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RHEOLOGICAL AND MECHANICAL BEHAVIOUR OF SELF-COMPACTING CONCRETE USING MODIFIED RECYCLED CONCRETE AGGREGATE

REOLOŠKO I MEHANIČKO PONAŠANJE SAMOZBIJAJUĆEG BETONA SA MODIFIKOVANIM RECIKLIRANIM BETONSKIM AGREGATOM

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Keywords
- construction materials
- flowability
- compressive strength
- durability
- waste raw materials

Abstract

Construction and demolition waste is increasingly used as a raw material in concrete manufacture which can assist in addressing environmental challenges associated with its disposal. In this study, recycled concrete aggregate (RCA) is used in Self-Compacting Concrete (SCC). As such, the work fills the gap in the literature by examining the influence of RCA impregnated with water glass solution on the physical and mechanical properties of fresh and hardened SCCs. Five different SCC mixtures are developed and tested. The replacement factor for RCA is 50 % (fractions II (4/8) and III (8/16)). Tests on hardened concrete reveal that the influence of water glass varies depending on the component it is coupled with, i.e., the combination with fly ash provides a maximal strength gain over 90 days, while the combination with silica fume gives low compressive strength during the entire testing period of 90 days.

Ključne reči
- građevinski materijali
- sposobnost tečenja
- čvrstoća na pritisak
- trajnost
- otpadne sirovine

Izvod

Građevinski i otpad od rušenja se sve više koristi kao sirovina u proizvodnji betona, što može pomoći u rešavanju ekoloških izazova povezanih sa njegovim odlaganjem. U ovoj studiji, reciklirani betonski agregat (RCA) je korišćen u samougrađujućem betonu (SCC). Kao takav, rad popunjava prazninu u literaturi ispitivanjem uticaja RCA impregniranog rastvorom vodenog stakla na fizička i mehanička svojstva svežeg i očvrslog SCC. Razvijeno je i testirano pet različitih mešavina SCC. Faktor zamene za RCA je 50 % (frakcije II (4/8) i III (8/16)). Testovi na očvrslom betonu pokazali su da uticaj vodenog stakla varira u zavisnosti od komponente sa kojom je u spoju, tj. kombinacija sa letećim pepelom je obezbedila maksimalni priraštaj čvrstoće tokom 90 dana, dok je kombinacija sa silikatnom prašinom dala nisku čvrstoću na pritisak tokom celog perioda ispitivanja od 90 dana.

INTRODUCTION

Self-compacting concrete or self-consolidating concrete (SCC) is a specific type of concrete mix that compacts and flows under its weight without the need for vibration. Due to its superior properties, SCC has emerged as a viable alternative to conventional concrete. SCC was first created in Japan in 1980, but because of its long-term benefits, it quickly expanded around the globe /1-3/. The main characteristic of SCC is that it passes through thick reinforcing cages and structural parts with unusual geometry with ease, in contrast to regular Portland cement concrete (PCC) /4/. Furthermore, SCC compacts itself without the use of mechanical vibrators, which are required for normal PCC mixtures. Thereby the SCC mixture's low yield stress and moderate viscosity guarantee ideal flowability and compaction /5, 6/. As previously mentioned, since SCC can fill formwork and reach all corners without segregation, it is perfect for intricate structures or areas with extensive reinforcement /7, 8/. Some of the key characteristics of SCC are: (1) high flowability as SCC may spread and flow through the formwork with ease when supported only by its weight; (2) absence of segregating as SCC keeps the mixture homogeneous, avoiding aggregate and other component separation; (3) self-levelling because SCC does not require vibration to fill in gaps and to solidify; (4) high passing ability since this type of concrete can move freely through crowded forms without being stuck or blocked; (5) high filling ability as SCC can efficiently fill the formwork's most complex voids; and (6) improved structural integrity as SCC makes sure that the formwork is filled which results in denser and stronger concrete structures /9, 10/. In the past few decades, numerous studies have been conducted on SCC. To fill up the spaces between the coarse aggregate particles and make the entire mixture denser and more durable, SCC's composition requires the introduction of extra finer materials, such as sand or cement. A number of chemical admixtures must be added to SCC in addition to the larger quantity of fine materials in order to make the consistency fluid and let it move throughout the formwork /11, 12/. Researchers have suggested using various industrial wastes in place of cement because using larger amounts of cement in SCC can raise costs and carbon emission. Incorporating waste raw materials into SCC improves its durability and workability and helps the goal to encourage the use of sustainable building products and a green, environmentally friendly concrete industry, /13, 14/.

Various studies were conducted to establish novel facts about the interrelations between installing the SCC and its performance. For instance, Inqiad et al. /2/ presented a way to forecast residual mechanical properties of hybrid fibre-reinforced self-compacting concrete (HFR-SCC) exposed to elevated temperatures. Li et al. /15/ proposed a novel approach for SCC pumping using equilibrium distances to investigate the evolution of rheological properties along the pipeline. Axial evolution of rheological characteristics of SCC are evaluated using 328-metre-long full-scale horizontal pumping circuits. Thirteen SCC mixtures were pumped at discharge rates ranging from 5.77 to 12.69 L/s, with water-to-cement (w/c) ratios ranging from 0.22 to 0.27. The results demonstrated that for the pumping configurations and the material under study, the influence of rheological equilibrium distances on variations in the pressure loss gradient is considerably influenced by both the discharge rate and the w/c ratio of SCC.

