

PROJEKTOVANJE SASTAVA SAMOZBIJAJUĆEG BETONA SA VISOKIM UDJELOM KALCIJSKOG ELEKTROFILTERSKOG PEPELA ZA PREFABRIKOVANE ELEMENTE

MIX DESIGN OF SELF-COMPACTING CONCRETE CONTAINING HIGH VOLUME CALCAREOUS FLY ASH FOR PRECAST ELEMENTS

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REZIME

U ovom radu proučavana je mogućnost projektovanja samozbijajućeg betona sa visokim udjelom kalcijskog elektrofilterskog pepela (W) za prefabrikovane elemente. Do sada su razvijene mnoge metode projektovanja sastava samozbijajućeg betona, a kao najpogodnija metoda u ovom istraživanju odabrana je UCL metoda projektovanja sastava samozbijajućeg betona. U prvoj fazi izvršena su preliminarna ispitivanja na malterskoj mješavini pomoću mini konusa i mini V-lijevka, nakon čega je definisan optimalan sastav mješavine. U drugoj fazi pripremljena je i ispitana mješavina samozbijajućeg betona. Na kraju, na osnovu definisane recepture izrađeni su prefabrikovani elementi i ispitana su njihova svojstva. Na osnovu provedenih ispitivanja utvrđeno je da je koristeći UCL metodu moguće u relativno jednostavnom postupku dobiti kvalitetan samozbijajući beton.

Original scientific paper

SUMMARY

In this paper, the possibility of proportioning self-compacting concrete with high volume calcareous fly ash (W) for precast elements has been investigated. So far, numerous mix design methods for self-compacting concrete have been developed, so as the most appropriate method in this investigation, the UCL method was chosen. In the first phase, the preliminary tests were conducted on the mortar mixtures using mini slump cone and mini V-funnel, and thereafter the optimal mixture composition was defined. In the second phase, self-compacting concrete mixture was prepared and tested. In the end, based on the defined recipe, the precast elements were made and their properties were tested. On the basis of the examinations, it was found that it is possible to obtain high quality self-compacting concrete by using the relatively simple procedure according to the UCL method.

1. UVOD

Samozbijajući beton je nova vrsta cementnog kompozita čijom se primjenom smanjuje vrijeme građenja, obim poslova, oprema na gradilištu i buka. Samozbijajući beton teče pod utjecajem vlastite težine bez pojave segregacije, te u potpunosti popunjava oplatu bez potrebe za zbijanjem upotrebom vibracijskih uređaja.

Od konvencionalnog betona razlikuje se po poboljšanoj tečljivosti i otpornosti na segregaciju, lakšoj ugradnji, osiguranoj kompaktnosti strukture, visokoj čvrstoći i povećanoj trajnosti, a samim tim i povećanoj ekonomičnosti. Zahvaljujući svojim izvanrednim svojstvima, samozbijajući beton se svrstava u betone visoke kvalitete [1].

1. INTRODUCTION

Self-compacting concrete is a new type of cement composite whose application reduces the construction time, workload, construction site equipment and noise. Self-compacting concrete flows under its own weight without segregation, and fills all voids without the need for compaction using vibrating devices.

It differs from conventional concrete in improved flowability properties and resistance to segregation, easier placement, insured structure compactness, higher strength and increased durability and hence increased cost effectiveness. Due to its extraordinary properties, self-compacting concrete is classified as high-quality concrete [1].

2. PROJEKTOVANJE SASTAVA SAMOZBIJAJUĆEG BETONA

Projektovanje sastava betona je kombinovanje sastavnih materijala u optimalnim omjerima kako bi se dobio beton željenih svojstava u svježem i očvrslom stanju [1]. Samozbijajući beton zahtijeva kombinaciju tri ključna svojstva: sposobnosti popunjavanja, sposobnosti prolaženja, i otpornosti na segregaciju [2]. Projektovanje sastava samozbijajućeg betona počinje definisanjem potrebnih svojstava. Kod samozbijajućeg betona suštinski važno je dobiti zadovoljavajuća svojstva samozbijanja, dok se u početku manje pažnje posvećuje svojstvima očvrsllog betona. Kriteriji samozbijanja upravljaju sadržajem grubog agregata, sadržajem paste, vodopraškastim omjerom, i doziranjem aditiva [3]. Za projektovanje sastava samozbijajućeg betona razvijene su brojne metode, koje su zasnovane na različitim principima. Jedna od metoda projektovanja samozbijajućeg betona je UCL metoda [1,3].

2.1. UCL metoda

UCL metoda je metoda projektovanja sastava samozbijajućeg betona i razvijena je na University College London [3]. Metoda je vrlo pogodna za one koji se prvi put susreću sa ovom vrstom betona. UCL metoda uključuje određivanje omjera komponenata mješavine za dati skup potrebnih svojstava, a nakon toga ispitivanje svojstava mješavine, i, ukoliko je potrebno, prilagođavanje i poboljšavanje sastava mješavine. Važna karakteristika prvog dijela procesa je ispitivanje konzistencije na uzorcima maltera pomoću mini konusa i mini V-lijevka. Na ovaj način se utvrđuje vodopraškasti omjer, kao i sadržaj aditiva sa kojima se postižu optimalna svojstva. Ispitivanje maltera je daleko brže i jednostavnije nego ispitivanje betona, a time se i veći broj parametara može relativno brzo istražiti. Ovo je vrlo efikasan postupak u procesu projektovanja sastava, a postoji vrlo dobra korelacija svojstava malterskih i betonskih mješavina samozbijajućeg betona [1,3]. Na slici 1. data je procedura UCL metode projektovanja sastava.

2.1.1. Specificirana svojstva betona

U tabeli 1 date su preporučene vrijednosti svojstava samozbijajućeg betona za različite vrste betonskih konstrukcija.

2. MIX DESIGN FOR SELF-COMPACTING CONCRETE

Proportioning of concrete is combining the constituent materials in optimum proportions in order to obtain desired concrete properties in fresh and hardened state [1]. Self-compacting concrete requires the combination of three key properties: filling ability, passing ability and segregation resistance [2]. Designing the composition of self-compacting concrete starts with defining the required properties. For self-compacting concrete it is essential to obtain the satisfactory self-compacting properties, while initially less attention is paid to the properties of hardened concrete. Self-compacting criteria govern the coarse aggregate content, the paste content, water/powder ratio and additive dosage [3]. Numerous methods for proportioning self-compacting concrete are developed, and they are based on different principles. One of those mix design methods for self-compacting concrete is UCL method [1,3].

2.1. UCL method

UCL method is mix design method for self-compacting concrete and it is developed at University College London [3]. The method is very suitable for those new to this type of concrete. UCL method involves proportioning of the mixture components for a given set of required properties, and then testing the properties of the mixture, and, if necessary, adjusting and improving the composition of the mixture. An important characteristic of the first part of the process is to examine the consistency of the mortar samples using mini cone and mini V-funnel. In this way the water/powder ratio is determined, as well as the additive dosage for achieving optimum properties. Testing mortar is much easier and more convenient than testing concrete, and thus a greater number of parameters can be readily examined. This is a very effective step in mix design process and there is a very good correlation between the mortar and concrete properties of self-compacting concrete [1,3].

Figure 1 shows the procedure of UCL mix design method.

2.1.1. Specified concrete properties

Table 1 shows the recommended properties of self-compacting concrete for various applications.

Tabela 1. Preporučena svojstva samozbijajućeg betona za različite vrste betonskih konstrukcija [3]
Table 1. Recommended properties of self-compacting concrete for various applications [3]

V-lijevak/ V-funnel	Klasa/ Class			
9 – 25 s	VF2	Rampe/ Ramms	Visoki i tanki elementi/ Tall and slender	
5 – 9 s	VF1		Zidovi/ Walls	
3 – 5 s	VF1	Podovi/ Floors		
Rasprostiranje slijeganjem (SF)/ Slump-flow		470-570 mm	540-660 mm	630-800 mm
Klasa/ Class		-	SF1	SF2/SF3

Zahtijevana svojstva treba uvijek da uključuju: rasprostiranje slijeganjem, viskozitet ili sposobnost prolaženja ovisno o primjeni ili oboje može biti potrebno, a takođe je neophodna adekvatna otpornost na segregaciju, iako vizuelna procjena za vrijeme ispitivanja rasprostiranja slijeganjem može biti dovoljna.

