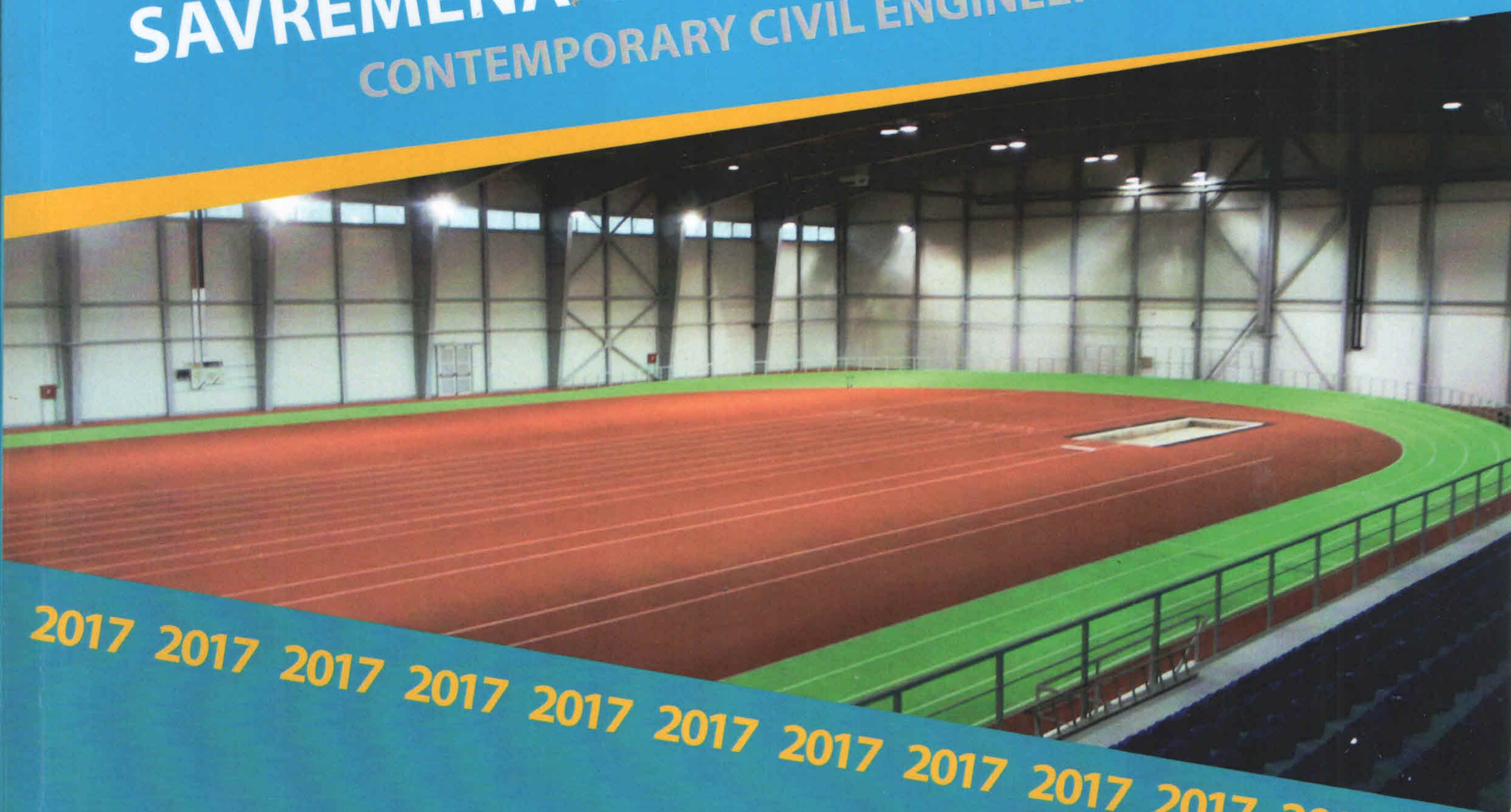
SAVREMENA GRAĐEVINSKA PRAKSA

CONTEMPORARY CIVIL ENGINEERING PRACTICE



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Andrevlje, 25. i 26. maj

DEPARTMAN ZA GRAĐEVINARSTVO I GEODEZIJU
FAKULTET TEHNIČKIH NAUKA
NOVI SAD

DRUŠTVO GRAĐEVINSKIH INŽENJERA NOVOG SADA
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DRUŠTVO GRAĐEVINSKIH INŽENJERA NOVOG SADA

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ISTRAŽIVANJE SVOJSTAVA SVEŽEG I OČVRSLOG SAMOZBIJAJUĆEG BETONA SA MINERALNIM DODACIMA NA BAZI INDUSTRIJSKIH NUSPRODUKATA

PROPERTIES OF FRESH AND HARDENED SELF-COMPACTING CONCRETES WITH MINERAL ADDITION OF INDUSTRIAL BYPRODUCTS

Rezime: *Predmet ovog istraživanja su svojstva jedne posebne vrste betona, samozbijajućeg betona (Self-compacting Concrete - skraćeno SCC) za koji se može reći da je formiran ekstrapolacijom koncepta upotrebe superplastifikatora, u pravcu dobijanja betona tečnijih konzistencija otpornih na segregaciju. U okviru ovog rada biće prikazani rezultati ispitivanja jedanaest mešavina SCC sa različitim mineralnim dodacima: referentna SCC mešavina sa krečnjačkim brašnom kao mineralnim dodatkom, tri mešavine sa delimičnom zamenom mase krečnjačkog brašna letećim pepelom, tri mešavine sa delimičnom zamenom mase krečnjačkog brašna sprašenim recikliranim betonom i četiri mešavine sa delimičnom zamenom mase krečnjačkog brašna sprašenim sumporom. U radu su prikazani rezultati ispitivanja fizičko-mehaničkih svojstava SCC mešavina, i izvedeni odgovarajući zaključci u vezi sa promenom pomenutih svojstava u zavisnosti od parametara upotrebljenog mineralnog dodatka. U svežem stanju ispitivanja su obuhvatila: zapreminsku masu, rasprostiranje sleganjem, L-boks, V-levak, otpornost prema segregaciji. U očvrslom stanju, ispitivani su: čvrstoća pri pritisku, "pull-off" čvrstoća, čvrstoća pri savijanju, brzina prostiranja ultrazvučnog impulsa i dinamički modul elastičnosti. Povećanje količine raspoloživih resursa za spravljanje SCC mešavina sa jedne i pozitivan uticaj na životnu sredinu putem smanjenja količine ovih materijala na deponijama, sa druge strane, dva su osnovna pozitivna efekta koja bi trebalo da proizađu iz istraživanja.*

Ključne reči: *SCC beton, filer, industrijski nusprodukti, fizičko-mehanička svojstva, održivo građevinarstvo*

Abstract: *The theme of the presented investigation was the investigation of the properties of one special type of concrete, Self-compacting concrete (SCC), which can be regarded as a product of extrapolation of superplasticizer use concept, towards the obtaining concrete of fluid consistency, but prone to segregation. Within this paper, results of investigation conducted on eleven SCC mixtures, made with different mineral additions, are presented. These mixtures are: reference SCC mixture with limestone filler as addition, three mixtures with partial replacement of limestone filler with fly ash, three mixtures with partial replacement of limestone filler with ground recycled concrete, and four SCC mixtures with the partial replacement of limestone filler with ground sulfur. The results of investigation of physical and mechanical properties of these mixtures are included in the paper together with the conclusion regarding the change of the mentioned properties with the parameter – the used mineral addition. In fresh state, following properties were investigated: density, slump flow, L-box test, V-funnel test, segregation resistance. In hardened state investigations included: compressive strength, "pull-off" strength, flexural strength, ultrasonic pulse velocity and dynamic modulus of elasticity. Increasing the amount of resources available for the preparation of SCC mixtures, with a positive environmental impact – reduction of these materials in landfills, can be considered as two main positive effects that should arise from the presented research.*

Key words: *Self-compacting concrete, mineral addition, industrial by-products, physical and mechanical properties, sustainable construction.*

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1. UVOD

Usled efekta globalnog zagrevanja i promena u klimi, poslednjih nekoliko decenija oslobađanje značajnih količina štetnih materija u atmosferu obeležava savremeno društvo. Kjoto protokol iz 1997. navodi oslobađanje ugljen-dioksida (CO_2) kao glavni problem uticaja na spoljašnju sredinu [1]. Građevinska industrija predstavlja jedan od značajnih izvora ovog zagađenja. Naime, utvrđeno je da se prilikom proizvodnje jedne tone cementa oslobodi skoro jedna tona ugljen-dioksida [2]. Dalje, proizvodnja cementa na godišnjem nivou prouzrokuje emisiju od više od 500 000 tona sumpor-dioksida, azotovih oksida i ugljen-monoksida [2]. Osim pomenutih sastojaka, gasovi emitovani u postrojenjima za proizvodnju cementa sadrže još i azot, ugljen-dioksid, vodu i kiseonik. Ovi gasovi sadrže izvesne količine prašine, hlorida, fluorida, organska jedinjenja i teške metale, što doprinosi količini štetnih materija koje se oslobađaju u atmosferu.

Savremeni konceptualni pristup u graditeljstvu zasniva se na principu da je u svakom smislu potrebno vršiti višeparametarsku optimizaciju – konkretno, u slučaju primene određenog građevinskog materijala, nije dovoljno da taj materijal ima povoljne ili prihvatljive fizičko-mehaničke karakteristike, jer postoji veliki broj drugih karakteristika ovog materijala, koje je neophodno sagledati pre eventualne primene, kao što su cena, tehnologičnost, trajnost, životni vek i dr. [3],[4]. Ovakva analiza mora obuhvatiti i ekološke efekte primene konkretnog građevinskog materijala, u smislu dejstva na čoveka i životnu sredinu.

Beton, kao jedan od najčešće upotrebljavanih građevinskih materijala, spravlja se sa cementom, pa stoga prethodno pomenuti aspekti imaju ključan uticaj na njegovu primenu i evoluciju. Konvencionalni beton se ugrađuje pomoću vibrirajuće opreme u cilju redukcije zaostalog vazduha u betonu, zatim eliminisanja kaverni i drugih šupljina na kontaktima sa armaturom i oplatom (takozvani normalno vibrirani beton, Normal Vibrated Concrete – NVC). Rezultat je gušći i homogeniji beton, što je osnov za njegovo prihvatljivo ponašanje u konstrukciji. Tehnološka operacija kompaktiranja tradicionalno igra ključnu ulogu u proizvodnji kvalitetnog betona sa optimalnom čvrstoćom i trajnošću [5].

Razvojem hemijskih dodataka, u prvom redu plastifikatora, odnosno superplastifikatora, omogućeno je lakše ugrađivanje betona krućih konzistencija [6]. Doziranjem malih količina superplastifikatora (najčešće do 2% u odnosu na masu cementa u betonu) struktura svežeg betona se optimizuje, tako što se smanjuje trenje između čestica, što za rezultat daje pokretljivije i obradljivije betone (betone tečnijih konzistencija) koje je lakše ugraditi, uz zadržavanje iste količine vode. Razvoj superplastifikatora najnovije generacije na

1. INTRODUCTION

Due to the global warming effect and the changes in climate, a significant amount of harmful materials are released in the atmosphere in the last several decades, which characterizes the contemporary society. The Kyoto protocol, from 1997, states the release of the carbon-dioxide as the key problem of influence on the environment [1]. The building industry was recognized as one of the most significant sources of this pollution. Namely, it was found that for the production of one ton of cement, almost one ton of carbon-dioxide is released in the atmosphere [2]. Further on, the production of cement annually causes the emission of more than 500000 tons of sulfur-dioxide, oxides of nitrogen and carbon monoxide [2]. Beside the mentioned components, gasses released from the facilities for cement production contain also nitrogen, carbon-dioxide, water and oxygen. These gasses contain certain quantities of dust, chlorides, fluorides, organic compounds and heavy metals, which contribute to the quantity of harmful matters released in atmosphere.

Contemporary conceptual approach in building industry is based on the principle that in every sense a multi-parameter optimization should be conducted – explicitly, in the case of use of certain building material, iti is not sufficient that this material has favorable or acceptable physical and mechanical properties, because there is a large number of other properties of this material, which is necessary to be considered ahead of the application, such as: price, technology, durability, pot-life etc. [3],[4]. Such analysis has to include ecological effects of building material use, in the sense of its effect on humanity and our environment.

Concrete, as one of the most common building materials, is made with cement, and therefore the fore mentioned aspects comprise key influence on its use and evolution. Conventional concrete is placed with the aid of vibrating equipment in the aim of reduction of entrained air in concrete, then to eliminate the caverns and other voids on contacts with re-bars and formwork (the so-called normal vibrated concrete – NVC). The result is the denser and more homogenous concrete, which is a must for its acceptable behavior in the structure. Technological operation of compaction traditionally plays the key role in the production of quality concrete with optimum strength and durability [5].

With the development of chemical admixtures, namely plasticizers, or superplasticizers, easier placing of stiffer concrete was enabled [6]. Using small quantities of superplasticizer (mostly up to 2% in relation to the mass of cement in concrete) a structure of fresh concrete is optimized, so the friction of the particles is reduced, giving as a result more flowable and more placeable concrete (fluid consistency concrete), which are easier to place, whilst maintaining the same quantity of wabazi polikarboksilata, koji su ušli u širu primenu 90-tih godina prošlog veka, omogućio je uspešnu primenu samozbijajućeg betona (Self-Compacting Concrete - skraćeno SCC). Ovi betoni se u literaturi, naročito anglosaksonskog porekla, ponekad nazivaju i Self-Consolidating Concrete, ali i Self-Leveling Concrete. Samozbijajući betoni se tako mogu definisati kao betoni koji će bez primene mehaničkih sredstava za ugrađivanje (potpuno nezavisno od stručnosti angažovanih radnika) popunjavati sve uglove oplate i uzane prostore između šipki gusto raspoređene armature (samo pod dejstvom sopstvene težine) tako da se u završnoj fazi dobije kompaktan beton veće trajnosti [7]. Na osnovu istraživanja obavljenog u SAD, može se reći da je SCC našao svoje mesto u industriji betona, obzirom da se približno 40% prefabrikovanih proizvoda u SAD dobija upotrebom SCC, dok je u segmentu proizvodnje betona izlivenog na licu mesta taj procenat 2-4% [8]. Može se reći da je, po pitanju primene SCC, i u drugim razvijenim zemljama u svetu situacija slična navedenoj.

2. KOMPONENTNI MATERIJALI

Materijali koji se primenjuju za spravljanje SCC su potpuno isti koji se i inače primenjuju kod NVC. Kod nas se za spravljanje SCC lokalni materijali uspešno upotrebljavaju već dugi niz godina [9],[10],[11].

2.1. Sastav

Samozbijajući betoni (SCC) imaju specifičan sastav koji se razlikuje od sastava normalno vibriranih betona (NVC). Prva razlika u sastavu između SCC i NVC odnosi se na fine čestice, gde je očigledno da se, osim cementa, u sastavu samozbijajućeg betona uvek nalaze i drugi praškasti materijali. U ove materijale spadaju filer i eventualno prisutne sitne čestice u pesku i krupnom agregatu.

Dalje, za samozbijajući beton je karakterističan i manji sadržaj vode u odnosu na NVC, zahvaljujući obaveznoj upotrebi superplastifikatora. Nešto veći sadržaj vazduha kod SCC, koji je logična posledica nepostojanja sredstava za ugrađivanje, uspešno se kompenzuje smanjenjem sadržaja vode (tj. niskim vodocementnim faktorom), tako da se ostvaruje čvršća, kompaktnija i na hemijske uticaje otpornija struktura samozbijajućeg betona. U odnosu na NVC, SCC sadrži manje krupnog agregata, pri čemu je najkrupnije zrno agregata u najvećem broju slučajeva ograničeno na 16 mm ili 22,5 mm.

2.2. Tipovi (kategorije) SCC

Za SCC je karakteristična podela u tri kategorije, odnosno tipa; to su praškasta, viskozna i kombinovana kategorija, u zavisnosti od pravca formiranja sastava, kojim se omogućava tražena

ter. Development of the last generation of superplasticizers, based on polycarboxilates, that entered the wider application during the 90-s of the last century, enabled the successful application of Self-compacting Concrete – SCC. These concrete are in paper, particularly of Anglo-Saxon origin, also referenced as Self-Consolidating Concrete, and Self-Leveling Concrete. SCC can be defined as concrete that will, without any means of mechanical compaction (and completely independent of the engaged workers competences) will fill all the formwork parts and narrow spaces between the bars of the densely arranged reinforcement bars (as the result of its own weight), ultimately producing compact concrete of higher durability [7]. Based on the investigation conducted in the USA, it can be said that SCC found its place in the industry of concrete, because approximately 40% of precast products in USA are obtained using SCC, while in the segment of the production of the ready mix concrete such percentage is only 2-4% [8]. The situation regarding the application of SCC is similar in the other developed countries in the world.

2. COMPONENT MATERIALS

Materials used for the production of SCC are completely the same, as the ones used for NVC. In our conditions, for production of SCC, local materials are successfully used for years [9],[10],[11].

2.1. Composition

Self-compacting concrete (SCC) has rather unique composition, different from the Normal Vibrated Concrete (NVC). The first difference between SCC and NVC refers the fine particles, where it is obvious that, besides cement, other powder materials are found in the composition of Self-compacting concrete. Filler and eventually fine particles found in sand and in coarse aggregate add up to that amount.