On the other side, numerous studies are dedicated to the research of synergistic effects of mineral additions (such as waste materials, nanoparticles, or specially designed additives) on the mechanical and durability properties of SCC. For instance, Moghaddam et al. /16/ investigated the influence of aluminium oxide (Al_2O_3) nanoparticles and glass fibres on SCC properties. In the experimental analysis, tests including compressive strength, splitting tensile strength, slump flow, L-box, V-funnel, ultrasonic pulse velocity, and bond strength were used to evaluate the mechanical performance and characteristics of fresh concrete. Tests for electrical resistance, water absorption, and water penetration depth were used to assess durability. Improved durability was demonstrated by a 46 % decrease in water absorption and a 265 % improvement in electrical resistance. Additionally, the mixture increased bond strength by 39 %, improving rebar and concrete adhesion. Furthermore, in SCC, nanoparticles are frequently used in two primary forms, i.e., as a powder or distributed in a solution (colloid). Titanium nanoparticles (TiO_2), aluminium nanoparticles (Al_2O_3), silica nanoparticles (SiO_2), iron nanoparticles (Fe_2O_3), and clay nanoparticles (nano-clay) are notable examples of applied nanoparticles /17-22/. According to Ahmadian et al. /23, 24/, grain refinement and phase formation were enhanced when copper and magnesium composites were reinforced with silicon carbide and multi-walled carbon nanotubes. Hussein et al. /25/ studied the impact of colloidal nano-silica (CNS) and polypropylene fibres (PP) on the properties of recycled concrete aggregate self-compacting concrete. It was discovered that adding more than 50 % fine recycled concrete aggregate (RCA) considerably lowers the concrete's strength, durability, and workability. By counteracting the deterioration in its characteristics in comparison to control SCC, the use of CNS and its pozzolanic impact is found to improve the strength and durability of SCC. This resulted in a 20 % improvement in strength and a 40 % decrease in water absorption by improving the interfacial transition zone (ITZ) in samples containing RCA. By preventing cracks through the bridging effect, PP enhanced the tensile strength and ductility of SCC. El Marzak et al. /26/ conducted a rheological and mechanical analysis of SCC incorporating rubber aggregates to clarify the connections between different rheological and mechanical characteristics to identify the optimal rubber aggregate ratio that preserves the concrete's structural integrity and self-compaction qualities. To achieve a balance between self-compaction and concrete strength, the best rubber aggregate ratios indicated in the mixture are 20 % fine particles, 25 % coarse aggregates, and 20 % a blend of fine and coarse aggregates. Bahmani and Mostofinejad /27/ established innovative fibre-reinforced SCC using activated slag from sugar factory lime waste. The results show that samples reinforced with 0.5 % and 1 % Barchip fibres obtained slump values of 690 mm and 688 mm, in respect, coupled with ideal discharge timings, consequently displaying excellent fresh concrete qualities. The steel fibre-reinforced samples, on the other hand, displayed the best mechanical properties, with compressive, bending, and tensile strengths of 53.6 MPa, 7.1 MPa, and 6.6 MPa, respectively, representing increases of 8 %, 65 %, and 69 % above fibre-free samples. According to the four-point bending test results, steel fibres produced a huge softening zone and barchip fibres provided a big hardening zone. Additionally, the LCA results showed that fibres with the lowest carbon footprints, polypropylene and barchip, were 222.4 and 227.9 kg CO_2 eq., respectively, underscoring their potential for use in sustainable building. Crushed-stone sand was used in the development of SCC in the research by Pavithra and Murali et al. /28/ Using limestone fines rather than crushed sand increases performance, inhibits the movement of chloride ions, and decreases the amount of water absorbed by capillaries. Extensive studies on the application of fly ash and Ground Granulated Blast Furnace Slag (GGBFS) were conducted by Shenbagam et al. /29/ and Bheel et al. /30/. According to X-ray diffraction analyses and scanning electron microscopy, adding fly ash to concrete improves its durability because it begins to react with the calcium hydroxide that is present, creating densified porosity in the concrete and reducing the thickness of the interfacial transition zone. By reducing the formation of ettringite, the higher amount of aluminium oxide in both admixtures not only preserves the hardened character but also increases compressive strength in the early phases. Mechanical performance of eco-friendly SCC mixtures and two-way slabs partially containing cement kiln dust (CKD) as cement replacement and internally reinforced with waste plastic mesh were investigated by Aadi et al. /31/. Two-way SCC slabs that were internally fortified with different designs of recycled plastic mesh and cast with CKD ratios ranging from 3 to 15% had their impact behaviour examined. Regardless of the CKD content, it is found that strengthening the SCC slabs with two layers of recycled plastic grids prevented the bullet from piercing through to the full thickness of SCC slabs. Three strategies including rubber particles, steel fibres and asphalt-coated coarse aggregate (ACCA) are introduced to improve the impact resistance of SCC after freeze-thaw cycles in the work by Li et al. /32/. Their crack propagation effect during the impact compression process is closely linked to the improvement of impact resistance for SCC using three different types of modifying materials. Tensile behaviour of self-compacting geopolymer concrete considering tension stiffening is conducted by Indriyantho et al. /33/. The results are comparable to the tensile performance of conventional concrete under identical conditions and in accordance with the standard building code. In construction phase, impacts of transporting and using geopolymer concrete on-site were similar to the conventional concrete, but with potentially lower overall emissions.

In this study, recycled concrete aggregate (RCA) is employed in SCC mix design. The integration of RCA into concrete has proven beneficial in altering certain properties, though effects vary depending on the concrete type, grain size distribution of RCA and dosage. This study addresses the gap in literature by investigating the effect of recycled concrete aggregate impregnated with water glass solution on the properties of SCC. Five different SCC mixes are prepared and tested. The reference mixture comprised only natural aggregate, whereas the remaining four combinations had 50 % of natural aggregate replaced by RCA fractions II (4/8) and III (8/16). Fly ash and silica fume were used as mineral additives in the SCC mix design. RCA was impregnated by submerging in a water glass solution. The physical and mechanical properties of fresh and hardened concrete were investigated, as well as the feasibility of employing recycled aggregate processed in this manner in structural concrete with high strength. The properties of fresh concrete were evaluated based on consistency, percentage of residual (entrained) air, and concrete temperature. The hardened concrete is evaluated for compressive strength, flexural strength, tensile splitting strength, static modulus of elasticity, ultrasonic pulse propagation speed, adhesion, and waterproofing. This research adds valuable insights to the optimisation of high-performance concrete by advancing the understanding on how impregnated RCA and fly ash, alternatively, silica fume, interact in SCC and how they change its rheological, physical, and mechanical properties.

