sa pepelom (29% više od etalona sa krečnjakom i 11.7% više od etalona sa silikatnom prašinom), među mešavinama sa III recikliranom frakcijom S50 (4.8% više od mešavina sa krečnjakom i 22.8 % više od mešavina sa pepelom), a među mešavinama sa II i III recikliranom frakcijom S100 (22.8% više od mešavina sa krečnjakom i 13.2% više od mešavina sa pepelom).

Upijanje vode se kreće u opsegu 0.85% (mešavina S50) do 2.12% (mešavina EP). Najveće upijanje vode su imale mešavine sa 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 sa pepelom. Prosečno upijanje vode kod mešavina sa silikatnom prašinom je iznosilo 0.9%, kod mešavina sa mlevenim krečnjakom 1% , a kod mešavina sa pepelom 2%.

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

MPa (P100) to 10.31 MPa (ES). The difference between these values is 2.34 MPa (22.7%).

The available data from the literature as well as previous research [2] shows that it is difficult to foreseen or find some rule/norm when it comes to shrinkage of concrete. The measurements show the largest shrinkage of concrete had mixtures with silica fume and III recycled fraction, S50, but the lowest control concrete with limestone EK, with difference of 56%. It is not possible to draw any regularity in these results: mixtures with III recycled fraction had greater shrinkage of the mixtures with II and III recycled fraction, whereby the differences in limestone and silica fume were more pronounced than in concrete with fly ash. If the classification were done according to concrete mineral addition, the largest shrinkage of concrete had a mixture of silica fume; if the criteria were aggregate, the largest shrinkage of concrete had mixture with fly ash (29% higher than the control concrete with limestone and 11.7% higher than the standards with silica fume), including mixtures of III recycled fraction S50 (4.8% more than the mixture with limestone and 22.8 % more than the mixture with fly ashes); the mixtures with II and III recycled fraction S100 (22.8% more than the mixture with limestone and 13.2% more than the mixture with fly ashes).

Water absorption goes in the range of 0.85% (mixture S50) to 2.12% (mixture EP). The highest water absorption were at mixtures of fly ashes, but the lowest by mixtures with silica fume, which is entirely in accordance with the achieved structure of concrete, and how was showed in SEM analysis, it was at most porous at concrete mixtures with fly ash. Average water absorption at mixtures with silica fume was approximately 0.9%, at mixtures with granulated limestone 1%, and at mixtures with the fly ashes 2%.

By testing of water-impermeability, ingress of water to concrete with limestone and silica fume was very low, about 2 cm, which defines these mixtures as impermeable, while by the mixtures with fly ashes there was higher penetration of wa-

7. ZAKLJUČCI

Zbog neospornih prednosti, kao što su smanjenje potrebne radne snage, odsustvo vibracija, smanjenje nivoa buke na gradilištu, ujednačena izgradnja koja u ovom slučaju zavisi samo od kvaliteta projektovane betonske mešavine, došlo je do toga da se trend samougrađujućeg betona iz Japana proširi na čitav svet. Poslednjih godina i u Srbiji se otpočelo sa proučavanjem, projektovanjem i primenom samougrađujućeg betona, 2012. je usvojena Evropska norma 12350 delovi (8-12) koji se odnose na ispitivanje ovog betona, a 2014. EN 206 – 9 (2010) kojom se ocenjuju rezultati ispitivanja.

Na osobine svežeg samougrađujućeg betona utiču i vrsta mineralnog dodatka i vrsta primenjenog agregata. Najbolja svojstva samougradljivosti se postižu 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 sa pepelom su imale najbolji odnos prečnika rasprostiranja (fluidnosti) i otpornosti na segregaciju. Zbog toga što su veoma sitne (oko 100 puta sitnije od zrna cementa ili pepela) sa jako velikom površinom zrna (15000 – 20000 m^2/kg), čestice silikatne prašine značajno povećavaju koheziju betona i nepovoljno utiču na samougradljivost svežeg betona. Mešavine sa silikatnom prašinom su bile teško pokretne, imale najmanje prečnike rasprostiranja ali i najveću otpornost na segregaciju. Primena recikliranog agregata, zbog oštroivičnog oblika zrna koji povećava trenje, takođe nepovoljno utiče na svojstva samougradljivosti betona, te je bilo neophodno intervenisati u smislu smanjenja III i povećanja I frakcije za 5%, kako bi se postigla željena konzistencija.