Lower water content than in the case of NVC is also characteristic for SCC, due to the use of superplasticizers. Further on, a higher entrained air content is the logical consequence of the absence of the placing equipment, and it is successfully compensated with lower water content (lower water to cement ratio). Therefore a stronger, more compact and on chemical influence resistant structure of SCC is formed. In comparison to NVC, SCC contains less coarse aggregate, whereas the bigger grain of aggregate in most cases doesn't exceed 16 mm or 22.5 mm.

2.2. Types (categories) of SCC

SCC is usually divided into three categories (types): powder type, viscose type and combined type, depending on its structure, which enables the aimed viscosity level [12],[13],[14].

Powder type of SCC is characterized by the viskoznost [12],[13],[14].

Kod praškastog tipa SCC karakterističan je nizak vodopraškasti faktor (W/P), kao i visok sadržaj praškastih (finih) čestica (najčešće od 550 kg/m^3 do 650 kg/m^3). Vodopraškasti faktor (W/P) se definiše kao odnos mase vode i mase praškaste komponente u betonu (cement, mineralni dodatak i druge praškaste komponente, generalno sitnije od 0,125 mm). Ovako definisan faktor se češće koristi za karakterizaciju sastava SCC betona nego vodocementni faktor (W/C), koji predstavlja odnos mase vode i mase cementa. Konačno, ukoliko se uvede pojam tečne (fluidne komponente) u koju osim vode spadaju i superplastifikator i ostale tečne komponente, mogu se po istom principu definisati i fluidopraškasti (F/P) i fluidocementni (F/C) faktor. Zbog visokog sadržaja filera, praškasti tip SCC je osetljiv na promene komponentnih materijala. U praktičnoj primeni se obično povećava sadržaj filera na račun količine cementa, da bi se postigle optimalne vrednosti čvrstoće pri pritisku i toplote hidratacije. Zbog niskog W/P faktora ovakvi betoni po pravilu imaju visoke čvrstoće i nešto veće vrednosti skupljanja, a nisku permeabilnost. Pri tome je neophodno obratiti posebnu pažnju na mogućnost interakcije superplastifikatora i filera. Ovaj tip SCC mešavine je i istorijski posmatrano bio prvi napravljen prototip.

Viskozni tip SCC karakteriše se visokim sadržajem hemijskog dodatka modifikatora viskoziteta (VMA), koji se dozira da bi se povećala plastična viskoznost. U poređenju sa praškastim tipom, viskozni ili VMA tip SCC sadrži veće količine superplastifikatora, kao i više vrednosti W/P faktora. Sa druge strane, sadržaj finih čestica može da bude manji (najčešće 350-450 kg/m^3). Ovo smanjenje sadržaja finih čestica omogućeno je obzirom da se odgovarajući nivo viskoznosti ovog tipa SCC kontroliše dodavanjem VMA. Kod viskoznog tipa SCC posebna pažnja treba da bude posvećena mogućoj nekompatibilnosti između superplastifikatora i VMA [15].

Treća kategorija, odnosno tip SCC naziva se kombinovani SCC. Ovaj tip SCC se najčešće formuliše u slučajevima kada je potrebno vršiti poboljšanje robusnosti praškastog tipa SCC dodavanjem male količine VMA. U ovim mešavinama je sadržaj VMA niži nego kod viskoznog tipa betona. Sadržaj praškastih čestica je kod ovog betona niži (odnosno W/P faktor je viši) nego kod praškastog tipa SCC. Odgovarajući nivo viskoznosti ovog tipa SCC se omogućava istovremenom upotrebom VMA i praškastih čestica. Za ovaj tip SCC karakteristična je veća sposobnost popunjavanja, visoka otpornost prema segregaciji i poboljšana robusnost [16]. Poseban problem kod kombinovanog tipa SCC predstavlja najveći broj komponenata, u odnosu na ostale dve kategorije, usled upotrebe dva tipa hemijskih dodataka, umesto jednog. Takođe, iz istog razloga, u najvećem broju slučajeva neminovno dolazi i do poskupljenja be-

low water to powder ratio (W/P), as well as by the high content of powder (fine) particles (usually 550 kg/m^3 to 650 kg/m^3). This W/P ratio is defined as ratio of two masses, mass of water and mass of powder component in concrete (cement, mineral additive and other powder components, generally finer than 0.125 mm). Defined this way, this ratio is more common for the characterization of SCC than water to cement ratio (W/C), which presents ratio of water and cement masses. Finally, if the term “fluid component” is defined as the mass of all fluid components (water, superplasticizer and other fluid components), fluid to powder (F/P) and fluid to cement (F/C) ratios can be defined based on the same principle. Thanks to the high content of filler, powder SCC type is sensitive to the changes of component materials. In the practical application, content of filer is usually increased and cement content is decreased, in order to achieve optimum values of compressive strength and heat of hydration. Owing to the low W/P ratio, such concrete has high compressive strength and high heat of hydration, but low permeability. Additionally, a lot of attention has to be aimed on the possibility of interaction of superplasticizer and filler. This SCC type was the first prototype, historically speaking.

Viscous SCC type is characterized by high content of chemical admixture – Viscosity modifying agent (VMA), which is applied to increase the plastic viscosity. Unlike the powder type, viscous or VMA type of SCC contains higher contents of superplasticizer, and also higher values of W/P ratio. On the other hand, content of fines can be lower (mostly 350-450 kg/m3). This decrease in fines content is enabled due to the fact that aimed viscosity levels of this SCC type are controlled with the VMA content. For the viscous SCC type, special attention should be paid to the possible incompatibility between superplasticizer and VMA [15].

The third type of SCC was named combined SCC type. This type is most commonly formulated in the cases when the improvement of robustness has to be performed, of the originally powder type of SCC. This is achieved by addition of low quantity of VMA. In these mixtures, content of VMA is lower than in the viscous type of concrete. Content of powder particles is lower for this type (higher W/P ratio) than for the powder type of SCC. Aimed level of viscosity of this SCC type is enabled by the simultaneous use of VMA and the powder particles. For this SCC type, higher filling ability is common, higher segregation resistance and improved robustness [16]. A particular problem of this, combined, type of SCC presents the number of components, which is highest of all mentioned categories, due to the use of two types of chemical admixtures. Also, from the same reason, this usually leads to the increase in the concrete price, in comparison to the previous two categories.

tona u odnosu na prethodne dve kategorije.

3. EKSPERIMENTALNA ISPITIVANJA

Jedan od ciljeva istraživanja predstavljenog u okviru ovog rada bio je da se istraže mogućnosti upotrebe raspoloživih komponentnih materijala prilikom spravljanja SCC u smislu upotrebe letećeg pepela iz domaćih termoelektrana, u dostavljenom stanju u svojstvu filera, uz postizanje zadovoljavajućih svojstava samougradljivosti. Takođe, cilj je bio i da se izvrše procene mogućnosti upotrebe sprašenog otpadnog sumpora (kao nusprodukta prilikom rafinacije nafte), odnosno sprašenog otpadnog betona, u svojstvu filera, što bi povećalo obim raspoloživih mineralnih dodataka betonu sa jedne, i utrošak ovih nusprodukata, sa druge strane.

Ispitivanja su sprovedena u Laboratoriji za materijale Instituta za materijale i konstrukcije Građevinskog fakulteta Univerziteta u Beogradu. U četiri SCC mešavine je ispitivan uticaj sadržaja letećeg pepela poreklom iz TE "Kolubara". U tri mešavine ispitivan je sadržaj sprašenog recikliranog betona, dok je još četiri mešavine spravljeno sa dodatkom sprašenog sumpora. Pritom, količine ostalih materijala u mešavinama održavane su konstantnim, tj. količine: cementa, vode, sitnog (rečnog peska) i krupnog agregata (druge i treće frakcije rečnog agregata).

3.1. Komponentni materijali

Za ispitivanja prikazana u ovom radu upotrebljen je frakcionisani prirodni agregat (rečni agregat, podeljen u tri standardne frakcije), poreklom iz reke Dunav. Granulometrijski sastav upotrebljenog agregata ispitan je prema [17] i prikazan grafički, na slici 1. Modul finoće (modul zrnavosti) frakcije I (0/4) iznosio je 2,92, i nalazio se u granicama 2,30-3,60 [18]. Izračunati moduli finoće (moduli zrnavosti) frakcija II (4/8) i III (8/16) iznosili su 6,04 i 6,99, respektivno. Sadržaj sitnih čestica u agregatu ispitivan je prema odgovarajućem standardu [19] i kod frakcije I (0/4) iznosio je 0,59% za zrna sitnija od 0,063 mm, odnosno1,68% za zrna sitnija od 0,09 mm. U krupnom agregatu (zrna krupnija od 4 mm) ovaj sadržaj je bio blizak nuli.

Svojstva SCC, kao i kod NVC, zavise od granulometrijskog sastava agregata, odnosno od učešća frakcija u mešavini. Međusobni odnos učešća frakcija krupnog agregata, frakcije II (4/8) i frakcije III (8/16) utvrđen je na osnovu ispitivanja najveće vrednosti zapreminske mase mešavine ove dve frakcije agregata u suvom zbijenom stanju. Pokazalo se da se visoke vrednosti zapreminske mase mešavine agregata mogu postići u širokom rasponu odnosa frakcija II (4/8) i III (8/16). Na osnovu ove analize je usvojeno da učešća frakcije II (4/8) i frakcije III (8/16) u mešavini agregata budu jednaka (međusobni odnos 1:1). U istraživanju je na osnovu prethodnih proba izvedenih na betoni-

3. EXPERIMENTAL INVESTIGATIONS

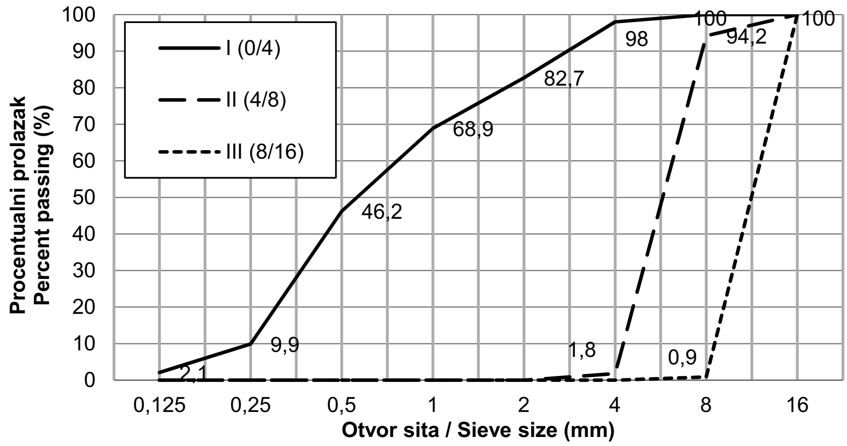
One of the aims of the investigation depicted in this paper was to study the possibilities of use of different component materials for the production of SCC, regarding the use of fly ash from our thermal power plants, in the original state, as filler, achieving the favorable properties of self compactness. Also, the aim was to estimate the possibility of using ground waste sulfur (as a byproduct obtained through oil refining), or ground waste concrete, as filler, which could increase the range of available mineral admixtures for the concrete in one hand, and the use of these byproducts on the other.

The investigation was conducted in Laboratory for materials, Institute of Materials and Structures of Civil Engineering Faculty, University of Belgrade. The influence of fly ash from Thermal Power Plant "Kolubara" was investigated in three SCC mixtures, besides reference. In another three mixtures an influence of the content of ground recycled concrete was investigated, while another four mixtures were made with the addition of ground sulfur. Also, the quantities of other materials in the mixtures were held constant, including: cement, water, fine (river sand) and coarse aggregate (second and third fraction of river aggregate).

3.1. Component materials

For the investigation depicted in this paper, natural aggregate was used (river aggregate, divided into three standard fractions), originated from the river Danube. Particle size distribution of the used aggregate was investigated according to [17] and graphically shown, on Figure 1. Fineness modulus of the fraction I (0/4) was 2.92, and was in the limits between 2.30 and 3.60 [18]. The calculated fineness moduli for II (4/8) and III (8/16) amounted to 6.04 and 6.99, respectively. Fineness content in aggregate was investigated according to the related standard [19] and for fraction I (0/4) it amounted 0.59% for the grains finer than 0.063 mm, and 1.68% for grains finer than 0.09 mm. In the coarse aggregate (grains coarser than 4 mm) this content was close to zero.

The properties of SCC, as for NVC, depend on particle size distribution of aggregate, and on the contributions of the fractions in the mixture. The ratio of coarse fractions of aggregate, fraction II (4/8) and fraction III (8/16) was determined on the basis of investigation of the highest density of mixture of these two aggregate fractions in dry compacted state. It turned out that the high values of density of aggregate can be achieved in a wide range of the ratios of fractions II (4/8) and III (8/16). Based on this analysis, contributions of fraction II (4/8) and fraction III (8/16) in the mixture of aggregate were adopted to be equal (ratio 1:1). In this investigation, based on the pilot trials, a quantity of fine aggregate was adopted to 31.8%, and coarse (ratio of fractions II : III = 1 : 1)



Slika 1. Granulometrijske krive upotrebljenih frakcija agregata (zajedno sa krivom mešavine)
Figure 1. Particle size distribution of the used fractions of aggregate (together with the mixture of aggregate)

ma usvojena količina sitnog agregata u iznosu od 31,8%, a krupnog (u odnosu frakcija II : III = 1 : 1) u iznosu od 32,6% u odnosu na ukupnu jediničnu zapreminu SCC (16,3% frakcija II i 16,3% frakcija III). Zapreminska masa upotrebljenog agregata iznosila je u proseku 1560 kg/m³, a specifična 2640 kg/m³.

U ispitivanjima sprovedenim tokom eksperimentalnog dela rada upotrebljen je "čist" cement tipa CEM I, deklarisan kao PC 42,5R, proizvođača Lafarge Beočinska fabrika cementa d.o.o., Beočin. Specifična površina cementa po metodi Blaine-a iznosila je 4240 cm²/g, a specifična masa 3040 kg/m3.

Obična voda iz gradskog vodovoda upotrebljena je prilikom spravljanja betona. Temperatura vode je merena prilikom svakog ispitivanja i kretala se u uskim granicama od 19-22°C.

U svim ispitivanjima koja su predmet ovog rada upotrebljena je samo jedna vrsta superplastifikatora na bazi polikarboksilata (specifične mase 1060 kg/m³), Glenium Sky 690, proizvođača BASF, Italija.

3.1.1 Upotrebljeni mineralni dodaci

Glavni mineralni dodatak u svim mešavinama bilo je krečnjačko brašno proizvođača "Granit Peščar" Ljig, srednje krupnoće zrna od 250 μm. Specifična masa ovog materijala iznosila je 2720 kg/m³, a zapreminska masa 1105 kg/m³. Rezultati ispitivanja hemijskog sastava krečnjačkog brašna prikazani su u okviru tabele 1, zajedno sa rezultatima ispitivanja hemijskog sastava sprašenog recikliranog betona i letećeg pepela.

Osim pomenutog mineralnog dodatka, u svojstvu filera u mešavinama su upotrebljeni leteći pepeo, sprašeni reciklirani beton i sprašeni sumpor. Učešća ovih industrijskih nusprodukata definisana su maseno, u odnosu na ukupnu masu filera u mešavini.

Leteći pepeo, poreklom iz TE "Kolubara" upotrebljen je u dopremljenom stanju. Zapreminska masa letećeg pepela u rastresitom i zbijenom stanju iznosila je 690 kg/m³ i 910 kg/m³. Specifična

in the quantity of 32.6% of the whole unit volume of SCC (16.3% fraction II and 16.3% fraction III). The average density of the used aggregate was 1560 kg/m³, and specific density was 2640 kg/m³.

For the investigations conducted through the experimental part of the investigation cement type CEM I (without additions) was used, declared as PC 42,5R, and produced by Lafarge Beočin cement factory. Specific area of cement according to Blaine amounted to 4240 cm²/g, and specific density 3040 kg/m3.

Drinking water was used for the production of concrete. Temperature of water was measured during each batching and it remained in narrow limits between 19°C and 22°C.

In all of the investigations shown in this paper the same polycarboxilate based superplasticizer was used (specific density of 1060 kg/m³) - Glenium Sky 690, produced by BASF, Italy.

3.1.1 The used mineral additions

The main mineral addition in all of the mixtures was limestone filler produced by "Granit Peščar" Ljig, with middle particle diameter of 250 μm. Specific density of this material amounted to 2720 kg/m³, and density was 1105 kg/m³. Results of the investigation of chemical composition of limestone filler are shown inside Table 1, together with the results of investigations of chemical composition of powdered recycled concrete and fly ash.

Besides the mentioned mineral addition, as fillers in the mixtures fly ash, powdered recycled concrete and powdered sulfur were used. Contributions of these industrial byproducts were defined by mass, in respect to the sum of the filler mass in the mixture.

Fly ash, originated from Thermal Power Plant "Kolubara" was used in original state, without any kind of mechanical or chemical activation. Density of fly ash in loose and compacted state amounted to 690 kg/m³ and 910 kg/m³. Specific density of this mineral filer amounted to 2190 kg/m³.

The idea of the application of powdered recycled concrete in this case was based on the use masa ovog mineralnog dodatka iznosila je 2190 kg/m^3.