EXPERIMENTAL PROCEDURE

Characterisation of raw materials

The experimental self-compacting concretes (SCCs) are developed using two types of aggregates: natural river aggregate (NRA) and recycled concrete aggregate (RCA). Given the specific composition of SCC, both types of aggregates are divided into three fractions: I (0/4), II (4/8), and III (8/16). RCA is obtained by crushing laboratory concrete testing cubes (Fig. 1) in a jaw crusher and then sieving and milling them to match a particular fraction. Since the RCA's fraction I is predominantly composed of cement stone which is highly porous and has a large specific surface area, this fraction is excluded from the final aggregate mixture. Fraction I would have a negative impact on the amount of water needed for cement hydration and the desired consistency of the concrete.

Grain-size distribution (GSD) of aggregates is determined in accordance with the standard methods provided in SRPS EN 933-1 /34/ and SRPS EN 933 /35/. GSD analysis is performed on a MATEST set of sieves using a mechanical sieve shaker. The mass of aggregate retained on each sieve, including the bottom, is measured once the sieving procedure is complete. The same procedure was conducted for each projected aggregate fraction. Results are presented as GSD curves in Fig. 2.

Figure 1. Laboratory concrete sample used in RCA production.

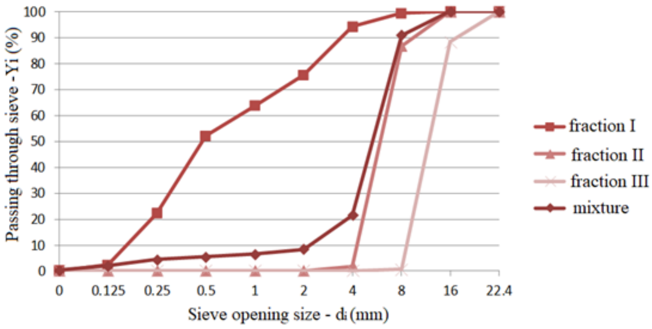


Figure 2. GSD analysis of aggregate.

The bulk density of RCA in a loose and compacted condition, as well as its natural humidity and water absorption, are determined because the RCA is less compact than NRA. Bulk densities of aggregates in the loose and compacted condition (Fig. 3) are determined according to standard SRPS ISO 6782 /36/. The water absorption of the RCA (Table 1) is tested according to SRPS ISO 7033 /37/.

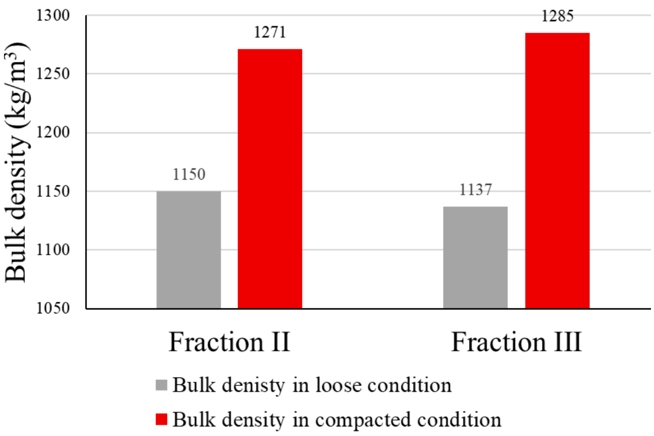


Figure 3. Bulk density of the recycled aggregate.

Table 1. Water absorption of RCA.

	RCA mass prior coating (g)	RCA mass after coating (g)	Water absorption (%)
Fraction II	800	831	3.9
Fraction III	1600	1658	3.6

Portland cement (Lafarge) is used as binder. Technical characteristics according to the product data sheet are: bulk density (3110 kg/m^3), specific surface area (410 cm^2/g), residue on the sieve with opening 32 μm (8.39 %), beginning and ending of the setting time (130 min, 160 min), consistency (28.4 %), compressive strength 2-d and 28-d (9.2 MPa, 60.9 MPa), and flexural strength 2-d and 28-d (9.7 MPa, 35.2 MPa). Limestone flour, a carbonate filler of 250 μm medium grain diameter, is used in the experiment. Technical characteristics according to the product data sheet are: bulk density without pores (2700 kg/m^3), bulk density with pores (2720 kg/m^3), absolute porosity (0.7 %), water absorption (0.12 %), compressive strength -dry, -wet, and -after frost (143 MPa, 137 MPa, and 132 MPa), flexural strength (21 MPa), and resistance to abrasion (18 cm^3/50 cm^3). The silica fume (*Sika*) is an extremely fine (0.1 μm), amorphous, latently reactive silica. The *Sika* fume - HR additive (density 0.7 kg/l) does not contain chlorides or other materials that promote steel corrosion and can therefore be used for reinforced as well as prestressed concrete. Fly ash (F-class) is obtained from the thermal power plant (TENT B). Chemical analysis of components is illustrated in Fig. 4. Tap water is utilised. Superplasticizer Cementol Hiperplast 463 is used in the preparation of experimental samples, /38/.