2.1.2. Podaci o materijalima

Svi materijali trebaju biti u skladu sa standardima za beton. Agregati, cement i dodaci bi trebali biti lokalno dostupni materijali. Tipovi i relativni odnosi cementa i dodataka utječu na čvrstoću i druga svojstva, stoga njihov izbor treba vršiti na osnovu prethodnog znanja o materijalima, njihovom ponašanju i svojstvima, kako onim u ranoj fazi, tako i o dugoročnim svojstvima [1,3].

Sadržaj krupnog agregata (V_{ca}) utječe na sva ključna svojstva samozbijajućeg betona. Početni sadržaj krupnog agregata zavisi od specificiranih svojstava betona. U tabeli 2 date su preporučene vrijednosti.

Volumen finog agregata (V_{fa}) se računa po izrazu:

$$V_{fa} = 0,45 \cdot (100 - V_{ca}) \quad (1)$$

Volumen paste (V_{pa}) se jednostavno izračuna prema izrazu:

$$V_{pa} = 100 - V_{ca} - V_{fa} \quad (2)$$

Sastav paste, vodopraškasti omjer i sadržaj aditiva se dobiju na osnovu ispitivanja rasprostiranja i tečenja maltera.

Required properties should always include: slump-flow, viscosity or passing ability depending on the application, or both may be required, and also, adequate segregation resistance is necessary, although visual assessment during the slump-flow test may be sufficient.

2.1.2. Materials data

All materials should be in accordance with the standards for concrete. Aggregates, cement and additives should be locally available materials. Types and relative proportions of cement and additives influence the strength and other properties, so their choice should be based on prior knowledge of the materials, their behavior and properties, as those in the early ages, and also the long-term properties [1,3].

The content of coarse aggregate (V_{ca}) affects all the key properties of self-compacting concrete. The initial content of the coarse aggregate depends on the specified properties of concrete. Table 2 shows the recommended values.

The volume of fine aggregate (V_{fa}) is calculated as:

$$V_{fa} = 0,45 \cdot (100 - V_{ca}) \quad (1)$$

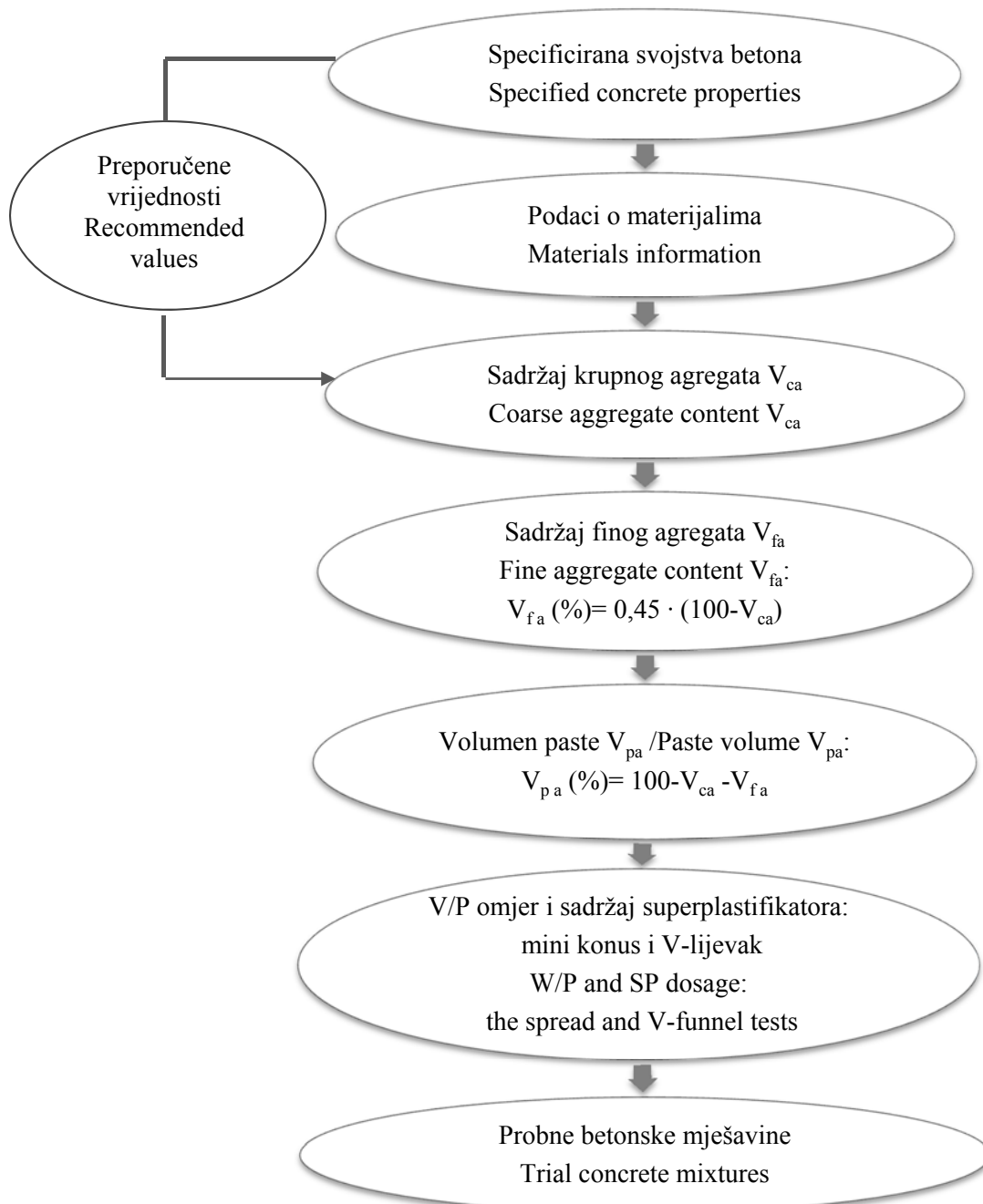
The paste volume (V_{pa}) is then simply calculated as:

$$V_{pa} = 100 - V_{ca} - V_{fa} \quad (2)$$

The paste composition, water/ powder ratio and additive dosage are obtained on the basis of tests on mortar using spread and V-funnel.

Ciljana svojstva maltera se određuju iz dijagrama na slikama 2. i 3. na osnovu zahtijevanih svojstava betona, te procijenjenog sadržaja krupnog agregata. Malteri se ispituju sve dok se ne postigne mješavina koja zadovoljava potrebne kombinacije rasprostiranja i vremena tečenja [3].

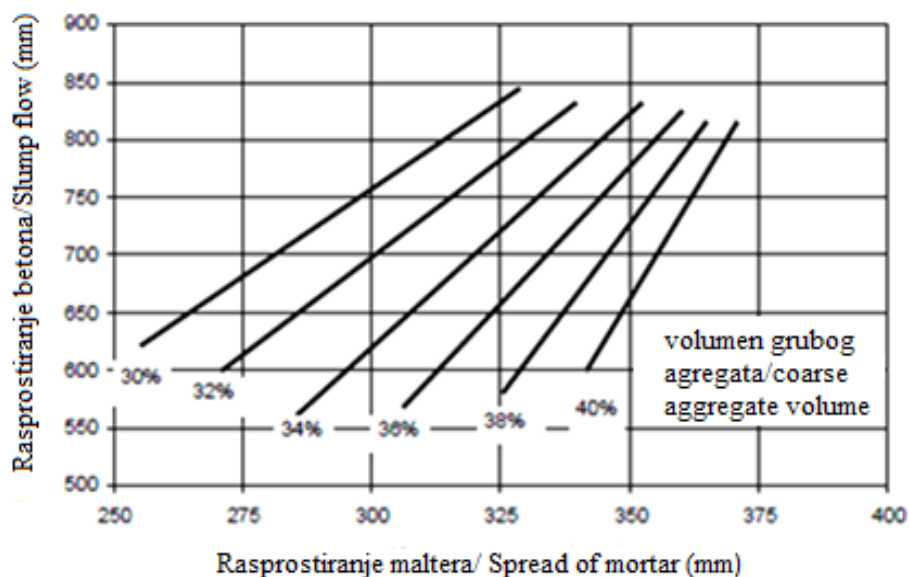
The target mortar properties are obtained from required concrete properties and the estimated coarse aggregate content using Figures 2 and 3. Mortars are tested until a mix that meets the required combinations of spread and flow time is obtained [3].