Suština primene sprašenog betona u ovom slučaju ogledala se u upotrebi praškastog materijala dobijenog finim sprašivanjem tri različite vrste sitnog agregata pomoću ultracentrifugalnog mlina. Ova tri sitna agregata dobijena su drobljenjem tri različite vrste betona kontrolisanog porekla [20]. U pogledu granulometrijskog sastava može se reći da su pomenuti fileri slični, sa specifičnom površinom od 4400 cm^2/g. Polazni betoni bili su:

- Normalno vibrirani beton (NVC) spravljen sa prirodnim agregatom, koji je nakon drobljenja prosejan i čija je najsitnija frakcija I (0/4 mm) dalje sprašena. Sprašivanjem ovog peska dobijen je reciklirani praškasti mineralni dodatak A;
- Normalno vibrirani reciklirani beton (RAC50), spravljen sa rečnim peskom i sa krupnim agregatom, koji se sastojao iz 50% rečnog krupnog agregata i 50% recikliranog krupnog agregata – dobijenog drobljenjem demoliranog betona. I ovaj beton je nakon drobljenja prosejan i njegova najsitnija frakcija I (0/4 mm) je dalje sprašena. Sprašivanjem ovog peska dobijen je reciklirani praškasti mineralni dodatak B;
- Normalno vibrirani reciklirani beton (RAC100) spravljen sa rečnim peskom i sa recikliranim krupnim agregatom. Celokupna količina krupnog agregata za ovaj beton dobijena je drobljenjem demoliranog betona. I beton RAC100 je takođe nakon drobljenja prosejan i njegova najsitnija frakcija I (0/4 mm) je dalje sprašena, tako da je dobijen reciklirani praškasti mineralni dodatak C.

Sumpor (specifične mase 2050 kg/m^3), koji je upotrebljavan u svojstvu mineralnog dodatka u ovom radu, potiče iz Rafinerije nafte Pančevo. Pre upotrebe sumpor je fino samleven u prah, pomoću ultracentrifugalnog mlina. Finoća mliva upotrebljenog sprašenog sumpora iznosila je 2600 cm^2/g.

of fine powder materials, obtained by fine grinding process of three different types of fine aggregate, using special grinding device. These three types of fine aggregate were obtained by grounding three different types of concrete with controlled origin [20]. Regarding particle size distribution, a conclusion can be made that these fillers were similar, with specific area of 4400 cm^2/g. Starting concretes were:

- Normal vibrated concrete (NVC) made with natural aggregate; after grinding it was sieved and its finest fraction I (0/4 mm) was further powdered (ground). By grinding this sand, recycled powder mineral addition A was obtained;
- Normal vibrated recycled concrete (RAC50), was produced with river sand and with coarse aggregate, containing 50% of river coarse aggregate and 50% of recycled coarse aggregate – obtained by grinding of demolished concrete. This concrete was also sieved after the grounding and its finest fraction I (0/4 mm) was further ground. By grinding this sand, recycled powder mineral addition B was obtained.
- Normal vibrated recycled concrete (RAC100) produced with river sand and with recycled coarse aggregate. The whole quantity of the coarse aggregate for this concrete was obtained by grinding demolished concrete. Concrete RAC100 was also sieved after the grinding and its finest fraction I (0/4 mm) was ground further, so that the recycled powder mineral addition C was obtained.

Sulfur (with specific density of 2050 kg/m^3) was also used as mineral filler in this paper, and originated from the Oil refinery in Pančevo. Before the application, sulfur was ground finely, with the aid of ultra centrifugal mill. The fineness of the used powdered sulfur amounted to 2600 cm^2/g.

Tabela 1. Hemijski sastav upotrebljenih mineralnih dodataka (%)
Table 1. Chemical composition of the used mineral additions (%)

Parameter	Krečnjačko brašno (Limestone filler)	Leteći pepeo (Fly ash)	Mineralni dodatak A (Mineral additon A)	Mineralni dodatak B (Mineral addition B)	Mineralni dodatak C (Mineral addition C)
SiO_2	0.21	58.60	67.13	60.55	61.31
Al_2O_3	0.5	21.92	6.58	6.84	6.65
CaO	54.86	6.12	12.94	17.77	16.06
Fe_2O_3	0.09	5.97	1.33	1.32	1.32
MgO	1.10	1.77	0.76	0.94	0.86
K_2O	0.05	1.50	0.86	0.83	0.79
Na_2O	<0.005	0.37	1.27	1.13	1.05
TiO_2	<0.005	0.49	<0.17	<0.17	<0.17
Gubitak žarenjem (Loss on ignition)	43.64	3.09	9.11	10.59	11.93

3.2. Definisanje sastava SCC betona

Za razliku od NVC, najvažnije karakteristike SCC betona definišu se kroz zahteve u vezi sa njihovim ponašanjem u svežem stanju. Pritom, poseban problem odnosi se na činjenicu da ne postoji tačno definisan metod za projektovanje sastava SCC betona i najčešće se postojeći predlozi metoda zasnivaju na grubom postizanju potrebnih svojstava svežeg SCC, a zatim i na njihovom finom podešavanju na osnovu metoda ispitivanja u svežem stanju, nakon proba i preciznijeg definisanja količina komponentnih materijala.

U radu je primenjena korigovana opšta metoda, zasnovana na principu "korak po korak", gde se parametri definišu za svaku fazu posebno. Ova metoda razvijena je na Univerzitetu u Tokiju [21],[22],[23]. U metodi se SCC posmatra kao dvokomponentni materijal koji se sastoji od maltera i krupnog agregata. Malter se sastoji od praškastih čestica (cement i fine čestice krupnoće ispod 0,09 mm), zatim sitnog agregata (čestice krupnije od 0,09 mm i sitnije od 4 mm), vode i hemijskog dodatka. Prema predmetnoj proceduri, potrebno je utvrditi pet karakterističnih parametara: sadržaj vazduha, zapreminu krupnog agregata u mešavini, zapreminu sitnog agregata u malteru, W/P faktor i procenat doziranja superplastifikatora u odnosu na masu praškastih čestica.

Prilikom projektovanja sastava SCC betona prema ovom postupku, najpre se uvodi pretpostavka da je zapremina vazduha u betonu 4-7% u slučaju upotrebe aeranta, odnosno 1% u slučaju kada nema aeranta. Zapremina krupnog agregata iznosi 50% u odnosu na ukupnu zapreminu agregata u suvom zbijenom stanju. Sadržaj sitnog agregata (čestice krupnije od 0,09 mm) u odnosu na zapreminu maltera podešava se da iznosi 40%. Vodopraškasti (W/P) faktor i količina superplastifikatora se procenjuju na bazi ispitivanja na nivou maltera. Rasprostiranje sleganjem maltera na malom konusu od 250 mm (relativno rasprostiranje maltera u iznosu od 5) i vreme mereno na malom V-levku od 9-11 s (relativna brzina rasprostiranja od 0,9-1,1) smatraju se odgovarajućim za proizvodnju SCC (slika 2).

Nakon što se izvrši podešavanje sastava maltera, dobijeni W/P odnos i sadržaj superplastifikatora u probama na betonu se dodatno koriguju, ukoliko je to neophodno, dok se ne postigne ciljano rasprostiranje sleganjem betona (npr. 650 mm) i ciljano vreme mereno pomoću V-levka (npr. 3-9 s).

Nakon analize rezultata dvanaest probnih pilot mešavina, prilikom kojih su vršene varijacije količine komponenata i praćenje promene svojstava u svežem i očvrslom stanju, usvojene su konačne recepture mešavina. Pored referentne mešavine E, u pitanju su SCC mešavine sa letećim pepelom (sa 10%, 20% i 50% zamene krečnjačkog brašna letećim pepelom, oznake

3.2. Defining the composition of SCC concrete

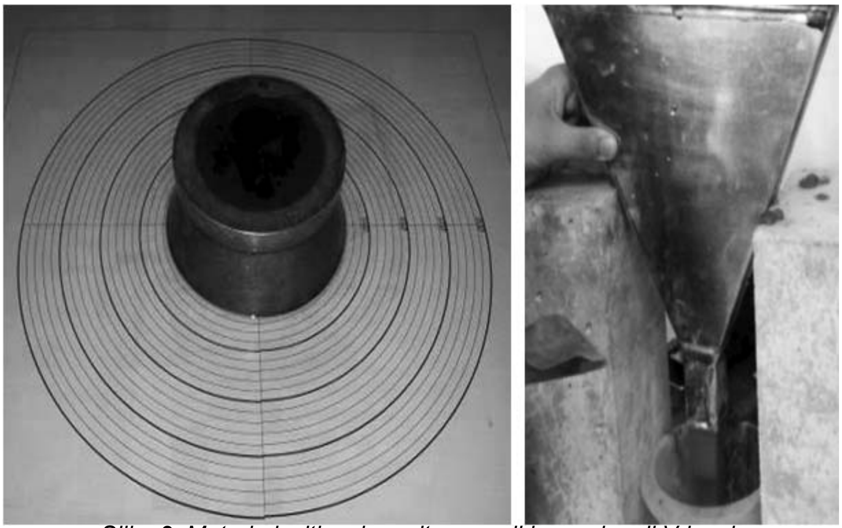
Unlike in the case of NVC, the most important properties of SCC are defined through the requirements regarding their fresh properties. Additionally, a unique problem remains the fact that there is no precisely defined method for SCC composition design, and therefore in most cases existing propositions of the methods are based on the approximate achieving the aimed properties of fresh SCC. Only after that the fine tuning of the fresh properties, after the trials, is performed, followed by final setting the quantities of components.

A corrected general-purpose mix design method was used in this investigation, based on the principle "step by step", where parameters are defined through several phases. This method was originally developed on the Tokio University [21],[22],[23]. Self-compacting concrete is regarded as two phase system, consisting of mortar and coarse aggregate. Mortar consists of powder particles (cement and fines under 0.09 mm), water and admixture. According to the mentioned procedure, five main parameters have to be defined: entrained air content, volume of the coarse aggregate in the mixture, volume of the fine aggregate in mortar, W/P factor and the superplasticizer content (as a mass percent of powder components).

When designing the composition of the SCC according to this procedure, a first assumption to be made is the quantity of air in the concrete (4-7% in the case when air entraining agent is used, or else 1%). The quantity of coarse aggregate is set to 50% of the aggregate volume in dry compacted state. The quantity of fine aggregate (particles larger than 0.09 mm) of the mortar volume is set to 40%. Water to powder (W/P) ratio and the quantity of superplasticizer are estimated through the investigation on mortar. Slump flow of mortar, (based on small cone method) of 250 mm (relative flow of 5) and time, measured on small V-funnel of 9-11 s (relative flow speed of 0.9-1.1 s) are regarded as valid for SCC production (Fig. 2).

After the composition of mortar is set, the obtained W/P ratio as well as the content of superplasticizer in trials on concrete are additionally corrected, if necessary, while the aimed slump flow (for instance 650 cm) of concrete is achieved, and the aimed time measured by V-funnel method (3-9 s).

After the analysis of the results for twelve trial mixtures, where the quantities of components were varied and the properties change in fresh and hardened state were recorded, final compositions of SCC mixtures were set. Besides the reference E, SCC mixtures with fly ash (10%, 20% and 50% of limestone filler mass replaced with fly ash, designated as LP10, LP20 and LP50, respectively), SCC mixtures with ground recycled concrete (with 50% of limestone filler replacement with ground recycled concrete type A, B and C, designated as



Slika 2. Metode ispitivanja maltera, mali konus i mali V-levak
Figure 2. Methods of investigation on mortar, small cone and small V-funnel

Tabela 2. Sastav ispitivanih SCC mešavina (kg/m^3)
Table 2. Composition of the investigated SCC mixtures (kg/m^3)

Mešavina (Mixture)	E	LP10	LP20	LP50	R0	R50	R100	S2	S5	S10	S20
Voda (Water) W	183	183	183	183	183	183	183	183	183	183	183
Cement C	380	380	380	380	380	380	380	380	380	380	380
Krečnjačko brašno (Limestone filler) KB	220	198	176	110	110	110	110	215.6	209	198	176
Leteći pepeo (Fly ash) LP	0	22	44	110	0	0	0	0	0	0	0
Praškasti mineralni dodatak (Ground mineral filler) A	0	0	0	0	110	0	0	0	0	0	0
Praškasti mineralni dodatak (Ground mineral filler) B	0	0	0	0	0	110	0	0	0	0	0
Praškasti mineralni dodatak (Ground mineral filler) C	0	0	0	0	0	0	110	0	0	0	0
Sumpor (Sulfur)	0	0	0	0	0	0	0	4.4	11	22	44
Pesak (Sand) (0/4mm)	840	840	840	840	840	840	840	840	840	840	840
Krupan agregat (Coarse aggregate) (4/8mm)	430	430	430	430	430	430	430	430	430	430	430
Krupan agregat (Coarse aggregate) (8/16mm)	430	430	430	430	430	430	430	430	430	430	430
Superplastifikator (Superplasticizer)	7.6	7.6	7.6	11.4	7.6	7.6	7.6	7.6	7.6	7.6	7.6

LP10, LP20 i LP50 respektivno), SCC mešavine sa sprašenim recikliranim betonom (sa 50% zamene krečnjačkog brašna sprašenim recikliranim betonima tipa A, B i C, oznake R0, R50 i R100 respektivno), kao i SCC mešavine sa sprašenim sumporom (sa 2%, 5%, 10% i 20% zamene krečnjačkog brašna sprašenim sumporom, oznake S2, S5, S10 i S20 respektivno), koje su u daljem toku eksperimentalnog rada detaljno istraživane. Ove konačne recepture prikazane su u tabeli 2.

R0, R50 and R100, respectively), and SCC mixtures with ground sulfur (with 2%, 5%, 10% and 20% of limestone filler replacement with ground sulfur, designated as S2, S5, S10 and S20) were made. These SCC mixtures are further analyzed and discussed in the paper. The final compositions are shown in table 2.

4. ANALIZA REZULTATA ISPITIVANJA SCC MEŠAVINA U SVEŽEM STANJU

Rezultati ispitivanja zapreminske mase betona u svežem stanju [24], zajedno sa metodama rasprostiranja sleganjem [25], V-levka [26], L-boksa [27] i faktora segregacije [28] kod svih ispitivanih SCC mešavina prikazani su u tabeli 3. Ambijentalna temperatura prilikom spravljanja svih predmetnih betona kretala se u granicama od 20,3°C do 23,9°C. Sve prikazane vrednosti predstavljaju prosek dva merenja, osim kod određivanja zapreminske mase koja je izračunata kao prosečna vrednost svih pojedinačnih uzoraka za mešavinu.

4. ANALYSIS OF THE FRESH PROPERTIES OF SCC MIXTURES

Results of the investigation of density of fresh SCC mixtures [24], together with the slump flow results [25], V-funnel [26], L-box [27] and segregation ratio [28] for all the investigated SCC mixtures are shown in table 3. Ambient temperature was in the range between 20.3°C and 23.9°C during the production of all of the mixtures. All of the measurements presented in table are average values, except for the density, which was calculated as the average value for all of the samples for each SCC mixture.

Tabela 3. Rezultati ispitivanja SCC mešavina u svežem stanju
Table 3. Results of the SCC mixtures investigation in fresh state

Mešavina (Mixture)	E	LP10	LP20	LP50	R0	R50	R100	S2	S5	S10	S20
Zapreminska masa svežeg betona (Fresh concrete density) (kg/m^3)	2397	2391	2370	2347	2387	2389	2391	2394	2387	2381	2375
Rasprostiranje sleganjem (Slump flow) (mm)	761	701	663	702	695	720	730	820	820	781	775
Vreme (Time) t_{500} (s)	2.62	5.71	10.91	11.32	4.78	4.85	4.53	2.59	2.84	3.42	3.07
Vreme V-levka (V-funnel time) t_v (s)	9.73	15.92	22.46	27.21	13.23	11.90	11.37	8.21	10.48	8.87	9.21
L-boks (L-box) (H_2/H_1)	0.97	0.92	0.92	0.95	0.95	0.95	0.95	0.98	0.98	0.96	0.96
Faktor segregacije (Segregated portion) (%)	3.5	3.0	2.0	1.7	4.6	4.8	4.0	4.3	3.8	4.2	3.6

Na osnovu rezultata ispitivanja, pad vrednosti zapreminske mase svežeg betona, u funkciji povećanja sadržaja letećeg pepela, može se predstaviti u obliku:

$$\gamma=-1{,}31p-2399{,}2 \quad (r^2=0{,}895)$$

gde je: γ (kg/m^3) zapreminska masa svežeg betona, a p (%) procenat zamene krečnjačkog brašna letećim pepelom. Primećeni pad vrednosti zapreminske mase može se objasniti superponiranim dejstvom dva faktora: povećanjem sadržaja uvučenog vazduha, koje je posledica pada konzistencije SCC, kao i povećanjem količine dodatog letećeg pepela (koji ima manju zapreminsku masu nego krečnjačko brašno koje zamenjuje).