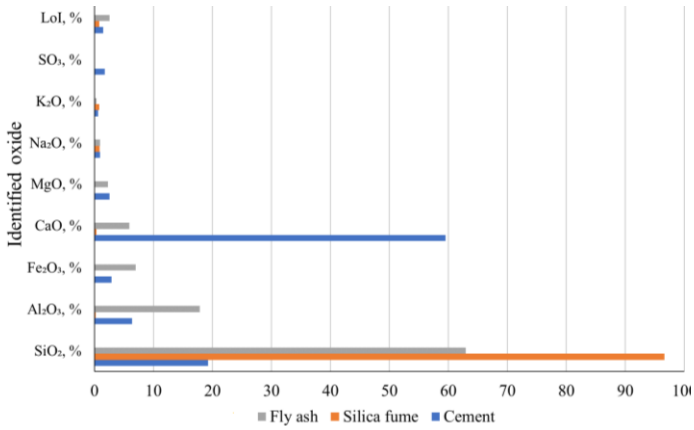


Figure 4. Chemical composition of binder and mineral additives.

The water glass (*Galenika*) used in the experiment contains SiO_2 and Na_2O in a 2.97:1 ratio. Water is added to the solution according to the formula:

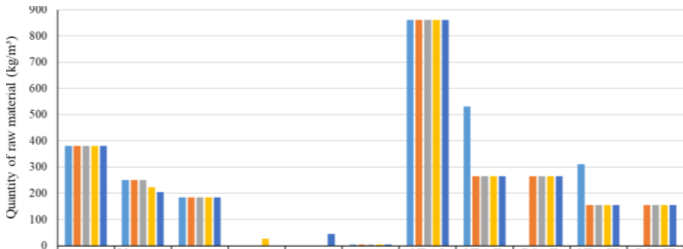
$$25.02 : x = 3.0 : 100 \text{ (by } SiO_2 \text{ mass)} \quad (1)$$

After 734 g of added water to 100 g of the obtained solution, or by volume 987.36 ml of water is added to 100 ml of the solution. The RCA is initially immersed in the aforementioned solution for 1 hour, and then it is filtered. The aggregate prepared in this way is left in the laboratory (ambient conditions) for 24 hours to fully dry.

Mix design of SCCs

SCC's compositions differ from that of 'vibrated' concrete; therefore, a chemical admixture (superplasticizer) is used to increase the mixture's workability. Filler, a mineral additive with particles smaller than 0.125 mm, is not commonly used in traditional concrete, but it is an important component of SCC because it improves the stability, lowers segregation, and promotes durability by reducing the free space between larger particles. Furthermore, aggregate mixtures cannot include grains larger than 16 mm. Part of the NRA is replaced with RCA. The shape and structure of RCA affect a number of physical factors, including bulk density, water absorption, and fine particle content. These RCA features also determine the overall water content of the mixture, the water-powder ratio, workability of fresh concrete, the method of adding components, and a number of mechanical properties of hardened concrete.

Five mix designs are prepared to assess the effect of recycled material replacement factors on physical and mechanical properties of self-compacting concrete: SCC-A - reference mixture with NRA, SCC-B - mixture with 50 % of RCA replacing NRA (fractions II and III), SCC-C - mixture with 50 % of water glass coated RCA replacing NRA (fractions II and III), SCC-D - mixture with 50 % of water glass coated RCA replacing NRA (fractions II and III) and silica fume, and SCC-E - mixture with 50 % of water glass coated RCA replacing NRA (fractions II and III) and fly ash. The mix design of SCC is given in Fig. 5.



	Cement	Limestone flour	Water	Slica fume	Fly Ash	Admix.	NRA I (0/4)	NRA II (4/8)	RCA II (4/8)	NRA III (8/16)	RCA III (8/16)
SCC-A	380	250	184	0	0	3.99	860	530	0	310	0
SCC-B	380	250	184	0	0	4.18	860	265	265	155	155
SCC-C	380	250	184	0	0	4.18	860	265	265	155	155
SCC-D	380	223.4	184	26.6	0	4.37	860	265	265	155	155
SCC-E	380	204	184	0	46	4.18	860	265	265	155	155

SCC-A SCC-B SCC-C SCC-D SCC-E

Figure 5. Mix design of SCC samples.

All experimental concrete mixtures are designed to achieve Slump-Flow (SF) values greater than 800 mm (i.e., SF3) according to recommendations given in /39/. Concrete mixtures are prepared in a laboratory mixer (Controls) of 60 l capacity. Componential materials are measured by mass, including water and admixture (Fig. 5). Each mixture is prepared in one mixing cycle with 44 l volume. Two Stage Mixing Approach (TSMA), favourable for RCA application, is employed in the preparation of all five mixtures. The mixing procedure lasted a total of 6 minutes and consisted of the following stages: (1) dry mixing all fractions of natural and recycled aggregate and limestone flour for 60 s; (2) adding 50 % of water without stopping the mixer and mixing for 30 s; (3) adding cement and the other half of water and mixing for 30 s; (4) adding superplasticizer and mixing for additional 30 s; (5) mixing for another 3.5 min.

After mixing, concrete is poured into moulds without further vibration. The concrete-filled moulds are then placed in a climate chamber for curing. After 2 hours, the samples are covered with damp gauze to keep the concrete mixtures from drying out. After 24 hours of installation, the samples are carefully taken from the mould, tagged with a marker, measured for mass, and stored in the pool. The samples are stored in water until the day of testing (Fig. 6). Thus, the loss of water required for the cement hydration process is avoided, as well as the negative effects of shrinkage over time.

Figure 6. Experimental SCC samples.

Methodology of SCC testing

Fresh concrete properties are measured by its consistency, proportion of residual (entrained) air, and temperature. The most significant distinction between normal vibrated concrete (NVC) and self-compacting concrete is their behaviour in the fresh condition. In order to assess the behaviour of SCC in the fresh state, more than ten methods are developed, five of which are standardised. In this experiment the following methods are applied: Slump flow test /40/, V-funnel test /41/, and J-ring test /42/. In addition to the above, tests for fresh SCC also include standardised methods common to NVC: sampling /43/, bulk density /44/, and air content - pressure methods /45/.