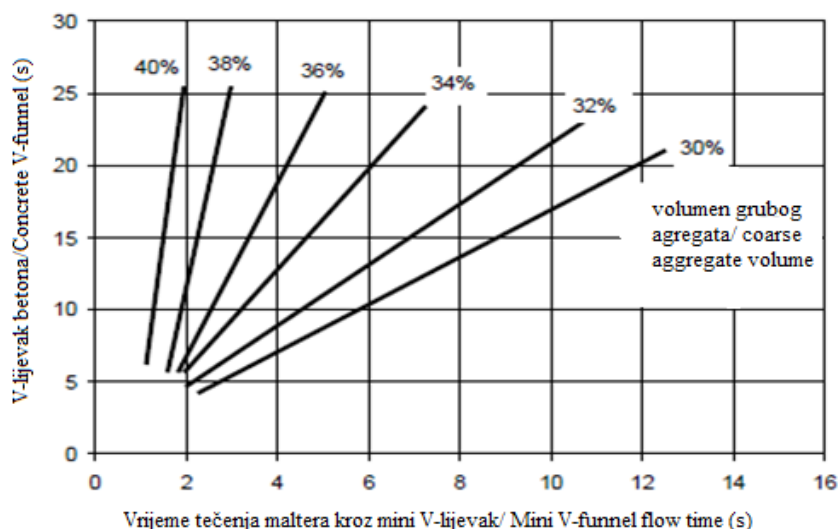
Slika 1. Procedura UCL metode projektovanja sastava [4]
Figure 1. Procedure of the UCL mix design method [4]

Tabela 2. Preporučene vrijednosti sadržaja krupnog agregata za početne mješavine [1,3]
Table 2. Recommended values of coarse aggregate content for initial mixes [1,3]

Specificirana svojstva/Specified properties (EFNARC)			Početni volumen grubog agregata/Initial coarse aggregate volume, V_{ca} (%)
Rasprostiranje slijeganjem/Slump-flow	Viskozitet/Viscosity V-lijevak/ V-funnel	Sposobnost prolaženja/ Passing ability J-prsten (razlika visina)/ J-ring (step-height)	
		59 mm	41 mm
SF1, SF2, SF3	Nije specificirano/ Not specified	Nije specificirano/ Not specified	38
SF1, SF2, SF3	≤ 8 s (VF1)	Nije specificirano/ Not specified	30
	> 8 i ≤ 15 (VF2)		35
	> 15 s (VF2)		38
< 700 (SF1/SF2)	≤ 8 s (VF2)	< 15 mm (PA1)	Nije moguće/ No mix possible
700 – 750 (SF2)			34
> 750 (SF3)			38
< 700 (SF1/SF2)	≤ 4 s (VF1)	< 15 mm (PA2)	Nije moguće/ No mix possible
700 – 800 (SF2/SF3)			32
> 800 (SF3)			35



Slika 2. Zavisnost rasprostiranja betona od rasprostiranja maltera [3]
Figure 2. Correlation between the concrete slump-flow and spread of mortar [3]



Slika 3. Zavisnost vremena tečenja betona od vremena tečenja maltera [3]

Figure 3. Correlation between the V-funnel flow time and mini V-funnel flow time [3]

3. EKSPERIMENTALNI RAD

Cilj ovog istraživanja je projektovanje sastava samozbijajućeg betona sa visokim udjelom elektrofilterskog pepela klase C za prefabrikovane elemente. Kako bi se ostvario postavljeni cilj istraživanja, formulisan je plan rada koji se sastojao od četiri faze: (1) analiza postojećih preporuka i projektovanje sastava prema odabranoj metodi; (2) laboratorijska ispitivanja i definisanje recepture za proizvodnju samozbijajućeg betona; (3) priprema betonske mješavine i ispitivanja svojstava betona u svježem stanju, te izrada laboratorijskih uzoraka i ispitivanja betona u očvrslom stanju; (4) izrada betonskih prefabrikata i ispitivanja njihovih svojstava.

3.1. Projektovanje sastava samozbijajućeg betona prema UCL metodi

Nakon razmatranja postojećih preporuka za projektovanje sastava samozbijajućeg betona, kao najpogodnija metoda u ovom istraživanju, izabrana je UCL metoda projektovanja sastava. Prema UCL metodi, prvi korak u projektovanju sastava mješavine je definisanje potrebnih svojstava za specifičnu primjenu. Kako je cilj rada izrada betonskih prefabrikata, tačnije prefabrikovanih ploča i tunelskih ivičnjaka, to se na osnovu tabele 1 vidi da su, za ovu specifičnu primjenu, potrebna sljedeća svojstva:

- klasa rasprostiranja SF3 (rasprostiranje slijeganjem >750 mm) i
- klasa viskoznosti VF1 (vrijeme prolaska kroz V-lijevak 5 – 9 s).

3. EXPERIMENTAL WORK

The research objective is to design high volume class C fly ash self-compacting concrete for precast elements. In order to realize the research objective, it has been formulated a plan consisted of four phases: (1) analysis of the existing recommendations and proportioning according to the selected method; (2) laboratory examinations and defining the recipe for the production of self-compacting concrete; (3) preparation of the concrete mixture and testing the concrete properties in fresh state, as well as the production of laboratory samples and testing of concrete properties in hardened state; (4) production of the precast elements and testing their properties.

3.1. Proportioning of self-compacting concrete according to the UCL method

After considering the existing recommendations for proportioning self-compacting concrete, as the most appropriate mix design method in this investigation, the UCL method was selected.

According to the UCL method, the first step in proportioning of the mixture is defining the required properties for the specific application. Since the research objective is to produce precast elements, more precisely prefabricated slabs and tunnel curbs, based on Table 1 it is observed that, for this specific application, the following properties are required:

- slump-flow class SF3 (slump-flow >750 mm) and
- viscosity class VF1 (V-funnel 5 – 9 s).

Za te klase rasprostiranja i viskoznosti odgovaraju:

- klasa sposobnosti prolaženja PA2 ($H_2/H_1 \geq 0,8$) i
- klasa otpornosti na segregaciju SR2 (omjer segregacije ≤ 15 %).

Prilikom projektovanja sastava mješavine prema UCL metodi prvi dio je ispitivanje na malteru, kako bi se utvrdio vodopraškasti omjer, kao i doziranje aditiva u cilju postizanja optimalnih svojstava. Sljedeći korak je određivanje volumnog procenta krupnog agregata na osnovu tabele 2, a zatim sitnog agregata i cementne paste prema jednačinama (1) i (2). Zadati maseni udio vezivne komponente, koju predstavlja smjesa cementa i elektrofilterskog pepela, je 400 kg/m^3 . Proračunat je sastav mješavine kod koje je cement zamijenjen elektrofilterskim pepelom, dok je, s obzirom da je sadržaj veziva fiksna, potrebni (proračunati) udio paste u mješavini betona postignut dodatkom krečnjačkog punila.

3.2. Laboratorijska ispitivanja i definisanje recepture samozbijajućeg betona

Istraživanje je izvršeno na malterskoj mješavini u kojoj je cement zamijenjen sa 50 % elektrofilterskog pepela, a sastav pripremljene malterske mješavine prikazan je u tabeli 3. Nakon izvršenog proračuna, prema recepturi predstavljenoj u tabeli 3, pripremljena je malterska mješavina, dakle mješavina bez frakcija agregata 4-8 i 8-16 mm.