U slučaju SCC mešavina spravljenih sa sprašenim recikliranim betonom, može se primetiti da je došlo do zanemarljivog pada vrednosti zapreminske mase svežeg SCC sa dodatkom sprašenog recikliranog betona. To se može objasniti porastom sadržaja uvučenog vazduha, kao i prisustvom neznatno lakših zrna malterske komponente u okviru sprašenog recikliranog betona. Kod svežih SCC mešavina sa dodatkom sprašenog sumpora, dolazi do pada zapreminske mase u funkciji povećanja sadržaja sprašenog

Based on the results of investigation, drop in the density of fresh concrete, as function of fly ash content, can be presented in the following form:

$$\gamma=-1{,}31p-2399{,}2 \quad (r^2=0{,}895)$$

where: γ (kg/m^3) presents density of fresh concrete, and p (%) is percentage of the limestone filer replacement by fly ash. The noticed drop in density value can be explained by combined effect of two factors: increase in entrained air content, which is a consequence of consistency drop, as well as the increase of fly ash content (which has lower density than limestone filler it replaces).

In the case of SCC mixtures made with ground recycled concrete, a note can be made that slight fall of fresh SCC density occurred, with the addition of ground recycled concrete. This can be explained with the entrained air content, as well as with the presence of the slightly lighter grains of mortar component in ground recycled concrete. For fresh SCC mixtures with addition of ground sulfur, a drop in density occurs, in function of ground sulfur content increase. This is logical, because ground sulfur has lower density than limestone filler it replaces. Therefore, the increase in ground sulfur content in SCC mixtures leads to the sumpora. Ovo je logično, jer sprašeni sumpor ima manju zapreminsku masu od krečnjačkog brašna koje zamenjuje, pa povećanjem količine sprašenog sumpora u SCC dolazi do smanjenja zapreminske mase SCC mešavine. Pomenuti pad je mali, i iznosi do 0.9% (za zamenu krečnjačkog brašna sprašenim sumporom do masenog iznosa od 20%).

Sa izmerenim vrednostima rasprostiranja sleganjem u rasponu od 664 mm do 820 mm svi spravljani SCC spadaju u kategoriju SF2 prema evropskim preporukama [29], sa izuzetkom betona E, S2 i S5, koji su nešto iznad gornje granice za datu kategoriju (750 mm) i spadaju u kategoriju SF3. Što se tiče promene sposobnosti tečenja merenom testom rasprostiranja sleganjem, može se primetiti da je došlo do pada ovog svojstva usled povećanja količine letećeg pepela (10%, 20%, 50%), zatim usled promene vrste sprašenog recikliranog betona, kao i usled povećanja količine sprašenog sumpora. Na osnovu prikazanih vrednosti može se primetiti da je pad vrednosti rasprostiranja sleganjem manji za slučaj zamene veće količine krupnog agregata recikliranim betonom u sprašenom betonu.

Uporedni prikaz vrednosti rasprostiranja sleganjem SCC mešavine sa 50% letećeg pepela poreklom iz TE "Kolubara" u odnosu na ukupnu masu filera – LP50 i prosečne vrednosti rasprostiranja sleganjem mešavina sa 50% sprašenog recikliranog betona u odnosu na ukupnu masu filera – označena kao R) dat je na slici 3. Oba mineralna dodatka na bazi industrijskih nusprodukata (leteći pepeo i sprašeni reciklirani beton) dovode do pada sposobnosti tečenja SCC mešavine merenog metodom rasprostiranja sleganjem.

Kod SCC mešavine spravljene sa letećim pepelom zabeležen je veći pad (7,7%), dok je kod SCC mešavine sa sprašenim recikliranim betonom ovaj pad iznosio 6,1%. Rasprostiranje sleganjem SCC mešavine sa letećim pepelom niže je od rasprostiranja sleganjem SCC mešavine sa sprašenim recikliranim betonom u iznosu od

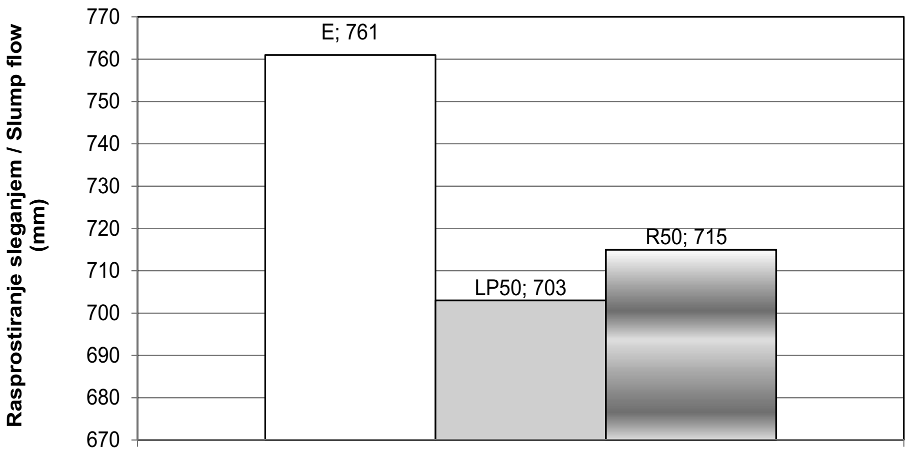
reduction of density of SCC mixtures. This drop is small, and it amounts to 0.9% (for replacement of limestone filler with ground sulfur up to content of 20% of limestone mass).

With the measured values of slump flow between 66.4 cm and 82.0 cm, all of the produced SCC mixtures fall in the category SF2, according to the European propositions [29], except concretes E, S2 and S5, which are above the upper limit for the given category (75 cm) and fall in the category SF3. As for the change of the flowing ability, measured by slump flow test, an observation can be made that the fall in this property took place, due to the increase of the quantity of fly ash (10%, 20%, 50%), and due to the change of type of ground recycled concrete, as well as due to the increase of the quantity of ground sulfur. Based on the shown values, it can be noticed that the fall of the slump flow values is lower in the case of higher replacement level of coarse aggregate with the recycled aggregate, which were both present in the ground concrete.

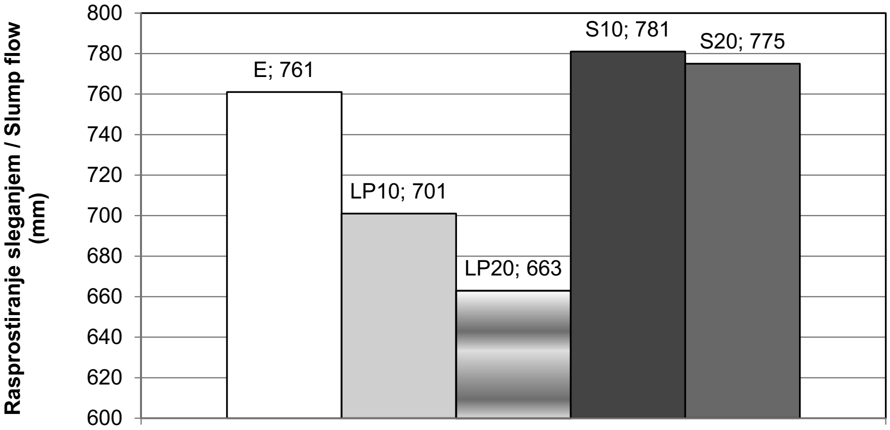
A comparative display of the slump flow values for the SCC mixtures with 50% of fly ash (originated from Thermal power plant "Kolubara") designated as LP50 and the average value of slump flow of the mixtures with 50% of ground recycled concrete in the total filler mass – designated as R) is given on the figure 3. Both mineral admixtures, based on industrial byproducts (fly ash and ground recycled concrete) initiate the fall in flow ability of SCC mixtures, measured by slump flow method.

A higher drop (7.7%) was recorded for SCC mixture made with fly ash, while for SCC mixture with ground recycled concrete this fall was 6.1%. Slump flow of SCC mixture with fly ash was 1.8% lower than the same value of the SCC mixture with ground recycled concrete, in respect to the slump flow of the SCC mixture with fly ash.

A comparative display of the slump flow values for SCC mixtures with 10% and 20% of fly ash originated from the TPP "Kolubara" with respect



Slika 3. Uporedni prikaz vrednosti rasprostiranja sleganjem SCC mešavina sa letećim pepelom i sa sprašenim recikliranim betonom
Figure 3. Comparative display of slump flow values of SCC mixtures with fly ash and with ground recycled concrete



Slika 4 Uporedni prikaz vrednosti rasprostiranja sleganjem (mm) SCC mešavina sa letećim pepelom i sa sprašenim sumporom

Figure 4. Comparative display of the slump flow values (mm) of SCC mixtures with fly ash and the mixtures with ground sulfur

1,8% u odnosu na rasprostiranje sleganjem SCC mešavine sa letećim pepelom.

Uporedni prikaz vrednosti rasprostiranja sleganjem SCC mešavina sa 10% i 20% letećeg pepela poreklom iz TE “Kolubara” u odnosu na ukupnu masu filera (LP10 i LP20) i mešavina sa 10% i 20% sprašenog sumpora u odnosu na ukupnu masu filera (S10 i S20) dat je na slici 4. Razlika u upotrebi ova dva filera ogleda se u suprotnim efektima na rasprostiranje sleganjem, naime, prisustvo letećeg pepela dovodi do pada vrednosti rasprostiranja sleganjem, dok prisustvo sprašenog sumpora dovodi do povećanja vrednosti rasprostiranja sleganjem u odnosu na referentnu mešavinu.

Što se tiče promene sposobnosti prolaska merene testom L-boksa (H_2/H_1), iz rezultata se primećuje da su, generalno, izmerene vrednosti za sve mešavine bile relativno bliske, u granicama od 0,92 do 0,98. Takođe, može se primetiti da je došlo do pada izmerenih vrednosti kod ovog svojstva usled promene količine letećeg pepela (10%, 20%, 50%). Kod SCC mešavina sa sprašenim recikliranim betonom, došlo je do pada vrednosti H_2/H_1 usled doziranja sprašenog recikliranog betona u iznosu od 50%, nezavisno od porekla sprašenog recikliranog betona. Prisustvo sprašenog sumpora u količinama od 2% do 20% u odnosu na ukupnu masu filera nije imalo značajan efekat na promenu vrednosti odnosa visina H_2/H_1 kod L-boksa. Prema kriterijumu sa tri šipke armature na L-boksu, svi betoni su postigli klasu PA2 (odnos visina na početku i kraju horizontalnog dela L-boksa: $H_2/H_1>0,8$) [29].

Izmerene vrednosti faktora segregacije su za sve mešavine bile u granicama dozvoljenih (vrednosti faktora segregacije niže od 20%) [29]. Sa povećanjem sadržaja letećeg pepela došlo je do povećanja otpornosti prema segregaciji. U slučaju upotrebe sprašenog recikliranog betona nije došlo do porasta otpornosti prema segregaciji, najverovatnije zbog činjenice da je u sprašenom betonu bila prisutna veća količina sitnih čestica

to the total amount of filler (LP10 i LP20) and the mixtures with 10% and 20% of ground sulfur in respect to the total amount of filer (S10 and S20) is displayed on Fig. 4. Difference in the use of these two fillers is in the opposite effects in slump flow values, namely, the presence of fly ash leads to the fall of slump flow values, while the presence of ground sulfur leads to the increase in the values of slump flow, in respect to the reference mixture.

As for the change of the passing ability measured by L-box test (H_2/H_1), based on the results it can be noticed that, generally, the measured values for all of the mixtures were relatively close and in the range between 0.92 and 0.98. Also, it can be noticed that the fall in the measured values of this property occurred, due to the increase in the quantity of fly ash (10%, 20%, 50%). In SCC mixtures made with ground recycled concrete, a fall in the value H_2/H_1 occurred, with the use of ground recycled concrete in the amount of 50% of the filler, and regardless of the origin of the ground recycled concrete. The presence of ground sulfur in quantities from 2% to 20% of the filler had no significant effect on the change of the H_2/H_1 values for L-box test. According to the criterion with three re-bars, all of the concretes achieved PA2 class (with height ratio on the beginning and on the end of horizontal part of L-box above 0.8 - $H_2/H_1>0.8$) [29].

The measured values of the segregated portion were inside the limits for all of the mixtures (values under 20%) [29]. With the increase of the fly ash content, segregation resistance increased. In the case of ground recycled concrete used, no drop in the segregated portion occurred, most probably due to the fact that in ground concrete higher content of fine particles was present (ground or powdered concrete) with higher specific density and slightly lower porosity. A similar conclusion can be obtained in the case of segregation of SCC mixtures with ground sulfur, where a slight increase in segregated portion occurred.

(sprašenog, samlevenog betona) veće specifične mase i donekle manje poroznosti. Sličan zaključak se može navesti i u slučaju faktora segregacije SCC mešavina sa sprašenim sumporom, gde je došlo do malog porasta faktora segregacije u odnosu na referentnu mešavinu.

Na osnovu poređenja faktora segregacije SCC mešavina kod kojih je izvršena zamena 50% krečnjačkog brašna istom masom letećeg pepela, ili pak sprašenog recikliranog betona, može se reći da je efekat upotrebe ovih dodataka u odnosu na referentnu SCC mešavinu različit: kod SCC mešavine sa letećim pepelom došlo je do povećanja otpornosti prema segregaciji u odnosu na referentnu SCC mešavinu u iznosu od 51,4%, a kod SCC mešavine sa sprašenim recikliranim betonom došlo je do smanjenja otpornosti na segregaciju u iznosu od 27,6% u odnosu na referentnu SCC mešavinu. Međutim, konkretne vrednosti su u odnosu na graničnu vrednost faktora segregacije (20%) mnogo niže.

Poređenjem SCC mešavina sa 10% i 20% letećeg pepela u odnosu na ukupnu masu filera (mešavine LP10 i LP20), sa SCC mešavinama sa 10% i 20% sprašenog sumpora (S10 i S20), može se zaključiti da odgovarajuća količina sprašenog sumpora dovodi do porasta vrednosti faktora segregacije, a time i do smanjenja otpornosti na segregaciju. Dakle, za iste količine mineralnog dodatka (10% ili 20%), efekti ova dva mineralna dodatka na vrednosti faktora segregacije su suprotni.

Što se tiče promene sposobnosti tečenja na osnovu merenja vremena t_{500} potrebnog za rasprostiranje i vremena tv izmerenog kod metode V-levka, može se primetiti da je došlo do pada ovog svojstva (sposobnosti tečenja) usled povećanja količine letećeg pepela (10%, 20%, 50%). Generalno posmatrano, prema evropskim preporukama [29] svi betoni spadaju u kategoriju VS2/VF2 sa >2 sec izmerenim vremenom t500, odnosno sa >9 sec izmerenim vremenom t_v. Pri tome, SCC mešavina oznake E je bila najbliža datoj granici dok je mešavina LP50 (sa 50% letećeg pepela poreklom iz TE “Kolubara”) pokazala visoku viskoznost (vreme od t_v =27,2 s). Kod ispitivanih mešavina SCC sa sprašenim recikliranim betonom došlo je do porasta vremena potrebnog za rasprostiranje betona u metodi rasprostiranja sleganjem u odnosu na referentnu mešavinu, spravljenu bez sprašenog recikliranog betona, kao i vremena V-levka.

Što se tiče smanjenja sposobnosti tečenja na osnovu merenja vremena t_{500} potrebnog za rasprostiranje i vremena V-levka t_v, može se primetiti da je došlo do promene (pada) sposobnosti tečenja u funkciji od porekla sprašenog recikliranog betona. Betoni sa sprašenim recikliranim betonom imali su slične vrednosti oba izmerena vremena (vremena t_{500} potrebnog za rasprostiranje i vremena potrebnog za isticanje betona iz V-levka t_v). Može se primetiti da zamena krečnjačkog

Based on the comparison of the segregated portion of the SCC mixtures with 50% of the limestone filer replaced with the same mass of fly ash, and the mixtures with ground recycled concrete, a statement can be made that the effect of the use of these additions, in respect to the reference SCC, is different: in SCC mixtures with fly ash an increase of the segregation resistance was recorded (51.4%), and for SCC mixtures with ground recycled concrete reduction in segregation resistance took place (27.6% in comparison to the reference SCC mixture). Nevertheless, all of the obtained values are significantly lower than the limit (20%).

By comparison of SCC mixtures with 10% and 20% of fly ash of total filler mass (mixtures LP10 and LP20), with SCC mixtures with 10% and 20% of ground sulfur (S10 and S20), a conclusion can be made that the same quantity of ground sulfur leads to the increase of the segregated portion, and therefore to the decrease of segregation resistance. For the same quantity of mineral filler (10% or 20%), the effects of these two mineral additions on the values of the segregated portion were opposite.

According to the measured time t_{500} (time of the slump flow of 50 cm) and tv (V-funnel time) a note can be made that decrease of this property (flowing ability) occurs due to the increase of the fly ash content (10%, 20% 50%). Generally, according to the European provisions [29] all of the concretes fall in category VS2/VF2 with >2 sec measured time t_{500}, or with >9 sec measured time t_v. Additionally, SCC mixture designated as E was the closest to the given limit, while the mixture LP50 (with 50% of fly ash, originated from TPP “Kolubara”) shown high viscosity (time t_v =27.2 s). In the investigated SCC mixtures, made with ground recycled concrete, time needed for slump flow of concrete in the slump flow method increased, in comparison to the referent mixture, made without ground recycled concrete, as well as V-funnel time.

As for the reduction of flowing ability, based on t_{500} measurement, and also t_v measurement, a note can be made that decrease of the flowing ability occurred, with different origin of ground recycled concrete. SCC mixtures with ground recycled concrete filler had similar values of the both measured times (time t_{500} needed for slump flow and time needed for V-funnel). It was noticed that the replacement of limestone filler with ground recycled concrete (in the amount of 50%) results with the increased t_{500} (increase of 72.9-82.4%). On the other hand, increase of the t_v value (needed for concrete to leave the V-funnel) in comparison to the referent mixture E, decreases with the increase of the quantity of coarse recycled aggregate in the ground recycled concrete.