Slump-Flow test with t_{500} is a common testing method which provides a good assessment of the concrete's ability to fill the form, whereby the flow rate and viscosity of the SCC are evaluated by measuring the t_{500} time. The test results provide insight into the segregation resistance. The Slump-Flow test is based on a standard test for NVC consistency (EN 12350-2). It is a quick and simple testing method that can be done on a construction site and requires only a flat solid surface and an Abrams cone. The Abrams cone is a 300 mm tall hemmed edge cone with base diameters of 100 mm and 200 mm. The base plate is flat and square, with an edge length of at least 900 mm. The board's surface should be level and smooth, with a non-absorbent layer at least 2 mm thick that resists cement pastes and corrosion. The data used to assess the SCC consistency are the mean diameter SF = $(d_m+d_r)/2$ of the poured concrete mass (after it has reached a constant value) and the time t_{500} necessary for the concrete to reach a diameter of 500 mm after spreading. Concrete's self-consolidating capacity is better when d_m is higher and t_{500} is lower.

For the V-Funnel Test, a funnel (Fig. 7) with an adequate base and dimensions is required to determine the viscosity of fresh SCC. The funnel's width remains constant throughout its height, measuring 75 mm. The upper, trapezoidal component of the funnel is 450 mm, while the base measures 500 mm (upper) and 75 mm (lower). The lower, rectangular part of the funnel is 150 mm tall, with sides of the square cross-section measuring 75 mm in length. The funnel bottom side has doors that may be opened and closed. This method requires that the funnel is filled to the top with concrete while the bottom door is closed. After completely filling the funnel and levelling the top surface, the door opens, allowing the concrete to flow freely out of the V-funnel. The time t_V taken for the concrete to entirely flow out of the funnel provides information on mixture viscosity. The shorter the period, the more fluid the SCC is. The ideal t_V time ranges between 8 and 12 s. Another test on the V-funnel is performed 5 minutes following the first test to assess the variability of the features of the fresh SCC mixture. The recommended time difference between t_{5min} and t_V is 3 s.

Figure 7. V-funnel test.

The J-Ring test method provides an accurate assessment of the concrete mixture's capacity to pass through reinforcement assemblies and, to some extent, determines resistance to segregation. The equipment consists of a steel ring with a rectangular cross section (30×25 mm) and vertical threaded holes through which reinforcement bars of various diameters and axle distances are inserted. The test is carried out using the Slump-Flow Test device. Following the test, the height difference between the concrete that remains in the ring and the concrete that passes between the reinforcement bars is measured. The maximal allowable height difference between the concrete directly in front of and behind reinforcement bars is 10 mm, while the degree of blockage with the J-ring (BJ) should not exceed 20 mm.

The hardened concrete is tested for compressive strength, flexural strength, static modulus of elasticity, ultrasonic pulse velocity, adhesion, and waterproofing. The bulk density of hardened concrete samples is tested using standard method given in SRPS EN 12390-7:2010 /44/. Specimens for compressive strength tests meet the shape and dimensions as specified in SRPS EN 12390-3:2010 /46/. The test was performed on concrete cubes with 10 cm edges, with incremental loading until the concrete sample cracked, using an AMSLER hydraulic press of capacity 2500 kN. Load application rate was 0.6±0.4 MPa/s. The test was also conducted on cubes with 15 cm edges. The compressive strength is measured after 1, 7, 28, and 90 days. Flexural strength testing was carried out on concrete prisms (12×12×36 cm) using the standard procedure outlined in SRPS ISO 4013 2000, /47/. The test is conducted on an AMSLER press of capacity 600 kN, with a single force applied in the middle of the 30 cm span. The test requires that the contact at the support points and the point of load application be linear. Flexural strength is calculated using elasticity theory to determine the stress in the most loaded area of the crucial section and is equal to the quotient of the bending moment's limiting value and the resisting moment of the prism cross section. Splitting tensile strength test is performed according to SRPS EN 12390-6:2012 /48/ on cube-shaped specimens with sides d = 15 cm.

The modulus of elasticity, i.e., stress-to-dilation ratio, identifies deformation in the elastic zone of a structure's behaviour. The static modulus of elasticity /49/ is the ratio of change in stress ($\Delta\sigma$) to the elastic deformation ($\Delta\varepsilon$) obtained by testing a prismatic or cylindrical sample under pressure. To eliminate all deformations except elastic, the sample is 'trained' by performing several cycles of loading and unloading in the working stress range (stresses less than $f_p/3$, where f_p is compressive strength of concrete), starting from a small value of stress σ_0 (usually 0.5 MPa). The $\Delta\sigma$ reflects the difference between the lowest (σ_0) and maximal (σ_b) stress values during the cycle. The device (Fig. 8) is connected to a concrete cylinder D×H = 15×30 cm, and its base measures l_0 = 200 mm. Initial stress σ_0 is recorded on the instrument. Load is steadily increased by 0.6±0.4 MPa/s until the stress σ_b is obtained. Stress is sustained for 60 s, after which the value on the instrument is recorded. The instrument is unloaded at the same rate as load is applied until initial stress (σ_0) is reached. The value on the instrument is recorded upon completing one cycle. The cycle is performed at least three times until readings are stable. After all measurements are completed, the sample is loaded with an axial compressive force until it breaks, followed by the removal of the measuring instrument. Thereby, the compressive strength of concrete cylindrical sample is also determined.

Figure 8. Static elasticity modulus test.

The 'Pull-off' test is carried out on concrete slabs 20×20×5 cm /50/. A thin layer is removed from the sample surface by mild grinding. Surfaces are then thoroughly cleaned using compressed air before aluminium seals (50 mm in diameter and 30 mm thick) are attached to the test sites (Fig. 9). The test is conducted with Controls apparatus 24 hours after the seals are glued (at concrete age of 28 days).

Figure 9. Pull-off test.