Those slump-flow and viscosity classes correspond to:

- passing ability class PA2 ($H_2/H_1 \geq 0,8$) and
- segregation resistance class SR2 (sieve segregation ≤ 15 %).

During the mixture proportioning according to UCL method, the first part is testing mortar in order to determine the water/powder ratio as well as the additives dosage to achieve optimal properties. The next step is to determine the volume of coarse aggregate based on Table 2, and then the volume of fine aggregate and cement paste according to equations (1) i (2). Proportion of the binder component, which is the mixture of cement and fly ash, is 400 kg/m^3 . The mixture composition, in which cement is replaced by fly ash, is calculated, while, with respect to the fixed binder content, the required (calculated) proportion of paste in the concrete mixture is achieved by adding the limestone filler.

3.2. Laboratory examinations and defining the recipe for self-compacting concrete

The investigation was carried out on mortar mixture in which cement is replaced with 50 % of fly ash, and composition of this mortar mixture is shown in Table 3. After proportioning according to the recipe presented in Table 3, the mortar mixture was prepared, a mixture without the addition of aggregate fractions 4-8 i 8-16 mm.

Tabela 3. Proračunati sastav mješavine samozbijajućeg betona

Table 3. Calculated composition of SCC mixture

Komponente/Components	Sastav SCC (1 m ³) Composition of SCC (1 m ³)
Cement/Cement (kg)	200,00
Elektrofilterski pepeo/Fly ash (kg)	200,00
Filer/Filler (kg)	70,00
Voda/ Water (dm ³)	174,95
Agregat/Aggregate 0-4 mm (kg)	942,84
Agregat/Aggregate 4-8 mm (kg)	317,52
Agregat/Aggregate 8-16 mm (kg)	476,28
SP (dm ³)	4,58
VMA (dm ³)	1,72

Na svježoj malterskoj mješavini izvršena su sljedeća ispitivanja:

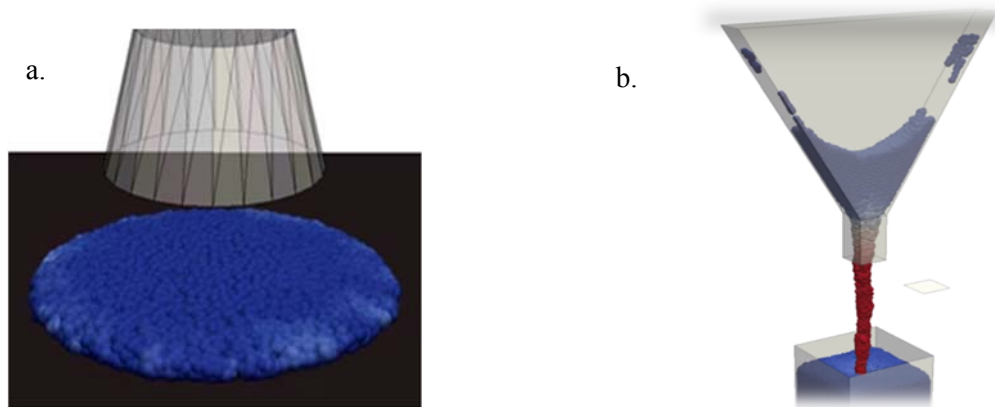
- rasprostiranje maltera i
- vrijeme prolaska kroz mini V-lijevak.

Rasprostiranje maltera (slika 4.a) predstavlja sposobnost tečenja maltera. Vrijeme prolaska kroz mini V-lijevak (slika 4.b) pokazuje brzinu tečenja maltera. U tabeli 4 predstavljeni su rezultati ispitivanja rasprostiranja maltera i vremena tečenja kroz mini V-lijevak.

Fresh mortar mixture was subjected to the following examinations:

- spread of mortar and
- mini V-funnel flow time.

Spread of mortar (Figure 4.a) represents the flowability of mortar. Mini V-funnel flow time (Figure 4.b) shows the flow rate of mortar. Table 4 shows the results of testing spread of mortar and mini V-funnel flow time.

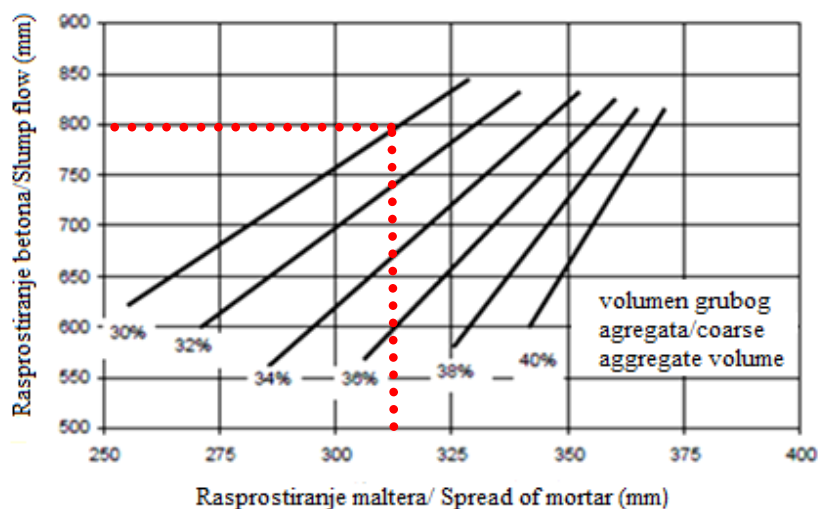


Slika 4. Ispitivanje maltera pomoću mini konusa (a) i mini V-lijevka (b) [7,8]
Figure 4. Testing mortar with mini slump cone (a) and mini V-funnel (b) [7,8]

Tabela 4. Rezultati ispitivanja svježe malterske mješavine

Table 4. Results of testing fresh mortar mixture

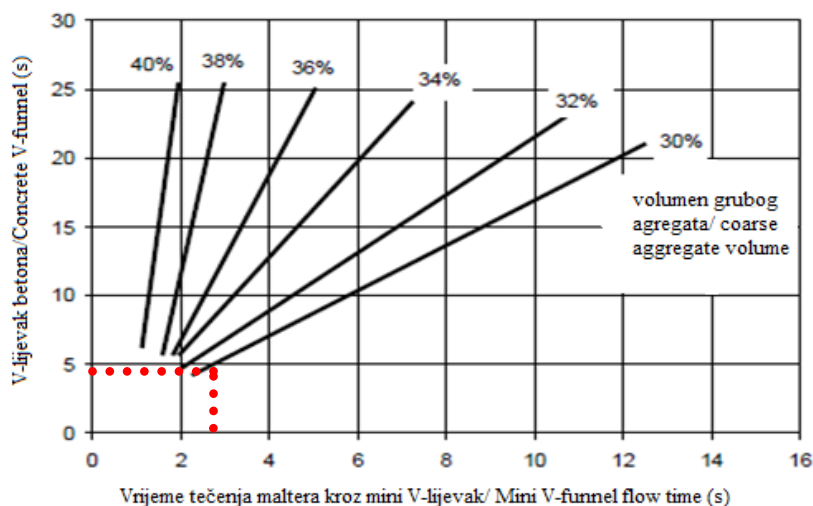
Ispitivanje/ Testing	Samozbijajući beton/ Self-compacting concrete
Rasprostiranje maltera (mm)/ Spread of mortar (mm)	315
Vrijeme prolaska kroz mini V-lijevak (s)/ Mini V-funnel flow time (s)	2,65



Slika 5. Zavisnost rasprostiranja betona od rasprostiranja maltera
Figure 5. The correlation between the concrete slump flow and spread of mortar

Zavisnost rasprostiranja betona od rasprostiranja maltera za različite volumne udjele krupnog agregata prikazana je na slici 5. Na osnovu grafičkog prikaza ovih korelacija, utvrđeno je da je izmjereno rasprostiranje maltera u skladu sa zadatim rasprostiranjem betona.

The correlation between the concrete slump flow and spread of mortar for different coarse aggregate volumes is showed in the Figure 5. By plotting these correlations, it was found that the measured slump-flow of mortar is in accordance with the set value of concrete slump-flow.