There was no bigger change of the measured values of t_{500} and t_v with increase of the ground sulfur quantities in SCC mixtures. Values of time t_{500}

brašna sprašenim recikliranim betonom (u iznosu od 50%) rezultira porastom vrednosti t_{500} u iznosu od 72,9-82,4%. Sa druge strane, porast vrednosti vremena t_v (potrebnog da beton isteče iz V-levka) u odnosu na referentnu mešavinu E, opada sa povećanjem količine krupnog recikliranog agregata u sprašenom betonu.

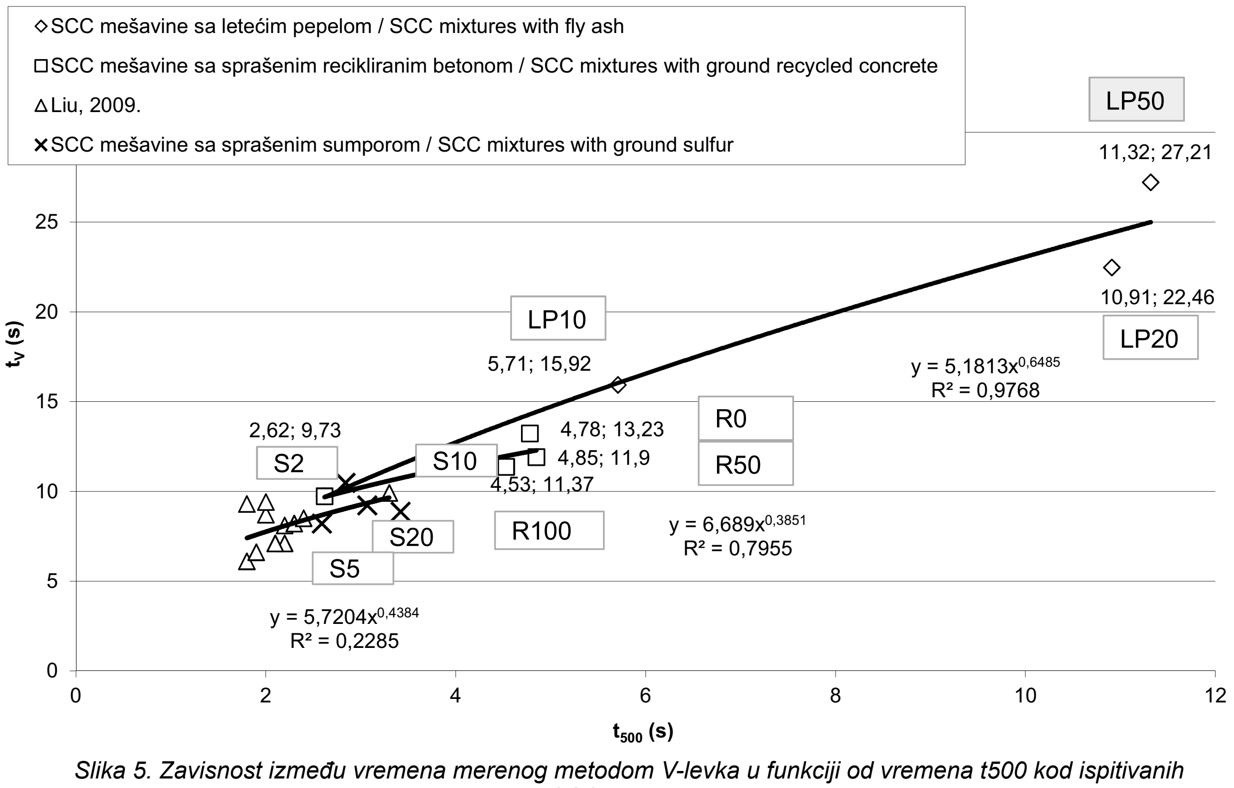
Kod SCC mešavina sa sprašenim sumporom nije došlo do jednoznačne promene izmerenih vrednosti t_{500} potrebnog za rasprostiranje i vremena t_v kod V-levka sa povećanjem količine sprašenog sumpora kao zamene dela mase krečnjačkog brašna u SCC mešavinama. Vrednosti izmerenih vremena t_{500} varirale su u granicama od -1,1% (za SCC mešavinu oznake S2) do 30,5% (za SCC mešavinu oznake S10). Vrednosti izmerenih vremena tv varirale su u granicama od -15,6% (za SCC mešavinu oznake S2) do 7,7% (za SCC mešavinu oznake S5).

Na slici 5 prikazane su zavisnosti između vremena t_v isticanja merenog metodom V-levka i vremena t_{500} merenog u metodi rasprostiranja sleganjem kod ispitivanih SCC mešavina (tri SCC mešavine sa letećim pepelom, tri mešavine sa sprašenim recikliranim betonom i četiri sa sprašenim sumporom). Formirane su funkcionalne zavisnosti, dobijene na osnovu prosečnih vrednosti ispitivanja na SCC betonima sa letećim pepelom, sa dobrom korelacijom (R^2=0,92), zajedno sa rezultatima ispitivanja SCC mešavina sa letećim pepelom autora Liu [30] (R^2=0,23) i sa rezultatima ispitivanja SCC mešavina sa sprašenim recikliranim betonom (R^2=0,80) i sprašenim

varied in the range from -1.1% (for SCC mixture S2) up to 30.5% (for SCC mixture S10). Values of the measured times tv varied in the range from -15.6% (for SCC mixture S2) up to 7.7% (for SCC mixture S5).

Correlations between time t_v (measured in the V-funnel method) and time t_{500} (measured in the slump flow method) for all of the investigated mixtures (three SCC mixtures with fly ash, three mixtures with ground recycled concrete and four with ground sulfur) are shown on the figure 5. Functional correlations were formed, on the basis of average values obtained on SCC mixtures with fly ash with good correlation (R^2=0.92), together with the results of the investigations by Liu [30] (R^2=0.23) and with the results of the investigation of SCC mixtures with ground recycled concrete (R^2=0.80) and ground sulfur (R^2=0.77). The correlation obtained on the basis of data from the referenced paper is valid for the narrow range of the values t_{500} and t_v and therefore it has a low correlation coefficient, but, as it can be observed from the graph, this functional correlation is similar to the one obtained on the basis of investigation for SCC mixtures with fly ash. As for the SCC mixtures with ground recycled concrete, it is obvious from the graph that between three SCC with ground recycled concrete there are no big differences in their behavior, because all of the values plotted on the graph are close to each other, and away from the reference SCC. Similar conclusion is valid in the case of ground sulfur.

In the case of comparison of times t500 and tv



Slika 5. Zavisnost između vremena merenog metodom V-levka u funkciji od vremena t500 kod ispitivanih SCC mešavina

Figure 5. Correlation between time measured by V-funnel method tv and time t500 measured on the investigated SCC mixtures

sumporom (R^2=77%). Zavisnost dobijena na osnovu podataka iz navedene literature važi za mali raspon vrednosti t_{500} i t_V i iz tog razloga ima nizak stepen korelacije, ali kao što se vidi sa dijagrama, ova funkcionalna veza je slična onoj dobijenoj na osnovu istraživanja za SCC mešavine sa letećim pepelom. Što se SCC mešavina sa sprašenim recikliranim betonom tiče, sa dijagrama se vidi da između tri SCC sa sprašenim recikliranim betonom nema velikih razlika u ponašanju, pošto su sve tri tačke na dijagramu grupisane i pomerene u odnosu na referentni SCC. Sličan zaključak važi u slučaju sprašenog sumpora.

U slučaju poređenja vremena t_{500} i t_V kod SCC mešavina sa 50% zamene krečnjačkog brašna jednim od dva industrijska nusprodukta (letećeg pepela i sprašenog recikliranog betona), već je rečeno da dolazi do porasta izmerene vrednosti t500 kod metode rasprostiranja sleganjem i vrednosti tv kod metode V-levka, u odnosu na referentnu mešavinu oznake E. Ova povećanja iznose 332,1% i 80,2% za upotrebu letećeg pepela i sprašenog recikliranog betona, respektivno, u slučaju vrednosti t_{500} kod metode rasprostiranja. Kod metode V-levka, povećanja iznose 179,7% i 25,0% za upotrebu letećeg pepela i sprašenog recikliranog betona, respektivno. Povećanje viskoznosti, odnosno smanjenje pokretljivosti SCC mešavine usled upotrebe ovih mineralnih dodataka, iako slabije izraženo kod primene sprašenog recikliranog betona, može se objasniti njihovom strukturom. Oba mineralna dodatka imaju generalno porozniju strukturu i lakše čestice nego krečnjačko brašno. Vrednosti izmerenih vremena t500 i tv su više kod SCC mešavine sa letećim pepelom u odnosu na SCC mešavine sa sprašenim recikliranim betonom u iznosu od 58,3% i 55,3%, respektivno.

Ako se porede SCC mešavine sa letećim pepelom i sa sumporom, može se primetiti da doziranje letećeg pepela u iznosu od 10% i 20% u odnosu na ukupnu masu filera u SCC mešavini rezultira značajnijim padom svojstva sposobnosti punjenja merenog pomoću vremena t_{500} (porast vrednosti od 107.7% i 238.5%, respektivno) dok doziranje sprašenog sumpora u istim iznosima rezultira malim padom sposobnosti punjenja merenog pomoću vremena t_{500} (porast vrednosti od 30.5% i 17.2%, respektivno). Što se vrednosti vremena tv tiče, pomenutim dozažama od 10% i 20% letećeg pepela odgovaraju porasti od 68.5% i 119.1%, respektivno, ali u slučaju upotrebe sprašenog sumpora evidentno je da je trend drugačiji. Naime, u ovom slučaju dolazi do izvesnog pada vrednosti vremena t_V, i to u iznosu od 8.8% kod SCC mešavine sa 10% sprašenog sumpora u odnosu na ukupnu masu filera i 5.3% kod SCC mešavine sa 20% sprašenog sumpora u odnosu na ukupnu masu filera.

Poređenjem vrednosti rezultata ispitivanja metodom rasprostiranja sleganjem i metodom

for SCC mixtures with 50% of the limestone filler replaced with one of the two industrial byproducts (fly ash and ground recycled concrete), it was already noticed that values of t_{500} and t_V increase in comparison to the reference E. These increases are 332.1% and 80.2% for the use of fly ash and ground recycled concrete, respectively, in the case of t_{500}. When it comes to V-funnel, increases are 179.7% and 25.0% for the use of fly ash and ground recycled concrete, respectively. The viscosity increase, and the decrease of flowing speed of the SCC mixture due to the use of these mineral additives, although not so considerable in the case of ground recycled concrete, can be explained by their structure. Both of the mineral additions have generally more porous structure and lighter particles than in the case of limestone filler. The values of the measured times t500 and tv are higher for SCC mixtures with fly ash, in comparison to the SCC mixtures with ground recycled concrete, in the amount of 58.3% and 55.3%, respectively.

If SCC mixtures with fly ash and with sulfur are being compared, a statement can be made that incorporation of fly ash in the amounts of 10% and 20% of the total amount of filler in SCC mixtures results with the more significant drop in the filling ability, measured through time t_{500} values (increase of the values was 107.7% and 238.5%, respectively), while incorporation of the ground sulfur in the same amounts results with the insignificant drop in filling ability measured through time t_{500} values (increase of the values was 30.5% and 17.2%, respectively). As for the value t_V, the contents of 10% and 20% of fly ash correspond to the increase of 68.5% and 119.1%, respectively, but in the case of use of ground sulfur, it is evident that the trend is different. Namely, in this case drop of the tv values occurs, in the amount of 8.8% for SCC mixtures with 10% of ground sulfur of the total amount of filler, and 5.3% for SCC mixture with 20% of ground sulfur of the total amount of filler.

Based on the comparison of the results of investigation by slump flow method and V-funnel method, it can be noted that for the similar flowing ability (measured by slump flow method) fly ash and ground recycled concrete cause quite different passing abilities in different concretes. Namely, while passing ability of SCC mixtures with ground recycled concrete is similar to the passing ability of referent SCC mixture, an observation can be made that the passing ability of SCC mixture with fly ash in the amount of 50% in the total mass of filler is much lower. If we add the fact that in the last mixture higher amount of superplasticizer (3% of the cement mass in the mixture, while in the reference mixture, as well as in the mixtures with ground recycled concrete, this percentage was 2%), the mentioned effect can present a problem for the practical use of such SCC mixture in practice.

V-levka, može se uočiti da za sličnu sposobnost tečenja (merenu metodom rasprostiranja) leteći pepeo i sprašeni reciklirani beton prouzrokuju u odgovarajućim betonima veoma različite sposobnosti prolaska. Naime, dok je sposobnost prolaska SCC mešavina sa sprašenim recikliranim betonom približna sposobnosti prolaska referentne SCC mešavine, može se primetiti da je sposobnost prolaska SCC mešavine sa letećim pepelom u iznosu od 50% u odnosu na ukupnu masu filera mnogo manja. Ako se tome doda i činjenica da je kod poslednje pomenute mešavine upotrebljena veća količina superplastifikatora (3% u odnosu na masu cementa u mešavini, dok je kod referentne mešavine, kao i kod mešavina sa sprašenim recikliranim betonom, ovaj procenat iznosio 2%), pomenuti efekat može predstavljati problem prilikom upotrebe ovakve SCC mešavine u praksi.

5. ANALIZA REZULTATA ISPITIVANJA SCC MEŠAVINA U OČVRSLOM STANJU

Ispitivanja očvrslih SCC mešavina obuhvatila su standardna ispitivanja: čvrstoću pri pritisku [31], atheziju merenu "pull-off" metodom [32], čvrstoću pri zatezanju savijanjem [33], brzinu ultrazvučnog impulsa [34] i dinamički modul elastičnosti [35].

Rezultati ispitivanja čvrstoće pri pritisku (po pet kocki ivice 10 cm za svaku starost svake od serija) ispitivanih SCC mešavina pri starosti od 3, 7, 28 i 90 dana su prikazani u tabeli 4. Kod SCC sa letećim pepelom vrednosti čvrstoće pri pritisku su bile više u odnosu na referentnu SCC mešavinu E (mešavinu spravljenu bez letećeg pepela) pri svim starostima, osim pri starosti od 3 dana, što se slaže sa rezultatima istraživanja koje je sproveo Siddique 2003. [36] za starosti od 7 do 180 dana, u istraživanju efekta delimične zamene peska letećim pepelom. Rezultati za starost od 3 dana pokazuju višu vrednost čvrstoće pri pritisku kod referentne mešavine, što se može objasniti kasnijim efektom pucolanske reakcije. Treba istaći da je pri svim starostima, osim pri starosti od 3 dana, SCC mešavina oznake LP50 pokazala 4,3-16,5% višu čvrstoću pri pritisku nego referentna mešavina spravljena bez letećeg pepela, oznake E. U tom smislu može se opaziti da je evidentan pozitivan efekat upotrebe letećeg pepela u odnosu na SCC mešavinu bez letećeg pepela.

U proseku, ukoliko se zanemari poreklo sprašenog recikliranog betona, vrednosti čvrstoće

5. ANALYSIS OF THE HARDENED PROPERTIES OF SCC MIXTURES

Investigation of the hardened SCC mixtures included standard tests: compressive strength [31], adhesion by "pull-off" method [32], flexural strength [33], ultrasonic pulse velocity [34] and dynamic modulus of elasticity [35].

Results of the investigation of compressive strength (five 10 cm cubes for each mixture at each age) at the age of 3, 7, 28 and 90 days are shown in table 4. For SCC mixtures with fly ash values of compressive stregth were lower in the comparison to the reference SCC mixture E (mixture made without fly ash) at all ages, except at 3 days of age, which complies with the results of the investigation conducted by Siddique 2003 [36] at the ages of 7 and 180 days, in the investigation of effect of sand partial replacement with fly ash.

Investigations at 3 days recorded higher compressive strength for reference E. This can be explained by the postponed pozzolanic reaction effect. It should be noted that at all ages, except for 3 days of age, SCC mixture designated with LP50 showed 4.3-16.5% higher compressive strength than the reference mixture made without fly ash, designated with E. That having said, an observation can be made that there is positive effect of fly ash use, compared to the SCC mixture without fly ash.

In average, if the origin of ground recycled concrete is neglected, the values of compressive strength for SCC with ground recycled concrete, in relation to the reference SCC mixture E were lower for all of the ages, with the variance being 2.9-5.0% for different ages.

Values of the compressive strength for SCC mixtures with ground sulfur, in comparison with SCC mixture E (referent mixture made without sulfur) were lower than the values for the reference mixture at all ages. Based on the obtained values, an observation can be formulated that the decrease of the compressive strength for SCC mixtures with ground sulfur, in comparison to the compressive strength of the referent SCC mixture ranged from 0.3% (for mixture with 5% of ground sulfur, with respect to the total amount of filler in SCC, at the age of 28 days) up to 11.9% (for mixture with 20% of ground sulfur, with respect to the total amount of filler in SCC, at the age of 28 days). Additionally, a statement can be made that for SCC with lower content of ground sulfur de-

Tabela 4. Rezultati ispitivanja čvrstoće pri pritisku (MPa) SCC mešavina
Table 4. Results of the investigation of compressive strength (MPa) of SCC mixtures

Starost / Age (dani / days)	E	LP10	LP20	LP50	R0	R50	R100	S2	S5	S10	S20
3	48.8	48.8	48.8	45.3	46.0	46.9	49.2	48.3	46.1	46.1	44.1
7	53.9	58.2	55.4	57.7	47.6	52.0	56.6	53.0	52.0	49.2	47.9
28	62.0	69.0	72.4	70.0	60.0	59.2	61.6	61.5	62.2	54.8	54.6
90	70.1	73.6	74.4	73.6	61.0	60.4	62.1	62.4	63.0	55.7	55.4

pri pritisku kod SCC sa sprašenim recikliranim betonom u odnosu na referentnu SCC mešavinu E su pri svim starostima bile niže, i to odstupanje iznosilo je 2,9-5,0% pri različitim starostima.