Ultrasonic pulse velocity technique involves measuring the speed at which longitudinal ultrasonic waves propagate through concrete. Since the rate of ultrasound directly depends on the attained density of concrete and since density is one of primary characteristics determining the compressive strength, this method is used to assess the strength of concrete *in situ*. The test is carried out according to SRPS U.M1. 042:1998 /51/. The MATEST device is used for ultrasonic testing (Fig. 10) which consists of a measuring instrument (a); two probes - a transmitter and receiver of ultrasonic pulses (b); cables connecting the measuring instrument to probes (c), and a calibrator for checking the zero on the instrument (d). The sample is placed between probes, allowing the passage time of ultrasonic pulse to be registered along the shortest path between transmitter and receiver (path - s). Accuracy of MATEST devices is ±0.1 μs. Ultrasonic pulse velocity is measured on prismatic samples (12x12x36 cm) aged 1, 3, 28, and 90 days.

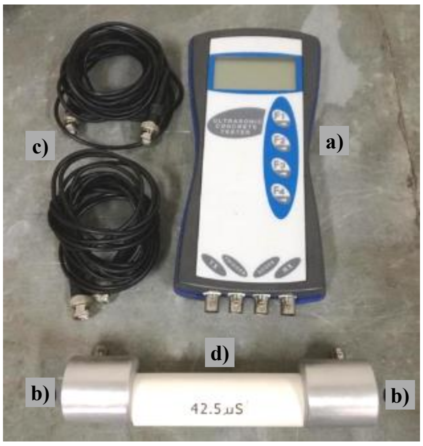


Figure 10. Ultrasonic pulse velocity test device.

The waterproofing test is carried out on cubical samples (15 cm). Concrete age at the start of test is 28 days. Before placing the sample in the apparatus, the area that would be subjected to water pressure is 'spiked' and cleaned with a wire brush to remove the surface layer of cement laitance and allow water to penetrate the sample. According to SRPS U.M1.015:1998 /52/, samples are subjected to 5 bar pressure for three days before being broken to measure the depth of water penetration.

RESULTS AND DISCUSSION

Rheological properties of fresh SCC mixes

Temperature of fresh SCC mixtures is measured using a digital thermometer. Obtained results are as follows: 26.8, 25.4, 25.4, 24.9, and 26.5 °C for SCC-A, SCC-B, SCC-C, SCC-D, and SCC-E, respectively. Maximal temperature is attained with SCC-A, demonstrating that RCA reduces heat of hydration and other exothermic reactions in the cement. The addition of fly ash increases the temperature of the mixture, indicating a boost in early-stage hydration reactions. Application of coated and uncoated RCA in SCC-B and SCC-C mixtures results in no temperature change. Based on the experiments, it is determined that application of water glass, i.e., coating of RCA, has no significant effect on the temperature of fresh concrete mix.

Flowability, or filling ability, is investigated by Slump-Flow test, with the Abrams cone in its normal position and its larger base on the bottom side. Acquired results are shown in Fig. 11. The SCC-A, SCC-B, SCC-C, and SCC-E all attained the flowability class of SF3. The SCC-D sample could not be classified since the measured values are less than 500 mm.

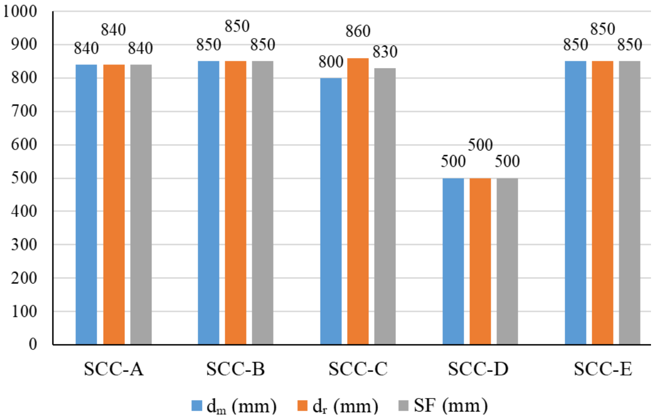


Figure 11. Flowability (Slump-Flow test) of fresh SCC mixtures.

Mixtures with RCA demonstrate greater flowability than mixture SCC-A formulated with NRA. The silica fume mixture (SCC-D) produced a very poor flowability value. Coated RCA in SCC-C mixture resulted in a variation of d_m and d_r values, but flowability was similar to that of mixtures with NRA and uncoated RCA.

The Slump-flow test indicated a high flowability of SCC mixtures. By replacing part of NRA with RCA, the flowability of SCC increased. In mix C (SCC-C), the recycled aggregate is treated with water glass, resulting in lower flowability than standard. Treatment of RCA aggregate with water glass and silica fume in SCC-D reduces flowability to a level that cannot be qualified as self-compacting concrete under the requirements of the test. The Slump-Flow test demonstrates that treating RCA with water glass or a combination of water glass and fly ash has no significant effect on the flowability of fresh concrete. Only treating RCA with water glass and silica fume significantly reduces the flowability of fresh concrete. It may be established that the influence of water glass on concrete flowability is determined by the used mineral additive.

Viscosity is determined by monitoring the time it takes for the concrete mixture to attain a diameter of 500 mm while spreading (t_{500}). The t_{500} test yields fresh concrete viscosity values of 2.2, 1.1, 1.4, 5.4, and 1.5 s for SCC-A, SCC-B, SCC-C, SCC-D, and SCC-E, in respect. As a result, SCC-A, SCC-B, SCC-C, and SCC-E belong to the VS1 viscosity class, whereas SCC-D is classified as VS2. Results show that mixture D has the stiffest consistency, and the negative impact of combining water glass and silica fume in the treatment of recycled aggregate can be noticed. However, combination B which contains uncoated RCA aggregate and no mineral additions, yields the greatest results.