Da bi se postigla projektovana konzistencija, trebalo je intervenisati u količini vode, tj. primeniti različit vodocementni faktor pri istim ostalim konstituentima betona, i to iz dva razloga: zbog primene različitog mineralnog dodatka i zbog primene recikliranog agregata. Primenjena je preporuka iz literature da se izmeri upijanje vode recikliranog agregata za 30 min i ta količina vode doda u beton, pri čemu je agregat najpre mešan sa delom potrebne vode (dakle, najpre zasićen) a onda su dodavane ostale komponente. Najveća količina vode za ostvarivanje željene konzistencije je bila potrebna kod mešavina sa pepelom, dok je i kod betona sa silikatnom prašinom trebalo značajno povećati količinu potrebne vode.

Uticaj silikatne prašine na čvrstoću betona pri pritisku: silikatna prašina je pucolan i za njeno aktiviranje je neophodno prisustvo kalcijum hidroksida. Kalcijum hidroksid nastaje u procesu hidratacije cementa tako da silikatna prašina može da se aktivira tek kad cement počne da reaguje. Kako beton počinje da vezuje i očvršćava, pucol-

ter, about 10cm, due to the increased porosity of these concrete mixtures. According to the criteria the penetration of water should not be higher than 4cm [4], which implies that concrete mixtures with fly ash could consider permeable.

7. CONCLUSIONS

By reason of undeniable advantages, such as reduction of needed labor, lack of vibration, reduction of noise levels at the site, balanced building process, which in this case depends only on the quality of the designed concrete mixture, the trend of self-compacting concrete spread from Japan to the whole world. Research began in Serbia recently too, also with design and application of self-compacting concrete. In year 2012 was adopted the European norm 12350 parts (8-12), related to the testing of this SCC concrete, and in 2014 also EN 206 - 9 (2010) which evaluated the test results.

The impact on the properties of fresh self-compacting concrete have mineral addition types and type of applied aggregates. Best self-compacting properties are obtained by usage of ground limestone. These concrete types had the best fluidity, viscosity, after passing through the reinforcement they were completely horizontal, but due to the highest dispersion resulted in lowest resistance to segregation. Mixtures with fly ashes had the best ratio of fluidity and resistance to segregation. Due to their small proportion (about 100 times smaller than a grain of cement or fly ash) with a very large grain surface (15000 - 20000 m^2/kg), powder of silica fume significantly increase the cohesion of concrete and adversely affect self-compacting of fresh concrete. Mixtures with silica fume were with severe mobility, had the lowest spreading diameters, but also the greatest resistance to segregation. The use of recycled aggregates, due to particle sharp edged grain shape, which increases friction, also adversely affect the properties of self-compacting concrete. It was necessary to intervene in terms of III fraction reduction and increase of III fraction for 5%, to achieve the desired consistency.

In order to achieve designed consistency, it was necessary to change something regarding amount of water, i.e. to apply different water-cement ratio at the other same constituents of concrete, by two reasons: because of the application of different mineral addition and due to the application of recycled aggregates. We have followed the recommended instruction and measured the water absorption of recycled aggregate for 30 minutes and then added that amount of water to the mixer; the aggregate is mixed at first with part of needed water (i.e., first-saturated) and then added other components. The highest amount of water for achievement of the desired consistency was needed for a mixture with fly ashes, but by concrete with silica fume the amount of required water should be significantly increased.