Vrednosti čvrstoće pri pritisku kod SCC sa sprašenim sumporom u odnosu na SCC mešavinu E (referentnu mešavinu spravljenu bez sumpora) su pri svim starostima bile niže nego kod referentne mešavine. Na osnovu dobijenih vrednosti može se izvesti konstatacija da se pad vrednosti čvrstoće pri pritisku SCC sa sprašenim sumporom u odnosu na čvrstoću pri pritisku referentne SCC mešavine kreće u granicama od 0.3% (za mešavinu sa 5% sprašenog sumpora u odnosu na ukupnu masu filera u SCC, pri starosti od 28 dana) do 11.9% (za mešavinu sa 20% sprašenog sumpora u odnosu na ukupnu masu filera u SCC, pri starosti od 28 dana). Takođe, može se konstatovati da je za SCC sa manjim sadržajem sprašenog sumpora pad čvrstoće pri pritisku manji nego za SCC sa većim sadržajem sprašenog sumpora, pri čemu taj pad ne prati povećanje sadržaja sprašenog sumpora linearno. Pri tome, vrednosti pada čvrstoće pri pritisku SCC sa 10% i 20% sprašenog sumpora su slične pri svim starostima, a sa povećanjem starosti razlike u procentualnom padu čvrstoće pri pritisku se smanjuju.

Osim pri starosti od 3 dana, pri svim starostima odnos rezultata ispitivanja referentne SCC mešavine, SCC mešavine sa letećim pepelom i SCC mešavine sa sprašenim recikliranim betonom je isti: mešavina sa letećim pepelom uvek ima višu čvrstoću pri pritisku u odnosu na referentnu SCC mešavinu (u granicama od 6,3% do 12,9%), a mešavina sa sprašenim recikliranim betonom uvek ima nižu čvrstoću pri pritisku u odnosu na referentnu SCC mešavinu (u granicama od 2,8% do 4,9%). Ovaj efekat primećen pri malim starostima kod SCC mešavine sa letećim pepelom je najverovatnije posledica činjenice da pucolanska reakcija (zaslužna za generalno poboljšanje strukture kod SCC sa letećim pepelom) pri malim starostima još nije dala rezultate u smislu povećanja čvrstoće pri pritisku, već je do izražaja došao isključivo fizičko-mehanički efekat prisustva zrna letećeg pepela (slabijih fizičko-mehaničkih karakteristika u odnosu na krečnjačko brašno).

Na osnovu analize vrednosti rezultata ispitivanja SCC mešavina sa 10% i 20% letećeg pepela, odnosno 10% i 20% sprašenog sumpora, može se izvesti nekoliko opažanja. Naime, pri svim starostima osim pri starosti od 3 dana, čvrstoće pri pritisku mešavina sa letećim pepelom su više od čvrstoće pri pritisku referentne SCC mešavine, a u slučaju upotrebe sprašenog sumpora, čvrstoće pri pritisku su niže u odnosu na referentnu mešavinu. Posledično, čvrstoće pri pritisku mešavina sa sprašenim sumporom su niže od čvrstoće pri pritisku mešavina sa letećim pepelom i to u granicama od 4.9% (SCC mešavine sa 10% letećeg pepela i sprašenog sumpora pri starosti od 3 dana)

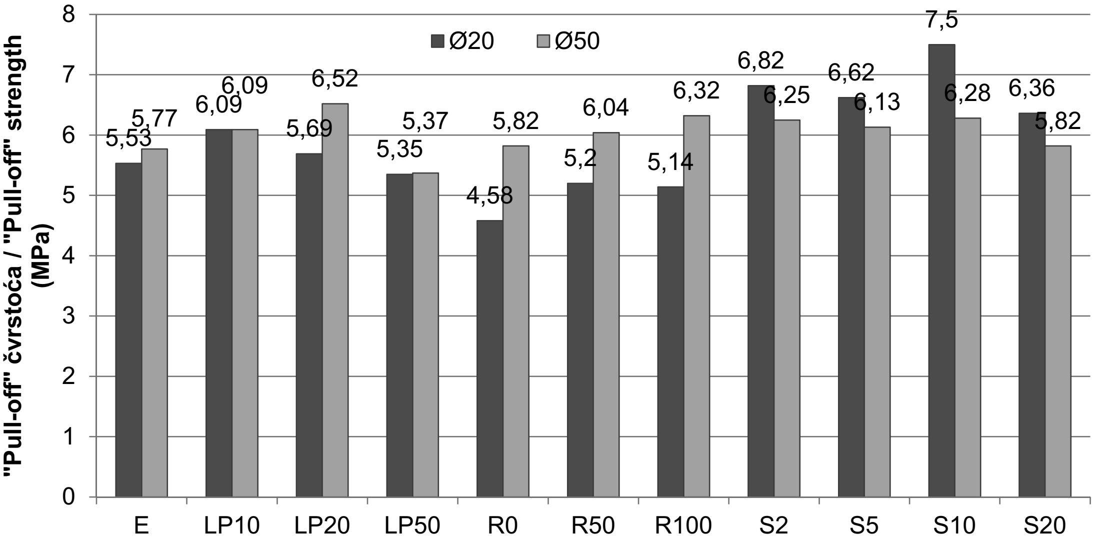
crease of compressive strength is lower than for SCC with higher content of ground sulfur, whilst that decrease does not follow the increase of the ground sulfur content linearly. Also, values of the decrease of compressive strength of SCC with 10% and 20% of ground sulfur are similar at all ages, and with the increase of age differences in decrease of compressive strength.

Except at the age of 3 days, at all ages general ratio of the values of results of investigation of referent SCC mixture, SCC mixture with fly ash and SCC mixture with ground recycled concrete was the same: mixture with fly ash always had higher compressive strength in comparison to the reference SCC mixture (from 6.3% to 12.9%), and mixture with ground recycled concrete always had lower compressive strength in comparison to the reference SCC mixture (from 2.8% to 4.9%). This effect was noticed at early ages for SCC with fly ash, and it is most probably the consequence of the fact that pozzolanic reaction (which generally improves structure of SCC with fly ash) did not yet result with improvement of compressive strength. In such case physical and mechanical effect of grains of fly ash (with weaker physical and mechanical properties, in comparison to the limestone filler) was dominant.

Based on the analysis of investigation of SCC mixtures with 10% and 20% of fly ash, or 10% and 20% of ground sulfur, several remarks can be made. Namely, at all ages, except for the 3 days of age, compressive strength of mixtures with fly ash were higher than the compressive strength of the reference SCC mixture, and in case of ground sulfur use, compressive strengths are lower than for the referent mixture. Consequently, compressive strengths of the mixtures with ground sulfur were lower than the compressive strengths of the mixtures with fly ash, ranging from 4.9% (SCC mixture with 10% of fly ash compared with the SCC mixture with the same amount of ground sulfur, at the age of 3 days) up to 22.7% (SCC mixture with 20% of fly ash compared with the SCC mixture with the same amount of ground sulfur, at the age of 28 days). Also, an observation can be made that these differences increase with the age and the quantity of the mineral filer used (differences range between 4.9% and 21.2% when SCC mixtures with 10% of ground sulfur and 10% of fly ash are compared, and between 11.8% and 22.7% when SCC mixtures with 20% of ground sulfur and 20% of fly ash are compared).

Graph showing values of adhesion of all SCC mixtures (investigation made by “pull-off” method [32]) is shown on Fig. 6. Five dollies of each different diameter (Ø20 mm and Ø50 mm) were used for the adhesion testing conducted by “pull-off” method, and the investigation was made at the age of 180 days.

In the case when dollies of Ø20 mm were used, it can be said that decrease of the adhesion of the



Slika 6. Vrednosti "pull-off" čvrstoće (MPa) svih SCC mešavina
Figure 6. Values of "pull-off" strength (MPa) of all SCC mixtures

do 22.7% (SCC mešavine sa 20% letećeg pepela i sprašenog sumpora pri starosti od 28 dana). Takođe, može se primetiti da ove razlike rastu sa porastom vremena i sa porastom količine upotrebljenog mineralnog dodatka (razlike u granicama od 4.9% i 21.2% pri poređenju SCC mešavina sa 10% sprašenog sumpora i 10% letećeg pepela, odnosno u granicama od 11.8% do 22.7% pri poređenju SCC mešavina sa 20% sprašenog sumpora i 20% letećeg pepela).

Što se tiče ispitivanja athezije svih SCC mešavina (ispitivanje obavljeno "pull-off" metodom [32]), odgovarajući dijagram prikazan je na slici 6. Pri ispitivanju athezije "pull-off" metodom, za svaku seriju upotrebljeno je po pet pečata dva različita prečnika (Ø20 mm i Ø50 mm), a ispitivanje je obavljeno pri starosti od 180 dana.

U slučaju upotrebe pečata prečnika Ø20 mm, može se reći da je došlo do pada vrednosti athezije pečata u odnosu na referentnu SCC mešavinu pri zameni 50% krečnjačkog brašna letećim pepelom (3,3%) ili sprašenim recikliranim betonom (11,2%) iste mase. U slučaju upotrebe pečata prečnika Ø50 mm, može se reći da je došlo do pada vrednosti athezije pečata u odnosu na referentnu SCC mešavinu pri zameni 50% krečnjačkog brašna letećim pepelom (6,9%) iste mase, odnosno do porasta (8,8%) vrednosti athezije pečata u odnosu na referentnu SCC mešavinu pri zameni 50% krečnjačkog brašna sprašenim recikliranim betonom iste mase.

U slučaju primene pečata prečnika Ø20 mm, porast vrednosti athezije merene "pull-off" metodom kod SCC mešavina sa sprašenim sumporom, u odnosu na referentnu SCC mešavinu, kretao se u granicama od 15.0% za mešavinu oznake S20 do 35.7% za mešavinu oznake S10. U slučaju primene pečata prečnika Ø50 mm, porast vrednosti athezije merene "pull-off" metodom, u odnosu na referentnu SCC mešavinu kretao se u granicama od 0.8% kod mešavine oznake S20

dollies took place, in comparison to the reference SCC when 50% of limestone filler were replaced with fly ash (3.3%) or ground recycled concrete (11.2%) of the same mass. In the case when dollies of Ø50 mm were used, a decrease of the adhesion of the dollies was recorded, in comparison to the reference SCC mixture with the replacement level of 50% of limestone filler replaced with fly ash (6.9%) of the same mass, and increase (8.8%) of the adhesion values, in comparison to the reference SCC mixture with 50% of limestone filler replaced with ground recycled concrete of the same mass.

When dolly diameter of Ø20 mm was used, increase in the adhesion measured by "pull-off" method for SCC mixtures with ground sulfur, in comparison to the reference SCC mixture, ranged in the limits of 15.0% for the mixture S20 up to 35.7% for the mixture S10. In the case of the use of dolly diameter of Ø50 mm, increase of the adhesion values measured by "pull-off" method, in comparison to the reference SCC mixture ranged between 0.8% for the mixture S20 up to 8.8% for mixture S10. On the bases of the displayed facts, it can be noticed that the use of ground sulfur in the SCC mixtures had positive effect on the values of adhesion, measured with "pull-off" method, independently of the diameter of the used dolly.

Results of the flexural strength investigation, conducted on three 12x12x36 cm prisms at the age of 180 days, are given in table 5. Investigation was conducted according to [33].

A decrease in flexural strength was recorded in all SCC mixtures (with fly ash, with ground recycled concrete and with ground sulfur) in comparison to the reference mixture E. In the case of mixtures with fly ash, this decrease was more pronounced with the decrease of fly ash content in the mixture (and it amounted to 23.8%, 18.1% and 1.0% for SCC mixtures designated with LP10, LP20 i LP50, respectively). Reference (Siddique

Tabela 5. Rezultati ispitivanja čvrstoće pri zatezanju savijanjem SCC mešavina (MPa)
Table 5. Results of flexural strength investigation conducted on SCC mixtures (MPa)

	E	LP10	LP20	LP50	R0	R50	R100	S2	S5	S10	S20
fz,s,180	10.5	8.0	8.6	10.4	9.4	9.2	8.9	8.6	8.1	7.8	6.9

do 8.8% kod mešavine oznake S10. Na osnovu svega rečenog, može se primetiti da je upotreba sprašenog sumpora u mešavinama SCC imala pozitivan efekat na vrednosti athezije, merene pomoću "pull-off" metode, nezavisno od prečnika primenjenog pečata.

Rezultati ispitivanja čvrstoće pri zatezanju savijanjem, obavljeni na po tri prizme dimenzija 12x12x36 cm pri starosti od 180 dana, dati su u tabeli 5. Ispitivanje je izvršeno prema [33].

Kod svih SCC mešavina (sa letećim pepelom, sa sprašenim recikliranim betonom i sa sprašenim sumporom) došlo je do pada čvrstoće pri zatezanju savijanjem u odnosu na referentnu mešavinu E. U slučaju mešavina sa letećim pepelom, ovaj pad bio je izraženiji sa smanjenjem količine letećeg pepela u mešavini (i iznosio je 23,8%, 18,1% i 1,0% kod SCC mešavina oznake LP10, LP20 i LP50, respektivno). Navodi iz literature (Siddique 2003. [36]) prema kojima se za delimičnu zamenu sitnog agregata letećim pepelom (10%, 20%, 30%, 40% i 50%) postiže viša vrednost čvrstoće pri zatezanju savijanjem, nisu mogli biti potvrđeni. Pad vrednosti dobijen na SCC mešavinama oznaka R0, R50 i R100 u odnosu na referentnu SCC mešavinu spravljenu bez sprašenog recikliranog betona, samo sa krečnjačkim brašnom u svojstvu filera, kretao se u granicama od 10.5% za mešavinu oznake R0 do 15.2% za mešavinu oznake R100, pri starosti od 180 dana.

Što se tiče vrednosti čvrstoće pri zatezanju savijanjem na SCC mešavinama oznaka S2, S5, S10 i S20, došlo je do pada ovog svojstva u odnosu na referentnu SCC mešavinu. Ovaj pad kretao se u granicama od 18.1% za mešavinu oznake S2 do 34.3% za mešavinu oznake S20, pri starosti od 180 dana. Može se konstatovati da kod SCC mešavina sa povećanjem količine sprašenog sumpora dolazi do pada čvrstoće pri zatezanju savijanjem gotovo linearno u funkciji od sadržaja sprašenog sumpora. Pri tome treba dodati da je već pri malim količinama sprašenog sumpora (2% u odnosu na ukupnu masu filera) evidentan pad čvrstoće pri zatezanju savijanjem od 18%.

Uporednom analizom čvrstoće pri savijanju kod ispitivanih SCC mešavina sa različitim industrijskim nusproduktima, može se primetiti da je kod primene letećeg pepela došlo do neznatnog pada (1%) čvrstoće pri savijanju u odnosu na referentnu vrednost (dobijenu za SCC mešavinu spravljenu sa krečnjačkim brašnom u svojstvu filera), a da je pad u slučaju upotrebe sprašenog recikliranog betona (u količini od 50% u odnosu na ukupnu masu filera) iznosio 15,2%. Najviša vrednost pada zabeležena je kod SCC mešavine sa sprašenim sumporom (čak 18%).

2003. [36]) according to which for the partial replacement of fine aggregate with fly ash (10%, 20%, 30%, 40% i 50%) lead to the increase in flexural strength, could not be confirmed. Decrease in the flexural strength of SCC mixtures designated with R0, R50 and R100, in comparison to the reference SCC (made without ground recycled concrete, only with limestone powder as a filler) ranged between 10.5% for SCC mixture R0 and 15.2% for mixture R100, at the age of 180 days.