Viscosity is also assessed using the V-funnel method, as explained in the Experimental Procedure section. Obtained t_v results are as follows: 17.8, 13.2, 23.5, 52.2, and 19.7 s for SCC-A, SCC-B, SCC-C, SCC-D, and SCC-E, respectively. As a result, all SCC mixtures except SCC-D can be classed as VF2. Results of this evaluation are rather similar to those of the t_{500} test (Fig. 12). Mixture SCC-D has the stiffest texture, whereas SCC-B is most plastic. As before, the SCC-E mixture yields closest results to the reference mixture.

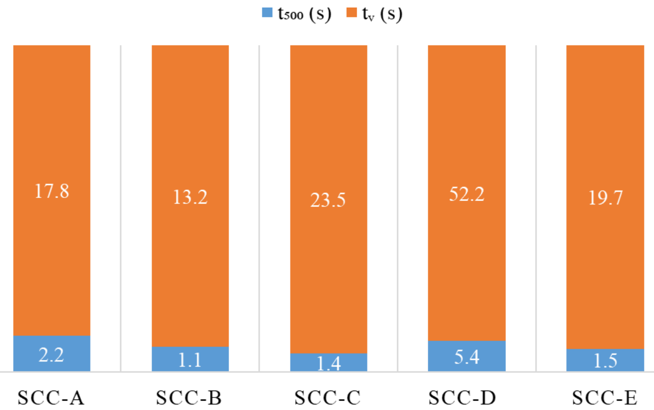


Figure 12. Viscosity of SCC mixtures obtained by t_{500} test and V-funnel method.

According to the V-funnel test, replacing NRA with RCA reduced the time necessary for fresh concrete to flow out of the funnel. Adding water glass to concrete (SCC-C) significantly extended this time, demonstrating the negative impact of water glass. As in the Slump-Flow test, the treatment of RCA with water glass and addition of silica fume shows a significant adverse effect.

The J-Ring test on fresh SCC mixtures is performed to provide an accurate assessment of concrete mixture's capacity to pass through reinforcement assemblies and, to some extent, show resistance to segregation. Figure 13 shows the results of the J-ring flow test. The J-Ring test reveals that SCC-D mixture has the stiffest consistency, whereas SCC-C and SCC-E samples have the greatest level of flowability. Time t (s) was 3.8, 2.8, 2.3, 5.4, and 2.5 s for SCC-A, SCC-B, SCC-C, SCC-D, and SCC-E, respectively.

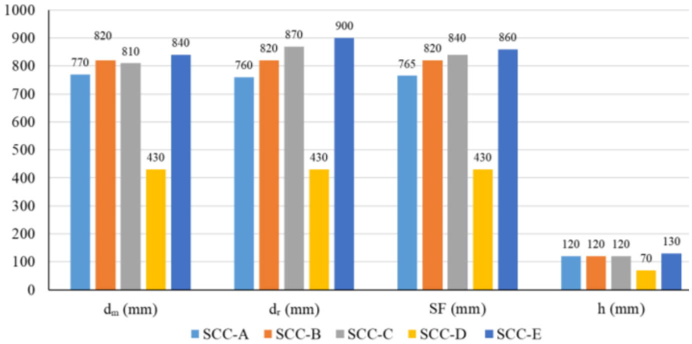


Figure 13. Results of the J-Ring test on fresh SCCs.

The J-Ring test for the benchmark mixture (SCC-A) reveals a lower degree of mobility than the mixture in which the NRA is partially substituted with RCA (SCC-B). In SCC-C, the RCA is treated with water glass, resulting in greater mobility than mixes SCC-A and SCC-B. The treatment of RCA with water glass and silica fume in mixture SCC-D reduces mobility, whereas the treatment with water glass and fly ash (SCC-E) provides the highest degree of mobility. The J-Ring test demonstrates that treatments of RCA with water glass, as well as a combination of water glass, have no significant effect on the mobility of fresh concrete, albeit that the difference is more obvious than that obtained by Slump-Flow test.

Results of evaluating the entrained air of a fresh concrete mix are as follows: 2.2, 0.8, 0.5, 1.4, and 0.4 % for SCC-A, SCC-B, SCC-C, SCC-D, and SCC-E, in respect. Mixtures including RCA produce less entrained air. Aggregates treated with water glass, as well as with water glass and fly ash, exhibit lower percentage of entrained air, whereas those treated with water glass and silica fume have higher percentage.

According to rheological tests, RCA treated with water glass adds to enhancing the mobility of the fresh concrete mix, however adding silica fume results in concrete with a consistency that does not match the criteria for self-compacting concrete in any parameter. The tests also reveal that concrete containing RCA pre-treated with water glass and fly ash performs nearly identically to the standard SCC with NRA in most criteria.

Physico-mechanical properties of SCC in hardened state

The bulk density of hardened concrete is proportional to multiple concrete characteristics and thus serves as a first indicator of concrete quality. Concrete is categorised by density, with typical value for construction concrete lying between 1900 kg/m³ and 2500 kg/m³. Figure 14. shows average bulk density values of hardened SCCs at different ages, measured on 10 cm cubically-shaped samples.

Bulk densities for all examined SCC samples at various ages range from 2200 to 2500 kg/m³. Thereby experimental SCCs can be categorised as construction concretes. SCC-A sample based on NRA has approximately 5-15 % higher bulk density than samples based on recycled concrete aggregate, except in the case of the SCC-B which has a bulk density of 2498 kg/m³ after a period of 90 days. SCC-C has the lowest bulk density of all investigated concretes at 1 and 3 days. At 28 days, the bulk densities of SCC-C, SCC-D, and SCC-E are approximately the same. Bulk density of SCC-B is up to 10 % higher than the rest of RCA-based samples, probably due to the coating of aggregates.