Slika 6. Zavisnost vremena tečenja betona od vremena tečenja maltera

Figure 6. *The correlation between the V-funnel flow time and mini V-funnel flow time*

Zavisnost vremena tečenja betona od vremena tečenja maltera za različite volumne udjele krupnog agregata prikazana je na slici 6. Na osnovu grafičkog prikaza ovih korelacija, utvrđeno je da je izmjereno vrijeme tečenja maltera u skladu sa zadatim vremenom tečenja betona.

The correlation between the V-funnel flow time and mini V-funnel flow time for different coarse aggregate volumes is showed in the Figure 6. By plotting these correlations, it was found that the measured mini V-funnel flow time is in accordance with the set value of V-funnel flow time.

3.3. Priprema i ispitivanje betonske mješavine

Nakon projektovanja sastava prema UCL metodi projektovanja sastava, pripremljena je mješavina samozbijajućeg betona. Nakon ispitivanja malterske mješavine izvršene su male korekcije u sastavu betonske mješavine, dok je sastav pripremljene betonske mješavine prikazan u tabeli 5.

3.3. Preparation and testing of the concrete mixture

After proportioning according to the UCL mix design method, a self-compacting concrete mixture was prepared. After testing mortar mixture some corrections in the compositions of concrete have been made, while the composition of prepared concrete mixture is shown in Table 5.

3.3.1. Komponente sastava samozbijajućeg betona

Za pripremanje mješavine samozbijajućeg betona korištene su lokalno dostupne sirovine. Kao vezivna komponenta korišten je Portland-cement CEM I 52,5 N. Elektrofilterski pepeo Termoelektrane „Kakanj“ je korišten kao mineralni dodatak. Kao agregat u betonskoj mješavini, korišten je trofrakcijski drobljeni krečnjak, sa frakcijama 0-4, 4-8 i 8-16 mm.

3.3.1. Components of the self-compacting concrete

For the preparation of self-compacting concrete mixture locally available raw materials were used. As binder component the Portland-cement CEM I 52,5 N was used. Fly ash from the Power plant „Kakanj“ was used as a mineral additive. As aggregate in the concrete mixture, the three-fraction crushed limestone aggregate, with fractions 0-4, 4-8 i 8-16 mm, was used.

U prilogu A data su najvažnija svojstva komponenti betona.

Mljeveni krečnjak je korišten kao punilo. Kao hemijski aditivi korišteni su superplastifikator (SP) na bazi polikarboksilat etera i modifikator viskoziteta (VMA).

In the appendix A are shown the main characteristics of concrete constituents.

Milled limestone was used as filler. As chemical admixtures the polycarboxylate-ether-based superplasticiser (SP) and viscosity modifying admixture (VMA) were used.

Tabela 5. Sastav betonske mješavine

Table 5. Composition of the concrete mixture

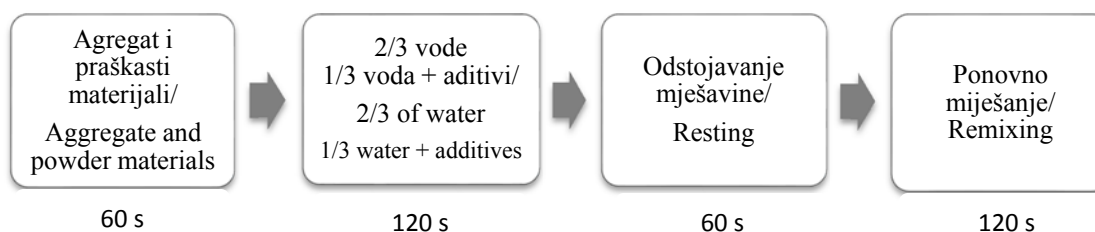
Komponente/Components	Sastav SCC (1 m ³) Composition of SCC (1 m ³)
Cement/Cement (kg)	200,00
Elektrofilterski pepeo/Fly ash (kg)	200,00
Filer/Filler (kg)	62,00
Voda/ Water (dm ³)	176,18
Agregat/Aggregate: 0-4 mm (kg)	941,58
Agregat/Aggregate: 4-8 mm (kg)	316,58
Agregat/Aggregate: 8-16 mm (kg)	475,25
SP (dm ³)	4,51
VMA (dm ³)	1,69

3.3.2. Priprema betonske mješavine

Priprema mješavine samozbijajućeg betona data je na slici 7.

3.3.2. Preparation of the concrete mixture

Preparation on the self-compacting concrete mixture is given in the Figure 7.



Slika 7. Procedura miješanja mješavine samozbijajućeg betona
Figure 7. The mixing procedure of self-compacting concrete mixture

3.3.3. Ispitivanje svojstava svježe mješavine samozbijajućeg betona

Na svježoj betonskoj mješavini izvršena su sljedeća ispitivanja:

- rasprostiranje betona,
- V-lijevak,
- L-kutija,
- otpornost na segregaciju,
- J-prsten.

3.3.3. Testing the properties of fresh self-compacting concrete mixture

Fresh concrete mixture was subjected to the following tests:

- Slump-flow,
- V-funnel,
- L-box,
- Segregation resistance,
- J-ring.

Rasprostiranje slijeganjem koristi se za procjenu sposobnosti popunjavanja samozbijajućeg betona, kao i tečenja samozbijajućeg betona [1,2,10]. Ispitivanje se vrši u skladu sa standardom BAS EN 12350-8.

Vrijeme tečenja kroz V-lijevak pokazuje brzinu tečenja svježe mješavine samozbijajućeg betona, kao i sposobnost popunjavanja samozbijajućeg betona [1,2,11]. Ispitivanje se vrši u skladu sa standardom BAS EN 12350-9.

L-kutija se koristi za procjenu sposobnosti prolaženja samozbijajućeg betona kroz uske otvore između armaturnih šipki i drugih prepreka bez segregacije ili blokiranja [1,2,12]. Ispitivanje se vrši u skladu sa standardom BAS EN 12350-10.

Otpornost na segregaciju se koristi za procjenu otpornosti samozbijajućeg betona na segregaciju. Ispitivanje se vrši u skladu sa standardom BAS EN 12350-11 [1,2,13].

J-prsten se koristi za procjenu sposobnosti prolaženja i ponašanja samozbijajućeg betona pri blokiranju. Ispitivanje se vrši u skladu sa standardom BAS EN 12350-12 [1,2,14].

Rezultati ispitivanja svježe betonske mješavine prikazani su u tabeli 6. Na osnovu rezultata predstavljenih u tabeli 6, može se zapaziti da se izmjerene vrijednosti rasprostiranja betona dobro slažu sa očekivanim vrijednostima koje su određene grafički pomoću slike 5.

The slump-flow is used to assess the filling ability of self-compacting concrete, as well as the flowability of self-compacting concrete [1,2,10]. The test is performed in accordance with the standard BAS EN 12350-8.

The V-funnel flow time shows the flow-rate of fresh self-compacting concrete mixture, as well as the filling ability of fresh self-compacting concrete [1,2,11]. The test is performed in accordance with the standard BAS EN 12350-9. L-box is used to assess the passing ability of self-compacting concrete to flow through tight openings between reinforcing bars and other obstructions without segregation or blocking [1,2,12]. The test is performed in accordance with the standard BAS EN 12350-10.

Segregation resistance is used to assess the resistance to segregation of self-compacting concrete. The test is performed in accordance with the standard BAS EN 12350-11 [1,2,13].

J-ring is used to assess the passing ability and behaviour of self-compacting concrete at blocking. The test is performed in accordance with the standard BAS EN 12350-12 [1,2,14].

The results of testing fresh concrete mixture are shown in Table 6. Based on the results showed in Table 6, it can be observed that the measured values of the concrete slump-flow are in accordance with expected values determined by plotting correlations in Figure 5.