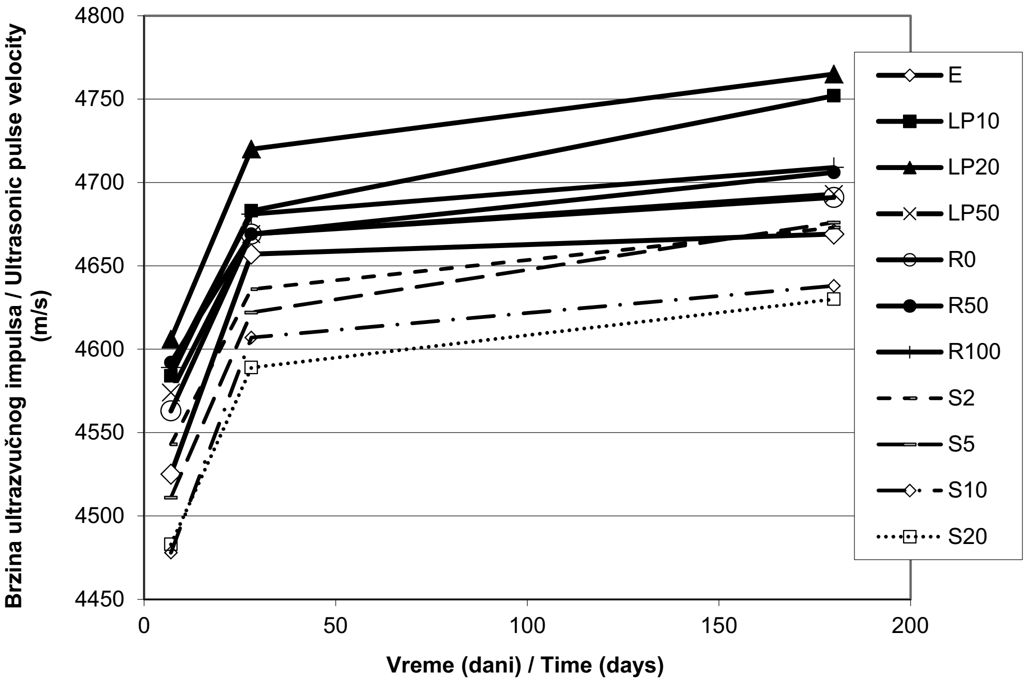
As for the flexural strength of SCC mixtures designated with S2, S5, S10 and S20, a decrease of this property was recorded, in comparison to the reference SCC mixture. This decrease ranged between 18.1% (for the SCC mixture S2) and 34.3% (for the mixture S20), at the age of 180 days. A note can be made that with increase in quantity of ground sulfur, an almost linear decrease of flexural strength occurs. Additionally, already at low quantities of ground sulfur (2% of the total filler mass) a high 18% drop in flexural strength is evident.

Based on the comparative analysis of flexural strength for investigated SCC mixtures with different industrial byproducts, an observation can be made that with the use of fly ash a slight decrease (1%) of flexural strength occurred in comparison to the referent value (obtained for SCC mixture made with limestone powder as filler), and that the decrease when ground recycled concrete was used (in the quantity of 50% of the total filler mass) was 15.2%. The highest value of the drop was recorded for SCC mixtures with ground sulfur (34.3%).

Change in the values of ultrasonic pulse velocity was investigated on three 12x12x36 cm prisms for each series, up to the age of 180 days. Values of the ultrasonic pulse velocity for all the investigated concretes are shown on Fig. 7, in function of the age of the concrete.

The lowest values of ultrasonic pulse velocity at all ages were recorded on the SCC mixture with 20% of ground sulfur (S20), and the highest SCC mixture with 20% replacement level of limestone powder with fly ash (LP20). Values of the ultrasonic pulse velocity for the other mixtures are positioned between the two mentioned, and can be regarded as close, especially when R0, R50, R100 and LP50 are observed. It can be concluded that the correlations of ultrasonic pulse velocity with time were independent of the type of the used ground recycled concrete.

A correlation between compressive strength and ultrasonic pulse velocity for all of the investigated mixtures is shown on Fig. 8. For the sake of simple analysis of the obtained results, three regression functional correlations were formed, one



Slika 7. Izmerene vrednosti brzine ultrazvučnog impulsa (m/s) za ispitivane betone pri starostima od 7, 28 i 180 dana
Figure 7. Measured values of ultrasonic pulse velocity (m/s) for investigated concretes at the ages of 7, 28 and 180 days

Promena vrednosti brzine ultrazvučnog impulsa praćena je na po tri uzorka dimenzija 12x12x36 cm, izrađena od svih ispitivanih SCC mešavina, do starosti od 180 dana. Na slici 7 su prikazane vrednosti brzine ultrazvučnog impulsa za sve ispitivane betone, u funkciji od starosti betona.

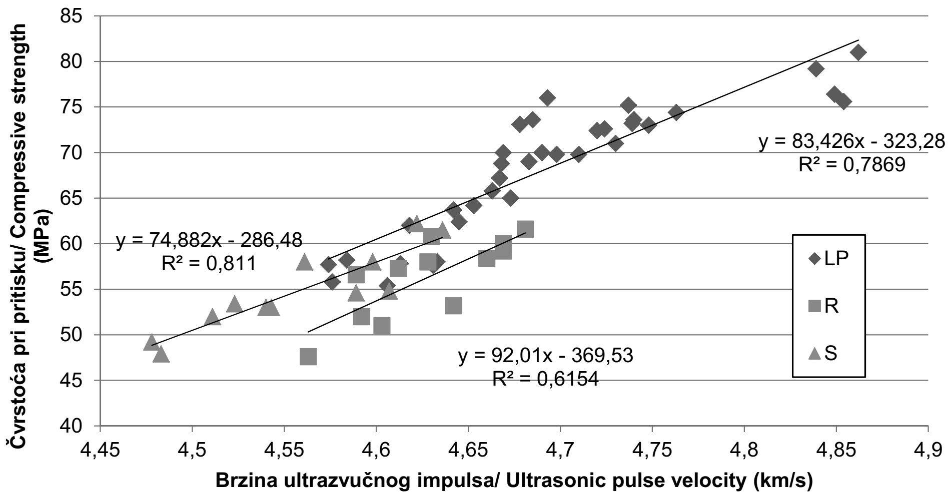
Najniže vrednosti ultrazvučnog impulsa pri svim starostima imala je mešavina sa 20% sprašenog sumpora (S20), a najviše SCC mešavina sa 20% zamene krečnjačkog brašna letećim pepelom (mešavina oznake LP20). Vrednosti brzine ultrazvučnog impulsa za ostale mešavine pozicionirane su između dve pomenute zavisnosti i mogu se smatrati bliskim, naročito kada se posmatraju R0, R50, R100 i LP50. Može se reći da su zavisnosti brzine ultrazvučnog impulsa od vremena nezavisne od vrste primenjenog sprašenog recikliranog betona.

Zavisnost između vrednosti čvrstoće pri pritisku i brzine ultrazvučnog impulsa za sve ispitivane mešavine prikazana je na slici 8. Radi jednostavnije analize dobijenih rezultata, formirane su tri regresione funkcionalne zavisnosti, jedna za betone sa različitim sadržajima letećeg pepela, druga za betone sa sprašenim betonom različitog porekla i treća za betone sa sprašenim sumporom. Kao što se vidi iz priloženog grafičkog prikaza, regresiona fukcionalna zavisnost formirana za betone sa letećim pepelom je viša od preostale dve zavisnosti, što znači da za iste izmerene vrednosti brzine ultrazvučnog impulsa betoni sa sprašenim recikliranim betonom u svojstvu zamene dela filera imaju generalno niže (cca 5 MPa) vrednosti čvrstoće pri pritisku, a betoni sa sprašenim sumporom najniže.

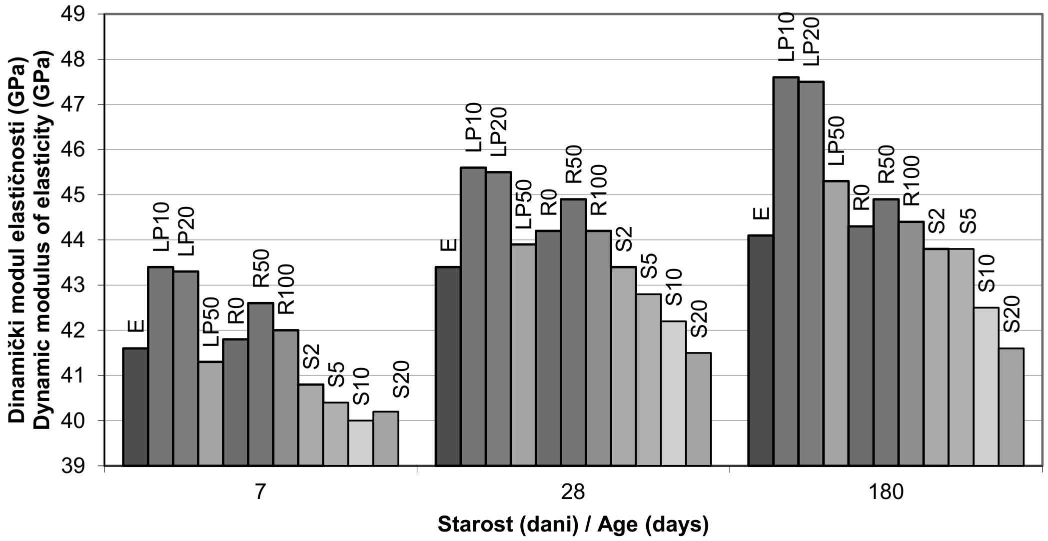
for the SCC mixtures with different content of fly ash, second for the SCC mixtures with ground recycled concrete of different origin, and the third for the SCC mixtures with ground sulfur. As it can be seen from the graphical display, regression function formed for the mixtures with fly ash is above the other two functions, meaning that for the same measured values of ultrasonic pulse velocity, SCC series with ground recycled concrete as a partial replacement of filer have generally lower (app. 5 MPa) values of compressive strength, and SCC mixtures with ground sulfur the lowest.

Values of the dynamic modulus of elasticity recorded at the age of 7, 28 and 180 days for all of the SCC series are shown on Fig. 9.

Based on the shown graphic display, an observation can be made that, generally, values of dynamic modulus of elasticity for SCC mixtures with fly ash are higher (for mixtures LP10 and LP20 significantly higher, up to 12%) than the values for the reference E. This effect is similar in the case of the use of ground recycled aggregate, increases ranging from 1.0% up to 2.6%. Values of the dynamic modulus of elasticity for mixtures with ground sulfur are generally lower and the trend of decrease of dynamic modulus of elasticity with the increase in ground sulfur content is noticeable.



Slika 8. Zavisnost između vrednosti pritisne čvrstoće (MPa) i brzine ultrazvučnog impulsa (m/s) za sve ispitivane betone
Figure 8. Correlation between the values of compressive strength (MPa) and ultrasonic pulse velocity (m/s) for the investigated concretes



Slika 9. Uporedni prikaz dinamičkog modula elastičnosti (GPa) kod očvrslih SCC mešavina
Figure 9. Comparative display of dynamic modulus of elasticity (GPa) in hardened SCC mixtures

Vrednosti dinamičkog modula elastičnosti zabeležene pri starosti od 7, 28 i 180 dana kod svih SCC mešavina prikazane su na slici 9.

Na osnovu prikazane grafičke predstave može se primetiti da su, generalno, vrednosti dinamičkog modula elastičnosti kod mešavina sa letećim pepelom više (kod mešavina LP10 i LP20 značajno više, do 12%) od odgovarajućih vrednosti za referentnu mešavinu E. Sličan je efekat i u slučaju upotrebe sprašenog recikliranog agregata, gde se porasti kreću u granicama od 1,0% do 2,6%. Vrednosti dinamičkog modula elastičnosti kod mešavina sa sprašenim sumporom su generalno niže i primećuje se trend smanjenja vrednosti dinamičkog modula elastičnosti sa povećanjem sadržaja sprašenog sumpora.

6. ZAKLJUČCI

Savremeno građevinarstvo napreduje i razvija se brzim tempom. Globalni problemi koji su pod-

6. CONCLUSIONS

Contemporary building industry advances and develops rapidly. Global problems that provoked expansion of sustainable development practice can be transferred to building industry in a considerable amount, and therefore they present a challenge for the investigators and practitioners, solution to which leads to one healthier and brighter future.

With respect to this posture, on one hand, and with the need for the valorization and use of industrial byproducts as potential components for concrete, on the other, thorough investigations of SCC mixtures in fresh and hardened state were conducted, leading to the detailed investigation of the properties of such concretes. The mentioned investigations were conducted on eleven SCC mixtures, including: reference SCC mixture with limestone filler as mineral filler, three mixtures with partial replacement of limestone filler with fly ash stakli formiranje prakse održivog razvoja u velikoj meri mogu se preslikati na građevinsku industriju, i kao takvi predstavljaju istraživačima i praktičarima izazov, čije rešavanje vodi jednoj zdravijoj i čistijoj budućnosti.

Vodeći računa o ovom stavu, sa jedne, kao i potrebom za utroškom i valorizacijom industrijskih nusprodukata kao komponentnog materijala, sa druge strane, obavljena su opsežna ispitivanja SCC mešavina u svežem i očvrslom stanju, radi detaljnog istraživanja svojstava ovih betona. Pomenuta ispitivanja sprovedena su na jedanaest SCC mešavina i to: referentna SCC mešavina sa krečnjačkim brašnom kao mineralnim dodatkom, tri mešavine sa delimičnom zamenom mase krečnjačkog brašna letećim pepelom poreklom iz TE Kolubara, tri mešavine sa delimičnom zamenom mase krečnjačkog brašna sprašenim recikliranim betonom i četiri mešavine sa delimičnom zamenom mase krečnjačkog brašna sprašenim sumporom. Ostale količine materijala držane su konstantnim: količine cementa, vode, sitnog (rečnog peska) i krupnog agregata (druge i treće frakcije prirodnog rečnog agregata). U mešavinama je upotrebljen čist cement PC 42,5R i voda iz vodovoda.

Uticaj zamene dela krečnjačkog brašna jednim od pomenutih industrijskih nusprodukata praćen je kroz ispitivanja zapreminske mase u svežem stanju, zatim sposobnosti tečenja, sposobnosti prolaska i otpornosti prema segregaciji. U očvrslom stanju istraživan je uticaj zamene dela filera pomenutim dodacima na: čvrstoću pri pritisku, čvrstoću pri zatezanju savijanjem, atheziju, brzinu ultrazvučnog impulsa i dinamički modul elastičnosti. U nastavku se daju sumarni zaključci po svojstvima.

Na osnovu izmerenih vrednosti zapreminske mase svežeg betona, može se izvesti zaključak da upotreba svakog od navedenih industrijskih nusprodukata dovodi do većeg ili manjeg pada ovog svojstva kod SCC mešavina. Pritom, ovaj pad je najizraženiji pri primeni letećeg pepela (oko 2%), a najmanje izražen kod upotrebe sprašenog recikliranog betona (manje od 0,5%).

Usled povećanja količine letećeg pepela u svojstvu filera u SCC mešavinama, dolazi do pada rasprostiranja sleganjem betona. Pritom treba imati u vidu da je mešavina sa 50% letećeg pepela (u odnosu na ukupnu masu filera) postigla sličnu vrednost rasprostiranja sleganjem kao mešavine sa 10% i 20% letećeg pepela, ali je pritom sadržaj superplastifikatora u mešavini morao biti povećan sa 2% na 3%. Efekat pada izmerene vrednosti rasprostiranja sleganjem je primetan, ali ne toliko izražen, prilikom upotrebe sprašenog recikliranog betona. Prisustvo sprašenog sumpora dovodi do povećanja vrednosti rasprostiranja sleganjem u odnosu na referentnu mešavinu (oko 3%).

Na osnovu ispitivanja sposobnosti prolaska merene testom L-boksa (H_2/H_1) može se zaključiti

from TPP "Kolubara", three SCC mixtures with partial replacement of limestone filler mass with ground recycled concrete and four SCC mixtures with partial replacement of limestone filler mass with ground sulfur. The quantities of other materials were held constant: quantities of cement, water, fine (river sand) and coarse aggregate (second and third fraction of natural river aggregate). In all of the SCC mixtures pure cement PC 42.5R was used, as well as drinking water.

The influence of the partial limestone powder replacement with one of the mentioned industrial byproducts was observed through investigation of fresh SCC density, flowing ability, passing ability and the segregation resistance. In hardened state, influence of partial replacement of filer with mentioned additions was investigated through following properties: compressive strength, flexural strength, adhesion, ultrasonic pulse velocity and dynamic modulus of elasticity. Summarized conclusions are given forward, regarding each of the properties.

On the basis of the measured values of density of fresh concrete, a conclusion can be drawn that the use of every of the mentioned industrial byproducts leads to higher or lower drop of this property of SCC mixtures. Additionally, this drop is most pronounced when fly ash is used (around 2%), and the least pronounced with the use of ground recycled concrete (less than 0.5%).

Due to the increase of the fly ash content in SCC mixtures, decrease of the slump flow of concrete takes place. It should be noted that the mixture with 50% of fly ash (of the total mass of filer) achieved similar value of slump flow as mixtures with 10% and 20% of fly ash, but the quantity of superplasticizer had to be increased from 2% to 3% in this mixture. Effect of the decrease of the measured slump flow is evident, but not so pronounced, in the case of use of ground recycled concrete. The presence of ground sulfur leads to the increase of slump flow in comparison to the referent mixture (around 3%).

On the basis of passing ability measured with L-box test (H_2/H_1) a conclusion can be made that, generally, measured values for all the mixtures were relatively close, in the range from 0.92 to 0.98. A decrease (5.1%) of the measured values of this property was measured with the change of fly ash content, as well as with the use of ground recycled concrete (drop of 2%), independently of the origin of the ground recycled concrete. Presence of the ground sulfur in quantities of 2% to 20% in the total amount of filler had no significant effect on change of H_2/H_1 value in L-box test.

In the case of flowing ability, investigations based on time t_{500} (measured at slump flow test) and t_V (measured at V-funnel test) measurement, a conclusion can be made that this property (flowing ability) decreased with the increase in quantity of fly ash in SCC mixtures with fly ash, as well da su, generalno, izmerene vrednosti za sve mešavine bile relativno bliske, u granicama od 0,92 do 0,98. Došlo je do pada (5,1%) izmerenih vrednosti ovog svojstva usled promene količine letećeg pepela, kao i usled doziranja sprašenog recikliranog betona (pad od 2%), nezavisno od porekla sprašenog recikliranog betona. Prisustvo sprašenog sumpora u količinama od 2% do 20% u odnosu na ukupnu masu filera nije imalo značajan efekat na promenu vrednosti odnosa visina H_2/H_1 kod L-boksa.