anska aktivnost silikatne prašine postaje dominantna reakcija. Zbog veće specifične površine i višeg sadržaja silicijm dioksida, silikatna prašina je mnogo reaktivnija od letećeg pepela. Ova pojačana reaktivnost će prvobitno znatno pojačati brzinu hidratacije C3S frakcije cementa ali se nakon 2 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 rezultujući poboljšanom čvrstoćom i nepropusnošću 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 (SiO_2) i kalcijum hidroksida ($Ca(OH)_2$) ili kreča, koji je nus produkt hidratacije Portland cementa. Slaba pucolanska reakcija se odvija tokom prvih 24 sata na 20°C. Zbog toga se za datu količinu cementa, sa povećanjem sadržaja letećeg pepela postižu niže rane čvrstoće. Prisustvo letećeg pepela usporava reakciju alita u okviru Portland cementa u ranom stadijumu. Međutim, produkcija alita se kasnije ubrzava zahvaljujući stvaranju jezgara hidratacije na površini čestica letećeg pepela. Kalcijum hidroksid se utiskuje na površinu staklastih čestica reagujući sa SiO_2 ili Al_2O_3- SiO_2 rešetkom. Sporiji priraštaj čvrstoće betona sa 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 praćenje 90 – dnevne čvrstoće betona. SEM analize jasno pokazuju izuzetno sunđerastu, tj. poroznu strukturu betona sa 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 sa druge strane, priraštaj dvodnevne čvrstoće potvrđuje da ove čestice predstavlja 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 sa krečnjakom imao bolje performanse u svežem stanju, što treba imati u vidu, posebno ako se uključi i ekonomski faktor.

Razlike u čvrstoći pri pritisku između betona sa pepelom i betona sa silikatnom prašinom se kreću od 13% (kod etalona) do 37% kod betona sa krupnim recikliranim agregatom, pri čemu be-

Silica fume influence in concrete compressive strength: silica fume is pozzolana and for its activation presence of calcium hydroxide is necessary. Calcium hydroxide is formed in the process of cement hydration; therefor silica fume can be activated only after the cement begins with reaction. As concrete starts with setting and strengthening, activity of pozzolanic in silica fume becomes the dominant reaction. Due to the high specific surface area and a higher content of silicium dioxide, silica fume is much more reactive than the fly ash. This increased reaction will initially enhance the speed of C3S hydration of cement fraction, but after two days the process is normalized. By reaction of silica fume and forming of calcium silicate hydrates, which results with filling of pores and voids. At the same time formed crystals made connection within the space between cement particles and aggregate grains. With only the physical presence of silica fume in the mix, the concrete matrix will be very homogeneous and dense, resulting in improved strength and impermeability. Clearly represented in the SEM images. Additionally, the particles of silica fume, due to their size, could cause "micro filer" effect, with filling the transit area in concrete.

Influence of fly ash on concrete compressive strength: when fly ash is added to concrete begins pozzolanic reaction between silicon dioxide (SiO_2) and calcium hydroxide ($Ca(OH)_2$) i.e. lime, which is a by-product of Portland cement hydration. Light pozzolanic reaction takes place during the first 24 hours at 20°C. Therefore, given amount of cement with increased fly ash results in lower early strength. The presence of fly ash slows reaction of alite within the Portland cement in the early stage. However, the production of alite would later accelerate thanks to the formation of hydration core on the surface of fly ash particles. Calcium hydroxide is imprinted on the surface of the glassy particles having its reaction with SiO_2 or SiO_2 Al_2O_3- grid. Slower growth of concrete strength with fly ash prevents its application, at the expected high early strength, which can be solved by applying the accelerator. At the available literature sources has been recommended process of the design and monitoring of the 90 - day long concrete strength. SEM analysis clearly shows an extremely spongy, i.e. porous concrete structure with fly ash, regardless of the type of applied aggregate.

Impact of ground limestone on concrete compressive strength: SEM analysis showed the presence of limestone particles in concrete after 28 days, and also the growth of the two-day strength confirms the fact about these particles as the hydration core C_3S and C_2S. They accelerate the hydration reaction, which confirms the ground limestone as chemically inert.