Tabela 6. Rezultati ispitivanja svježe betonske mješavine

Table 6. Results of testing fresh concrete mixture

Ispitivanje/ Testing		Samozbijajući beton/ Self-compacting concrete
Rasprostiranje slijeganjem/ Slump flow	Prosječni dijаметar(mm)/ Average diameter (mm)	790 800 _{gr} *
	T ₅₀₀ (s)	1,00
V-lijevak (s)/ V-funnel (s)		4,54 4,80 _{gr} **
L-kutija (H ₂ /H ₁)/ L-box (H ₂ /H ₁)		0,90
Omjer segregacije (%)/ Segregation ratio (%)		8,84
J-prsten/ J-ring	Prosječni dijаметar (mm)/ Average diameter (mm)	790
	T ₅₀₀ (s)	1,00
	Razlika visina (mm)/ Step height (mm)	8

*SF_{gr} – Rasprostiranje određeno grafičkom metodom na slici 4/

*SF_{gr} – Slump-flow determined by plotting the correlations in Figure 4

**Vrijeme tečenja_{gr} - Vrijeme tečenja određeno grafičkom metodom prema slici 5/

**Flow-time_{gr} - Flow-time determined by plotting the correlations in Figure 5

Takođe, na osnovu rezultata predstavljenih u tabeli 6, može se zapaziti da se izmjerene vrijednosti vremena tečenja kroz V-lijevjak dobro slažu sa očekivanim vrijednostima koje su određene grafički pomoću slike 6.

3.3.4. Priprema i njega laboratorijskih uzoraka samozbijajućeg betona

Betonska mješavina je izlivena u kalupe i dobiveni su laboratorijski uzorci samozbijajućeg betona. Uzorci su u obliku kocki dimenzija 150x150x150 mm i prizmi dimenzija 100x100x400 mm. Nakon 24 sata, uzorci su izvađeni iz kalupa i potopljeni u vodu do starosti od 2, 14, 28, 56 i 90 dana.

3.3.5. Ispitivanje svojstava samozbijajućeg betona u očvrslom stanju

Na uzorcima samozbijajućeg betona izvršena su sljedeća ispitivanja:

- čvrstoća na pritisak i
- brzina ultrazvučnog impulsa.

Rezultati ispitivanja čvrstoće na pritisak i brzine ultrazvučnog impulsa dati su u tabelama 7 i 8, i na slikama 8 i 9.

Also, based on the results showed in Table 6, it can be observed that the measured values of the V-funnel flow-time are in accordance with expected values determined by plotting correlations in Figure 6.

3.3.4. Preparation and curing of the laboratory self-compacting concrete samples

The concrete mixture was poured into moulds and laboratory samples were obtained. Samples were in form of cubes of dimensions 150x150x150 mm, and prisms of dimensions 100x100x400 mm. After 24 hours, samples were demoulded and submerged in water until the age of 2, 14, 28, 56 and 90 days.

3.3.5. Testing hardened properties of self-compacting concrete

Self-compacting concrete samples were subjected to the following examinations:

- compressive strength and
- ultrasonic pulse velocity.

The results of testing compressive strength and ultrasonic pulse velocity are shown in Tables 7 and 8, and in Figures 8 and 9.

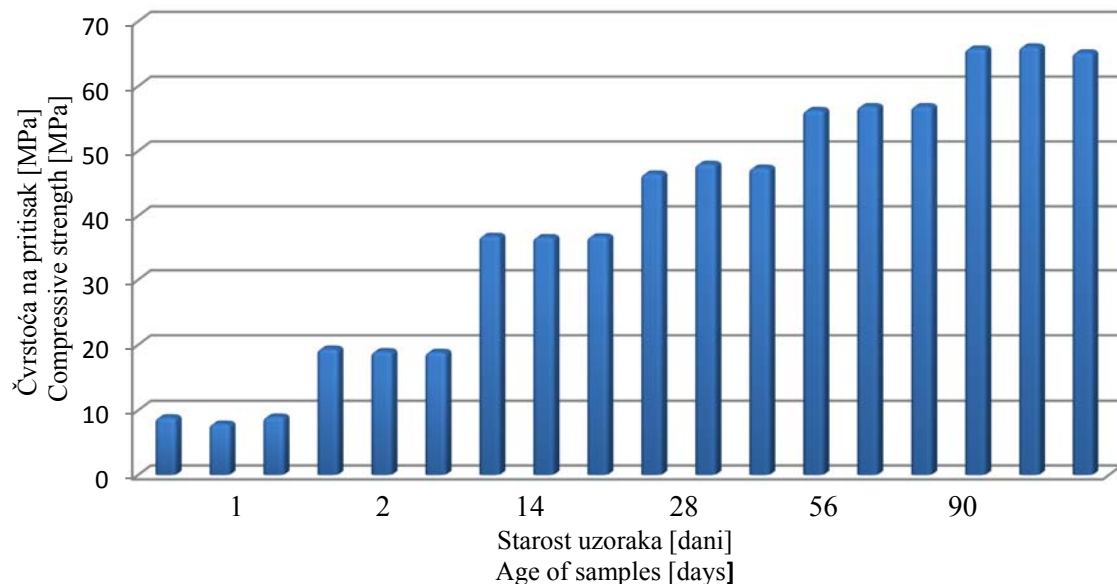
Tabela 7. Rezultati ispitivanja čvrstoće na pritisak uzoraka samozbijajućeg betona

Table 7. Results of testing compressive strength of self-compacting concrete samples

Ispitivanje/ Testing		Samozbijajući beton/ Self-compacting concrete	
Čvrstoća na pritisak (MPa)/ Compressive strength (MPa)	1 dan/ 1 day	Uzorak/ Sample I	8,9
		Uzorak/ Sample II	7,9
		Uzorak/ Sample III	9,0
	2 dana/ 2 days	Uzorak/ Sample I	19,4
		Uzorak/ Sample II	19,0
		Uzorak/ Sample III	18,9
	14 dana/ 14 days	Uzorak/ Sample I	36,9
		Uzorak/ Sample II	36,7
		Uzorak/ Sample III	36,8
	28 dana/ 28 days	Uzorak/ Sample I	46,5
		Uzorak/ Sample II	48,0
		Uzorak/ Sample III	47,4
	56 dana/ 56 days	Uzorak/ Sample I	56,3
		Uzorak/ Sample II	56,9
		Uzorak/ Sample III	56,9
90 dana/ 90 days	Uzorak/ Sample I	65,8	
	Uzorak/ Sample II	66,1	
	Uzorak/ Sample III	65,2	

Ispitivanje čvrstoće na pritisak uzoraka samozbijajućeg betona vrši se prema standardu BAS EN 12390-3. Ispitivanje je izvršeno na betonskim kockama dimenzija 150x150x150 mm. Ispitivana je čvrstoća na pritisak nakon 1, 2, 14, 28, 56 i 90 dana.

Testing compressive strength of self-compacting concrete samples is performed according to standard BAS EN 12390-3. The testing was performed on concrete cubes of dimensions 150x150x150 mm. The compressive strength was tested after 1, 2, 14, 28, 56 and 90 days.



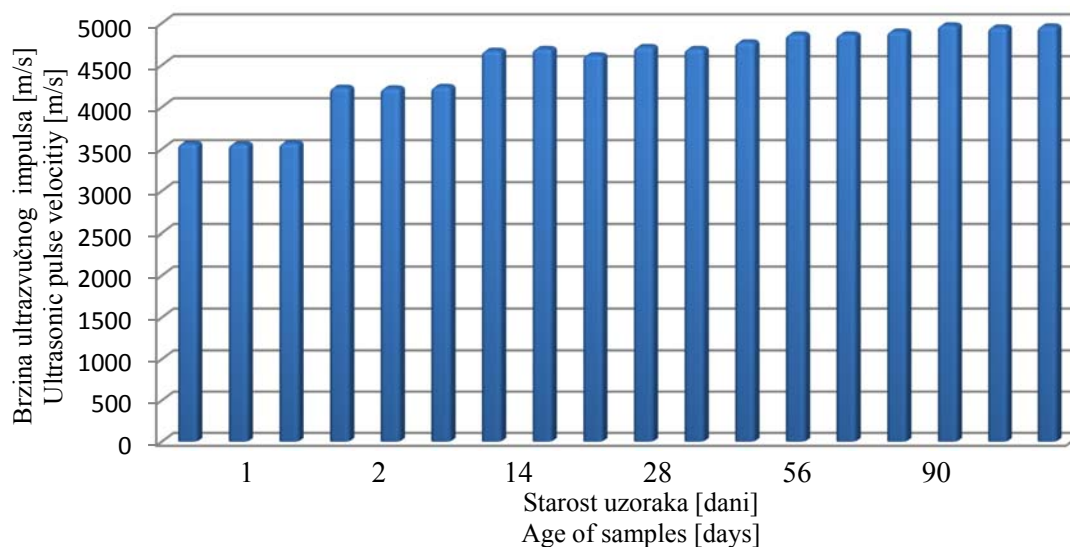
Slika 8. Čvrstoća na pritisak uzoraka samozbijajućeg betona
Figure 8. Compressive strength of the self-compacting concrete samples