Kada je u pitanju sposobnost tečenja, ispitivanja na osnovu merenja vremena t500 potrebnog za rasprostiranje i vremena tv izmerenog kod metode V-levka, može se zaključiti da je došlo do pada ovog svojstva (sposobnosti tečenja) usled povećanja količine letećeg pepela u SCC mešavinama sa letećim pepelom, kao i usled povećanja količine sprašenog recikliranog betona u SCC mešavinama sa sprašenim recikliranim betonom. Ovaj pad je izraženiji kod SCC sa letećim pepelom, a vrednosti izmerenih vremena t_{500} i t_V su više kod SCC mešavina sa letećim pepelom u odnosu na SCC mešavine sa sprašenim recikliranim betonom 58,3% i 55,3% respektivno. U slučaju povećanja količine sprašenog sumpora u SCC mešavinama, došlo je do malog pada vrednosti vremena t_{500} (17,2-30,5%) i povećanja vrednosti vremena t_V (5,3-8,8%).

Generalno, kod svih ispitivanih mešavina SCC sa letećim pepelom, sa povećanjem količine doziranog letećeg pepela došlo je do pada obradljivosti u odnosu na referentnu mešavinu, spravljenu sa istom količinom vode, što je u saglasnosti sa stavovima drugih autora [37]. Uopšteno posmatrano, svi SCC spravljani sa recikliranim sprašenim betonom pokazali su veoma slično ponašanje i opažanja u vezi sa njihovim ponašanjem u najvećem broju slučajeva se mogu svesti na efekat doziranja sprašenog recikliranog betona, nezavisno od vrste (“A”, “B” ili “C”). Upotreba sprašenog sumpora u svojstvu delimične zamene krečnjačkog brašna (do 20%) nije dovela do značajnih promena u svojstvima svežeg betona, pri čemu su praćena svojstva u izvesnom broju slučajeva čak bila malo bolja. Takođe, treba napomenuti da je poređenje mešavina samo na osnovu izmerene vrednosti rasprostiranja sleganjem neprihvatljivo, jer se tako ne bi uzeo u obzir efekat sposobnosti tečenja koji, kao što je to ovde evidentno, može da značajno varira, čak i za slične vrednosti rasprostiranja sleganjem.

Kada su u pitanju ispitivanja u očvrslom stanju, na osnovu ispitivanja čvrstoće pri pritisku može se zaključiti da je zamena određenog masenog procenta krečnjačkog brašna letećim pepelom imala pozitivan efekat na čvrstoću pri pritisku SCC mešavina, naročito pri većim starostima. Na ispitivanim SCC mešavinama su izmerene do 16,8% više vrednosti čvrstoće pri pritisku (pri starosti od 28 dana) u odnosu na referentnu mešavinu

as due to the increase of the quantity of ground recycled concrete in SCC mixtures with ground recycled concrete. This drop is more pronounced in SCC with fly ash, and the values of the measured times t500 and tv are higher in SCC mixtures with fly ash in comparison to the SCC mixtures with ground recycled concrete 58.3% and 55.3%, respectively. In the case of the increase of ground sulfur quantity in SCC mixtures, a small drop in values of time t_{500} (17.2-30.5%) and increase in time t_V (5.3-8.8%) was recorded.

Generally, for all of the investigated SCC mixtures with fly ash, with the increase of fly ash quantity a drop in workability occurred in comparison to the referent mixture, made with the same amount of water, which is in compliance with the findings of other authors [37]. All SCC mixtures made with recycled ground concrete showed very similar behavior and the findings regarding their behavior in the most cases can be reduced to the effect of dosage of ground recycled concrete, regardless the type (“A”, “B” or “C”). The use of ground sulfur as partial replacement of limestone powder (up to 20%) led to no significant changes in properties of fresh concrete, whereas the investigated properties in a number of cases were even a little better. Also, a notice has to be made that the comparison of the SCC mixtures only on the basis of the measured values of slump flow is unacceptable, because effect of flowing ability couldn’t be taken into account, although it can, as it was evident from these investigations, can vary significantly, even for the similar or same values of slump flow.

When it comes to the investigations in hardened state, based on the tests of compressive strength, a conclusion can be made that the exchange of the certain mass percent of limestone filler with fly ash had positive effect on compressive strength of SCC mixtures, especially at later ages. On the investigated SCC mixtures 16.8% higher values of compressive strength were measured (at the age of 28 days) in comparison to the referent mixture designated as E (without fly ash). This effect can be contributed to the pozzolanic effect of fly ash (especially at quantities up to 20% of the total mass of filler). When it comes to SCC mixtures with ground recycled concrete, in most cases drop in the compressive strength occurred (up to 11.2% at the age of 28 days) in comparison to the referent mixture. With time, similar increase of strength was recorded for all of the mixtures. A general conclusion can be made that the use of ground recycled concrete in the same quantity as fly ash showed opposite effect in terms of compressive strength, because decrease in compressive strength of 7.7% was recorded, in respect to the SCC mixture with fly ash. Compressive strengths of SCC mixtures with ground sulfur were lower in comparison to the reference mixture and higher for higher values of ground sulfur content. Nevertheless, the values of decrease of oznake E (bez letećeg pepela). Ovaj efekat se može pripisati pucolanskom efektu letećeg pepela (pogotovu pri količinama do 20% u odnosu na ukupnu masu filera). Kada je reč o SCC mešavinama sa sprašenim recikliranim betonom, u najvećem broju slučajeva došlo je do pada vrednosti čvrstoće pri pritisku (do 11,2% pri starosti od 28 dana) u odnosu na referentnu mešavinu. Sa vremenom, zabeležen je sličan porast čvrstoće za sve mešavine. Može se izvesti generalni zaključak da je upotreba sprašenog recikliranog betona u istoj količini kao i letećeg pepela pokazala suprotan efekat u smislu čvrstoće pri pritisku, jer je došlo do pada vrednosti čvrstoće pri pritisku od 7,7% u odnosu na SCC mešavinu sa letećim pepelom. Čvrstoće pri pritisku SCC mešavina sa sprašenim sumporom su niže u odnosu na referentnu mešavinu. Primetan je veći pad čvrstoće pri pritisku sa većim sadržajem sprašenog sumpora. Međutim, vrednosti pada čvrstoće pri pritisku SCC sa 10% i 20% sprašenog sumpora su slične pri svim starostima, a sa povećanjem starosti razlike u procentualnom padu čvrstoće pri pritisku se smanjuju.

Vrednosti čvrstoće pri zatezanju savijanjem i athezije SCC sa letećim pepelom nisu značajnije odstupale od odgovarajućih vrednosti zabeleženih kod referentne mešavine E. Mešavina oznake LP20 (SCC mešavina spravljena sa letećim pepelom poreklom iz TE “Kolubara”, u iznosu od 20% u odnosu na ukupnu masu filera u betonu) imala je najviše vrednosti u odnosu na sve ispitivane SCC mešavine (u proseku do 10% pri starosti od 28 dana). Može se izvesti generalni zaključak da vrednosti čvrstoće pri zatezanju savijanjem i athezije načelno opadaju (cca 8-12%) sa promenom vrste sprašenog betona u SCC.

Porast količine letećeg pepela u odnosu na ukupnu masu filera kod SCC mešavina rezultira padom vrednosti brzine ultrazvučnog impulsa SCC mešavine (u iznosu do 1%), nezavisno od vrste upotrebljenog letećeg pepela i nezavisno od starosti uzoraka SCC mešavine pri ispitivanju. Upotreba sprašenog recikliranog betona u svojstvu filera kod SCC mešavina rezultira porastom (najviše 1,5% pri starosti od 7 dana) vrednosti brzine ultrazvučnog impulsa SCC mešavine.

Povećanje količine letećeg pepela poreklom iz TE “Kolubara” sa 10% na 20% i 50% u odnosu na ukupnu masu filera rezultiralo je padom vrednosti dinamičkog modula elastičnosti Ed u iznosu od 0,2% (za povećanje sa 10% na 20%) i 3,7-4,9% (za povećanje sa 10% na 50%) pri svim starostima. U zavisnosti od porekla upotrebljenog sprašenog recikliranog betona, najveći pad vrednosti dinamičkog modula elastičnosti (1,8-3,7%) uvek je bio kod SCC mešavine spravljene sa sprašenim recikliranim betonom poreklom od NVC sa 50% recikliranog betona u svojstvu krupnog agregata, a najmanji (0,5-1,9%) kod SCC mešavine spravljene sa sprašenim recikliranim

compressive strength of SCC with 10% and 20% of ground sulfur were similar at all ages, and with the increase of ages, differences in percentage decrease of compressive strength are lower.

The values of flexural strength and adhesion of SCC with fly ash didn’t deviate significantly from the relating values measured on reference E. Mixture designated as LP20 (SCC mixture made with fly ash originated from TPP “Kolubara”, in the quantity of 20% of the total mass of filler in concrete) had the highest values of all the investigated SCC mixtures (in average, up to 10% at the age of 28 days). A general conclusion can be drawn that the values of flexural strength and adhesion show decrease (approximately 8-12%) with the change in type of ground concrete in SCC.

Increase in the quantity of fly ash, as a percentage of the total mass of filler in SCC mixtures, results with decrease of ultrasonic pulse velocity in SCC mixtures (up to 1%), independently of the type of the used fly ash and independently of the age of samples of SCC mixtures at test. The use of ground recycled concrete as filler in SCC mixtures results with the increase (up to 1.5% at the age of 7 days) of the values of ultrasonic pulse velocity of SCC mixtures.

Increase in the quantity of fly ash, originated from TPP Kolubara from 10% to 20% and 50% of the total mas of filler resulted with the decrease of dinamic modulus of elasticity Ed in amount of 0.2% (for increase from 10% to 20%) and 3.7-4.9% (for increase from 10% to 50%) at all ages. Depending on the origin of the used ground recycled concrete, the highest decrease of dynamic modulus of elasticity (1.8-3.7%) was always for SCC mixture made with ground recycled concrete, made from NVC with 50% of recycled concrete in the coarse aggregate, and the lowest (0.5-1.9%) for SCC mixtures made with ground recycled concrete made from NVC with natural aggregate. On the other hand, based on the investigation, a conclusion can be drawn that the use of ground sulfur in SCC mixtures showed positive effect in terms of adhesion, measured with “pull-off” method, independently of the diameter of the used dolly (increase of 0.8-35.7%).

Flexural strength was 11.9% lower in SCC mixtures with ground recycled concrete, compared to the flexural strength of the SCC mixtures with fly ash, at the age of 180 days. When flexural strength and adhesion are in question, general observation can be made, that these values change insignificantly with the change of the type of ground concrete in SCC. In the case of neglecting the type of used ground recycled concrete, an observation is made that the replacement of limestone filler with ground recycled concrete in amount of 50% results with decrease in the values of investigated properties. This drop is most visible in the case of flexural strength (13%).

In the case of the ultrasonic pulse velocity, a betonom poreklom od NVC. Sa druge strane, na osnovu ispitivanja, može se zaključiti da je upotreba sprašenog sumpora u SCC mešavinama imala pozitivan efekat na vrednosti athezije, merene pomoću "pull-off" metode, nezavisno od prečnika primenjenog pečata (porast od 0,8% do 35,7%).

Čvrstoća pri savijanju je niža kod SCC mešavina sa sprašenim recikliranim betonom u iznosu od 11,9% u odnosu na vrednost čvrstoće pri savijanju SCC mešavine sa letećim pepelom, pri starosti od 180 dana. Kada su ispitivanja čvrstoće pri zatezanju savijanjem i athezije u pitanju, može se izvesti generalna konstatacija da se ove veličine ne menjaju značajno sa promenom vrste sprašenog betona u SCC. U slučaju da se zanemari vrsta upotrebljenog sprašenog recikliranog betona, primećuje se da zamena krečnjačkog brašna sprašenim betonom u iznosu od 50% rezultira padom vrednosti posmatranih svojstava. Ovaj pad je najuočljiviji u slučaju čvrstoće pri zatezanju savijanjem (13%).

Kada je u pitanju brzina ultrazvučnog impulsa, može se izvesti zaključak da su sve izmerene vrednosti brzine ultrazvučnog impulsa relativno bliske, odnosno da se kreću u relativno uskim granicama od najviše 2,8% (za starost od 180 dana). Najviše vrednosti ovog svojstva zabeležene su kod SCC mešavine sa masenom zamenom krečnjačkog brašna letećim pepelom u iznosu od 20%, a najviše kod SCC mešavine sa masenom zamenom krečnjačkog brašna sprašenim sumporom u iznosu od 20%. Pritom, može se reći da su u svim slučajevima brzine ultrazvučnog impulsa izmerene kod SCC mešavine sa 50% letećeg pepela u odnosu na ukupnu masu filera niže nego brzine ultrazvučnog impulsa izmerene kod proseka za SCC mešavine sa 50% sprašenog recikliranog betona u odnosu na ukupnu masu filera.

Međusobnim poređenjem sračunatih funkcionalnih zavisnosti između čvrstoće pri pritisku i brzine ultrazvučnog impulsa SCC mešavina sa letećim pepelom i SCC mešavina sa sprašenim recikliranim betonom, može se zaključiti da je za SCC mešavine sa sprašenim recikliranim betonom dobijena funkcionalna zavisnost ispod zavisnosti formirane za mešavine sa letećim pepelom. Betoni sa sprašenim sumporom imaju najniže vrednosti čvrstoće pri pritisku, za iste izmerene vrednosti brzine ultrazvučnog impulsa.

Pri starostima do 28 dana, SCC mešavina sa letećim pepelom ima 1,0-2,0% nižu vrednost dinamičkog modula elastičnosti, a pri starosti od 180 dana 1,7% višu vrednost u odnosu na prosečnu vrednost za SCC mešavine sa sprašenim recikliranim betonom. Sa povećanjem sadržaja sprašenog sumpora, primetan je trend pada vrednosti dinamičkog modula elastičnosti kod ispitivanih SCC mešavina.

Ispitivanja prikazana u ovom radu koncipirana su u duhu mogućnosti postizanja potrebnih informacija koje bi omogućile praktičnu primenu različitih mineralnih dodataka kod SCC mešavina

general conclusion can be drawn that all the measured values of ultrasonic pulse velocity are relatively close, and that they fall in relatively narrow field of less than 2.8% (for the age of 180 days). The highest values of this property are recorded in SCC mixture with mass replacement of limestone powder with fly ash in amount of 20%, and the highest in SCC mixture with mass replacement of limestone powder with ground sulfur in amount of 20%. Also, in all of the cases of ultrasonic pulse velocities measured in SCC mixture with 50% of fly ash in respect to the total filler mass lower than the ultrasonic pulse velocities measured as average for SCC with 50% of ground recycled concrete of the total filler amount.

After the comparison of the calculated functional correlations between compressive strength and ultrasonic pulse velocity of SCC mixtures with fly ash and SCC mixtures with ground recycled concrete, a conclusion can be made that the functional correlation obtained for SCC mixtures with ground recycled concrete is below the correlation formed for the mixtures with fly ash. Concretes with ground sulfur have the lowest values of compressive strength, for the same measured values of ultrasonic pulse velocity.

At the ages up to 28 days, SCC mixture with fly ash has 1.0-2.0% lower value of dynamic modulus of elasticity, and for ages of 180 days 1.7% higher value in comparison to the average value for SCC mixtures with ground recycled concrete. With the increase in ground sulfur content, occurs a noticeable trend of decrease in dynamic modulus elasticity of investigated SCC mixtures.

Investigations shown in this paper were conceived in a spirit of possible achievement of the needed information which could enable practical application of different mineral additives in SCC mixtures [38], [39], [40]. Also, the use of fly ash in world is significantly higher than in Serbia and it amounts around 90% of the produced fly ash. Besides the fly ash, whose application can lead to significant advantages in achieving the properties of hardened concrete, it occurred that the use of ground recycled concrete and ground sulfur is also possible, without significant drops in properties of hardened SCC mixtures. Namely, based on the conducted wide range investigations, an overall conclusion can be made that the use of the mentioned industrial byproducts in certain, lower amounts, won't lead to the serious degradation in properties of SCC mixtures in which these byproducts were used.

[38],[39],[40]. Napominje se i činjenica da je u svetskim okvirima upotreba letećeg pepela (bila ona stimulisana regulativama ili ne) značajno veća nego u Srbiji i iznosi oko 90% proizvedenog letećeg pepela. Pored letećeg pepela, čijom se primenom mogu ostvariti značajne prednosti u postizanju svojstava očvrslog betona, pokazalo se da je primena sprašenog recikliranog betona i sprašenog sumpora takođe moguća, bez značajnih padova u svojstvima očvrslih SCC mešavina. Naime, na osnovu sprovedenih opsežnih ispitivanja, može se reći da upotreba pomenutih industrijskih nusprodukata u određenim, nižim procentima, neće dovesti do ozbiljnog narušavanja svojstava SCC mešavina u kojima su upotrebljeni.

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ФАКУЛТЕТ ТЕХНИЧКИХ НАУКА НОВИ САД

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U nadi da će naša saradnja biti na ovako visokom nivou i u budućnosti,

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