Compressive strength differences between concrete with silica fume and limestone does not exceed 10% at the same cement quantity, whereby the concrete with limestone had a better pertoni sa pepelom imaju veću ekološku vrednost jer rešavaju problem deponovanja ogromnih količina letećeg pepela.

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

Skupljanje u cementnoj pasti je povećano kada se koristi silikatna prašina o čemu treba posebno voditi računa, što je u skladu da 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 propratiti.

Najmanje upijanje vode su je zabeleženo kod betonskih mešavina sa silikatnom prašinom a najveće kod betona sa pepelom. Ipak, ova razlika nije previše velika (oko 1%) obzirom na sunđerastu građu betona sa 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 sa pucolanskom aktivnošću letećeg pepela da učestvuje u C-S-H formacijama i popunjava pore. Svi betoni su imali dobru vodonepropustljivost osim mešavina sa letećim pepelom, što je u skladu sa ostvarenom mikrostrukturom.

Glavni problem primene recikliranog agregata jeste povećana poroznost koja je posledica postojanja zaostale stare cementne paste na zrnima agregata. Postojanje stare cementne paste je osnovni 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.

Samougrađujući betoni sa recikliranim agregatom mogu biti vodonepropustljivi. Na ovu osobinu utiče kapilarna poroznost kako starog cementnog kamena preostalog na agregatu, tako i kapilarna poroznost cementnog kamena novog betona. Ukoliko je agregat dobijen drobljenjem betona male poroznosti, vodonepropustljivost novog betona će zavisiti od ostvarene strukture novog cementnog kamena.

Primenom sva tri ispitivana mineralna dodatka se mogu 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 čini da ovakvi betoni s pravom ponesu naziv ekološki.

formances in the fresh state. This fact should be borne in mind, especially if we include the economic factor in the equation.

Compressive strength differences between concrete with fly ash and with silica fume are in range from 13% (for standards) to 37% by/in concrete with recycled coarse aggregate, while concrete mixtures with fly ash have greater ecological value, because it solves the problem of depositing huge quantities of fly ash.

Results of tensile strength by bending are consistent and show that kind of mineral addition and aggregate does not affect the value of this strength.

Shrinkage at the cement paste is increased by usage of silica fume, which should be specifically taken into account, according to the available data. Rule of shrinkage is not possible to determine as well some general conclusion, which means careful monitoring of shrinkage process for each concrete mixture.

Minimum water absorption is recorded in concrete mixtures with silica fume, and the largest in concrete with fly ash. However, this difference is not too significant (about 1%) regarding to the spongy structure of concrete with fly ash, which could be explained by a lower content of open pores with 1- 10 µm; water flow through them is the fastest, which is also related to the pozzolanic activity of fly ash to participate in the CSH formations and fills the pores. All concretes had a good water-impermeability, except for mixtures with fly ash, which is in accordance with the achieved microstructure.

The main problem regarding the application of recycled aggregates is increased porosity, which is caused by old cement paste at aggregate grains. Cement paste is also responsible for unequal quality of the aggregates and it leads to a reduction in compressive strength of concrete. There are methods of aggregates "purifying", which increase the cost of concrete, but the environmental benefits are significant.

Self-compacting concrete with recycled aggregate can be water – impermeable. This concrete property is affected by capillary porosity, from old cement remaining in the aggregate as well as by capillary porosity of the cement stone in new concrete. If the aggregate is obtained by crushed concrete of small porosity, water – impermeability of new concrete will depend on the structure of the new cement stone.

Applying of all three mineral additions, opens possibility for obtaining self-compacting concretes of high performances. The main addition is silica fume, but having in mind economic and environmental components of fly ash, as well as the slight difference in obtained results, it should certainly be taken into account. Due to the use of recycled aggregates, these concrete types could be classified as ecological.

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