Tabela 8. Rezultati ispitivanja brzine ultrazvučnog impulsa uzoraka samozbijajućeg betona
Table 8. Results of testing ultrasonic pulse velocity of self-compacting concrete samples

Ispitivanje/ Testing		Samozbijajući beton/ Self-compacting concrete	
Brzina ultrazvučnog impulsa (m/s) / Ultrasonic pulse velocity(m/s)	1 dan/ 1 day	Uzorak/ Sample I	3565,1
		Uzorak/ Sample II	3558,7
		Uzorak/ Sample III	3571,4
	2 dana/ 2 days	Uzorak/ Sample I	4232,8
		Uzorak/ Sample II	4223,9
		Uzorak/ Sample III	4241,8
	14 dana/ 14 days	Uzorak/ Sample I	4672,9
		Uzorak/ Sample II	4694,8
		Uzorak/ Sample III	4618,0
	28 dana/ 28 days	Uzorak/ Sample I	4717,0
		Uzorak/ Sample II	4694,8
		Uzorak/ Sample III	4773,3
	56 dana/ 56 days	Uzorak/ Sample I	4866,2
		Uzorak/ Sample II	4866,2
		Uzorak/ Sample III	4902,0
	90 dana/ 90 days	Uzorak/ Sample I	4975,1
		Uzorak/ Sample II	4950,8
		Uzorak/ Sample III	4962,8

Ispitivanje brzine ultrazvučnog impulsa se vrši prema standardu BAS EN 12504-4. Ispitivanje je izvršeno na betonskim prizmama nakon 1, 2, 14, 28, 56 i 90 dana.

Testing ultrasonic pulse velocity is performed according to standard BAS EN 12504-4. The testing was performed on concrete prisms after 1, 2, 14, 28, 56 and 90 days.



Slika 9. Brzina ultrazvučnog impulsa uzoraka samozbijajućeg betona
Figure 9. Ultrasonic pulse velocity of the self-compacting concrete samples

3.3.4. Izrada betonskih prefabrikata i ispitivanje njihovih svojstava

Nakon laboratorijskih ispitivanja samozbijajućeg betona, slijedila je faza provjere kvaliteta samozbijajućeg betona sa elektrofilterskim pepelom. Stoga su u industrijskim uvjetima proizvedeni betonski elementi realnih dimenzija. Izradene su dvije prefabrikovane ploče dimenzija 5080×2020 mm i dva tunelska ivičnjaka dimenzija 1500×300×300 mm. Nakon 28 dana, ispitana su svojstva prefabrikovanih ploča i tunelskih ivičnjaka. Ploče i ivičnjaci su ispitani sklerometrom i ultrazvučnom metodom.

Rezultati ispitivanja prefabrikata dati su u tabeli 9 i na slikama 10 i 11.

3.3.4. Production of precast elements and testing their properties

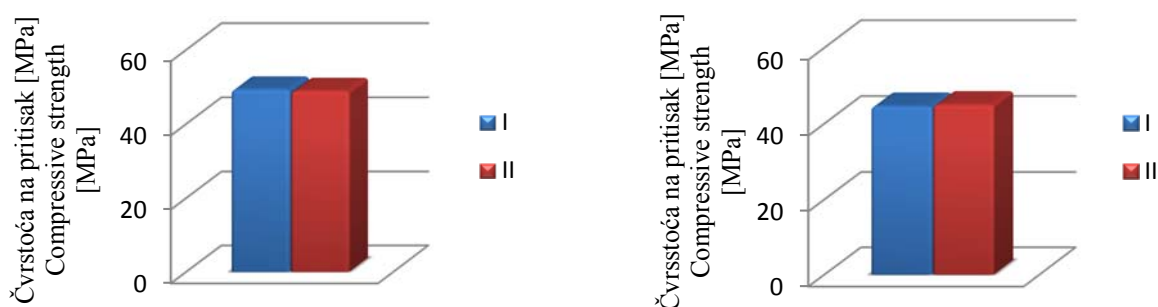
After laboratory testing of self-compacting concrete, the following was verifying the quality of self-compacting concrete with fly ash. Hence, the concrete elements of real dimensions were produced in industrial conditions. Two prefabricated slabs of dimensions 5080×2020 mm and two tunnel curbs of dimensions 1500×300×300 mm were produced. After 28 days, the properties of prefabricated slabs and tunnel curbs were tested. The slabs and curbs were tested by sclerometer and ultrasonic method.

The results of testing precast elements are shown in Table 9 and in Figures 10 and 11.

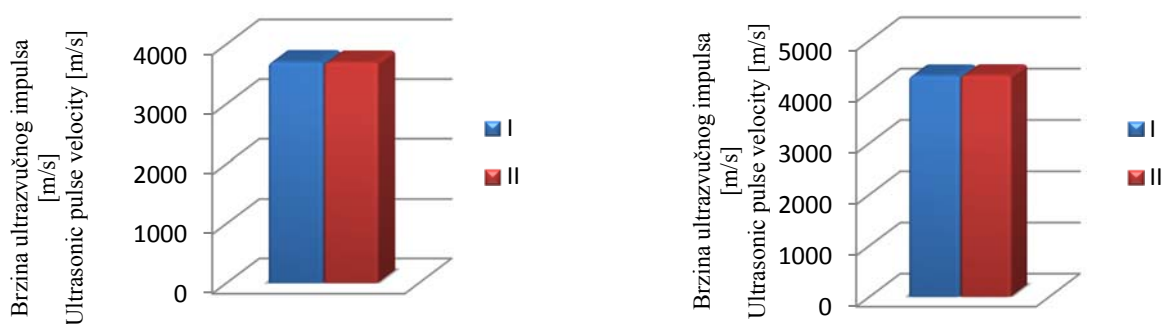
Tabela 9. Rezultati ispitivanja prefabrikovanih elemenata

Table 9. Results of testing precast elements

Ispitivanje/ Testing	Samozbijajući beton/ Self-compacting concrete		
Čvrstoća na pritisak (MPa)/ Compressive strength (MPa)	Ploče/ Slabs	Uzorak/ Sample I	49,3
		Uzorak/ Sample II	48,9
	Ivičnjaci/ Curbs	Uzorak/ Sample I	44,6
		Uzorak/ Sample II	45,0
Brzina ultrazvučnog impulsa (m/s) / Ultrasonic pulse velocity(m/s)	Ploče/ Slabs	Uzorak/ Sample I	3699,6
		Uzorak/ Sample II	3691,5
	Ivičnjaci/ Curbs	Uzorak/ Sample I	4312,8
		Uzorak/ Sample II	4317,8



Slika 10. Čvrstoća na pritisak ploča (lijevo) i ivičnjaka (desno) nakon 28 dana
Figure 10. Compressive strength of slabs (left) and curbs (right) after 28 days



Slika 11. Brzina ultrazvučnog impulsa ploča (lijevo) i ivičnjaka (desno) nakon 28 dana
Figure 11. Ultrasonic pulse velocity of slabs (left) and curbs (right) after 28 days

4. ZAKLJUČAK

Na osnovu predstavljenog istraživanja može se potvrditi da je UCL metoda naročito pogodna za tehnologe i istraživače koji imaju iskustvo u radu sa konvencionalnim betonima, a prvi put se susreću sa samozbijajućim betonima.

Eksperimentalnim ispitivanjima utvrđeno je da projektovani samozbijajući beton sa udjelom elektrofilterskog pepela od 50 mas. % posjeduje zadovoljavajuća svojstva:

- Rasprostiranje slijeganjem: za mješavinu sa 50% elektrofilterskog pepela iznosi 790 mm.
- J-prsten: rasprostiranje slijeganjem za mješavinu sa 50 % elektrofilterskog pepela iznosi 790 mm.
- V-lijevak: vrijeme potrebno za prolazak betonske mješavine kroz V-lijevak iznosi 4,54 s za mješavinu sa 50 % elektrofilterskog pepela.
- L-kutija: razlika visina za mješavinu sa 50 % elektrofilterskog pepela iznosi $H_2/H_1=0,9$.

4. CONCLUSION

Based on the presented research, it can be confirmed that the UCL method is particularly suitable for technologists and researchers who have experiences dealing with conventional concrete, but they first time encounter with self-compacting concrete.

By experimental investigation it has been found that designed self-compacting concrete containing 50 w. % has satisfactory properties:

- Slump-flow for mixture with 50 % of fly ash is 790 mm.
- J-ring: Slump-flow for mixture with 50 % of fly ash is 790 mm.
- V-funnel: V-funnel flow time is 4,54 s for mixture with 50 % of fly ash.
- L-box: passing ratio for mixture with 50 % of fly ash is $H_2/H_1=0,9$.
- Segregation resistance: segregation ratio for mixture with 50 % of fly ash is 8,84 %.

- Otpornost na segregaciju: za mješavinu sa 50 % elektrofilterskog pepela iznosi 8,84 %.
- Čvrstoća na pritisak nakon 28 dana: za laboratorijske uzorke iznosi 47,3 MPa.
- Brzina ultrazvučnog impulsa nakon 28 dana za laboratorijske uzorke iznosi 4728,1 m/s.
- Čvrstoća prefabrikovanih ploča nakon 28 dana iznosi 49,1 MPa, a tunelskih ivičnjaka 44,8 MPa.
- Brzina ultrazvučnog impulsa nakon 28 dana za prefabrikovane ploče iznosi 3695,6 m/s, a za ivičnjake 4315,3 m/s.

Dobiveni rezultati upućuju na zaključak da je moguće proizvesti kvalitetan samozbijajući beton za betonske prefabrikate u kome je 50 mas. % cementa zamijenjeno kalcijem elektrofilterskim pepelom.

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- Compressive strength after 28 days: for laboratory samples is 47,3 MPa.
- Ultrasonic pulse velocity after 28 days for laboratory samples is 4728,1 m/s.
- Compressive strength after 28 days for prefabricated slabs is 49,1 MPa, while compressive strength for tunnel curbs is 44,8 MPa.
- Ultrasonic pulse velocity after 28 days for prefabricated slabs is 3695,6 m/s, and for tunnel curbs is 4315,3 m/s.

The experimental investigations results indicate a conclusion that is possible to produce a high quality self-compacting concrete for precast concrete elements in which 50% of cement was replaced with calcareous fly ash.

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PRILOG A / APENDIX A

Tabela A.1. Osnovne karakteristike Portland-cementa CEM I iz Tvornice cementa Kakanj
Table A.1. Properties of Portland cement CEM I (Cement plant Kakanj)

Oksid / Oxide	Mas. % / Wt. %
SiO ₂	20,71
Al ₂ O ₃	5,69
Fe ₂ O ₃	3,03
CaO	63,66
MgO	1,29
Na ₂ O	0,08
K ₂ O	0,54
SO ₃	2,74
CaO (slobodni) Cao (free)	1,46
Specifična površina po Blaine-u (cm ² /g) Blaine specific surface (cm ² /g)	4130

Tabela A.2. Granulometrijski sastav Portland-cementa CEM I iz Tvornice cementa Kakanj
Table A.2. Particle size distribution of Portland cement CEM I (Cement plant Kakanj)

Sito [mm] Sieve [mm]	Kumulativna masa [%] Cumulative mass [%]
0,0	0
0,045	87,9
0,08	97,2
0,09	98,1
0,125	99,3
0,200	100,0
0,600	100,0

Tabela A.3. Hemijski sastav i fizičke karakteristike elektrofilterskog pepela TE Kakanj

Table A.3. Chemical composition and physical characteristics of fly ash (Thermal power plant Kakanj)

Komponenta / Component	Mas. %
G.Ž. / L.O.I.	0,14
SiO ₂	44,85
Fe ₂ O ₃	8,58
Al ₂ O ₃	20,20
CaO	16,83
CaO (slobodni) / CaO (free)	1,17
MgO	2,62
K ₂ O	1,44
Na ₂ O	0,33
Cl ⁻	0,001
SO ₃	1,16
Specifična površina po Blaine-u [cm ² /g] Blaine specific surface [cm ² /g]	2530 cm ² /g
Gustoća [g/cm ³] / Density [g/cm ³]	2,65 g/cm ³

Tabela A.4. Granulometrijski sastav elektrofilterskog pepela TE Kakanj
Table A.4. Particle size distribution of fly ash (Thermal power plant Kakanj)

Sito [mm] Sieve [mm]	Kumulativna masa [%] Cumulative mass [%]
0,0	0
0,045	62,2
0,08	73,4
0,09	74,9
0,125	79,9
0,200	93,3
0,600	100,0

Tabela A.5. Granulometrijski sastav agregata
Table A.5. Particle size distribution of aggregate

Sito [mm] Sieve [mm]	Kumulativna masa [%] Cumulative mass [%]		
	0 – 4 mm	4 – 8 mm	8 – 16 mm
22,4	100	100	100
16	100	100	93,6
12,5	100	100	35,3
8	100	98,5	4,03
6,3	99,1	63,2	3,8
4	97,71	3,85	3,2
2	65,38	2,54	2,4
1	46,99	2,1	2,0
0,7	34,53	2,05	1,56
0,5	28,96	1,96	1,24
0,25	21,38	1,84	1,1
0,125	16,52	1,26	0,95
0,063	13,09	0,41	0,77
0	0,01	0,02	0,03

Tabela A.6. Gustoća i upijanje vode agregata
Table A.6. Density and water absorption of aggregate

Svojstvo Property	Frakcija agregata Aggregate fraction		
	0 – 4 mm	4 – 8 mm	8 – 16 mm
Gustoća u suhom stanju (ρ_{rd}), Mg/m ³ Oven dry density (ρ_{rd}), Mg/m ³	2,65	2,69	2,69
Prividna gustoća agregata (ρ_a), Mg/m ³ Apparent density (ρ_a), Mg/m ³	2,74	2,74	2,72
Gustoća u zasićenom površinski suhom stanju (ρ_{ssd}), Mg/m ³ Saturated surface dry density (ρ_{ssd}), Mg/m ³	2,68	2,70	2,70
Upijanje vode (WA_{24}), Mg/m ³ Water absorption (WA_{24}), Mg/m ³	0,23	0,21	0,21

Tabela A.7. Karakteristike superplastifikatora
Dynamon PC 30 ES

Table A.7. Characteristics of superplasticizer
Dynamon PC 30 ES

Tipična svojstva za aditiv Dynamon PC 30 ES	
Agregatno stanje / Aggregate state	Tekućina / liquid
Boja / Color	Smeđa / brown
Gustoća / density	1,05 – 1,09 g/cm ³
pH	5,5 – 7,5
Miješanje sa vodom na 20°C Mixing with water at 20°C	Potpuno / complete

(<http://www.mapei-betontechnik.com/>)

Tabela A.8. Karakteristike modifikatora
viskoziteta Stabilizer strong ES

Table A.8. Characteristics of viscosity modify agent Stabilizer strong ES

Tipična svojstva za aditiv Stabilizer strong	
Agregatno stanje / Aggregate state	Tekućina / liquid
Boja / Color	Bijela / white
Gustoća / density	1,00 – 1,04 g/cm ³
pH	10,5 – 12,5
Miješanje sa vodom na 20°C Mixing with water at 20°C	Potpuno / complete

(<http://www.mapei-betontechnik.com/>)

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