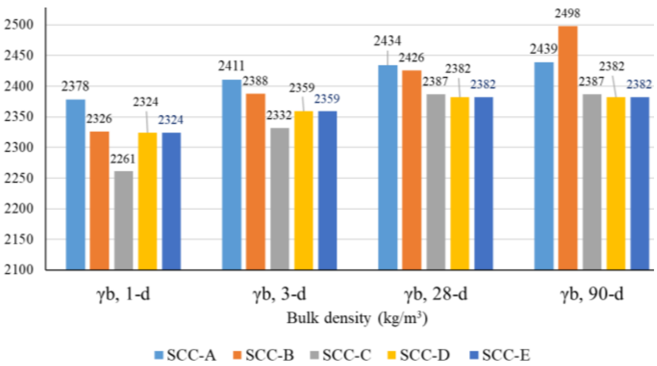


Figure 14. Bulk density of hardened SCCs aged 1, 3, 28, 90 days.

Compressive strength is an essential indicator of quality of hardened concrete. As such, it should be tested on all concrete types. For equal water-powder factor values, there is no substantial difference in compressive strength between SCC and NVC. However, choice of aggregate (river, crushed, recycled) has a far greater effect on compressive strength of NVC than SCC since SCC has a much more homogenous matrix and a lower content of coarse aggregate that decreases its impact. Test is carried out on cubic samples measuring 10 cm and 15 cm in size, as well as on cylindrical samples. Compressive strength is tested at ages 1, 7, 28, and 90 days. Compressive strength results of cubic samples (10×10×10 cm) are given in Fig. 15. Compressive strength results at 28 days are transformed into a 15 cm-edged cube (Fig. 15). Strength classes according to SRPS EN 206-1 standard /54/ are provided in Table 2.

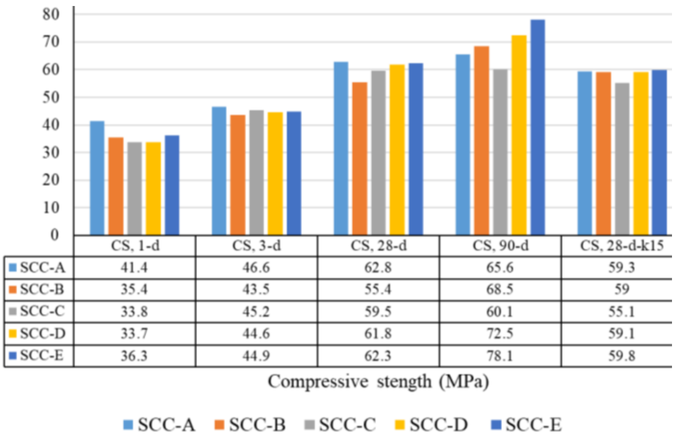


Figure 15. Compressive strengths of hardened SCCs aged 1, 3, 28 and 90 days.

Results show that at the age of one day, the SCC-A sample based on NRA has the highest compressive strength (41.4 MPa), while mixtures SCC-C and SCC-D exhibit the lowest strengths (33.7 and 33.8 MPa). At 3 and 28 days, SCC-A still has the highest compressive strength, while SCC-B sample has the lowest strength (55.4 MPa). Compressive strengths determined after 90 days provide a completely different picture from the test conducted on the first day. Between the 28th and 90th day, compressive strengths increase significantly for SCC-B (19 %), SCC-D (15 %), and SCC-E (21 %). As a result, the inclusion of uncoated RCA increases compressive strength between the 28th and 90th days, but values for the sample with coated aggregate (SCC-C) remain nearly constant. Addition of fly ash (sample SCC-E) and silica fume (SCC-D) to the water glass coated aggregate improve the late compressive strengths.

Table 2. Concrete strength classes.

Compressive strength class	Minimum cylinder strength $f_{ck,cyl}$ (MPa)	Minimum cube strength $f_{ck,cube}$ (MPa)
C8/10	8	10
C12/15	12	15
C16/20	16	20
C20/25	20	25
C30/37	30	37
C35/45	35	45
C40/50	40	50
C45/55	45	55
C50/60	50	60
C55/67	55	67
C60/75	60	75
C70/85	70	85
C80/95	80	95
C90/105	90	105
C100/115	100	115

Reference concrete (SCC-A) exhibits the highest compressive strength. Partial replacement of NRA with RCA reduces strength by 10 % but including water glass boosts strength. Treatment of RCA with water glass and silica fume also leads to improved strength, while concrete containing RCA treated with water glass and fly shows the highest strength. Thereby, water glass increases compressive strength of concrete, and the inclusion of mineral components amplifies this effect.

Flexural strength of prismatic 12×12×36 cm samples is determined by calculating the stress in the most loaded part of the critical section using elasticity theory, and it is equal to the quotient of bending moments limiting value and the resisting moment of prism cross section. Flexural strengths of SCCs obtained after 28 days of solidification are shown in Fig. 16, indicating that flexural strength of SSC-B is 6 % higher than that of the sample with NRA (SCC-A). In all other cases, the flexural strength of referent sample SCC-A is higher (for approximately 30 %). Thereby, the coating of RCA negatively influences the late flexural strengths of designed self-compacting concretes. Flexural strength tests show a significant decrease in strength in mixtures that had water glass treatment compared to those that did not get the aforementioned procedures.

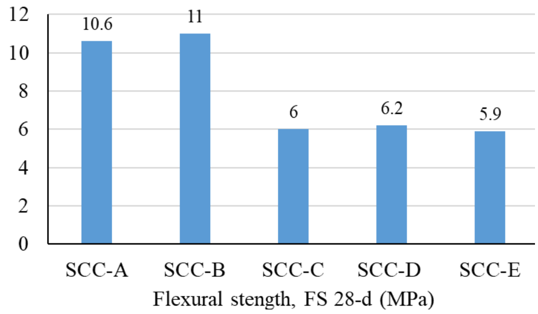


Figure 16. Flexural strengths of hardened SCCs at 28th day.

Splitting tensile strength values are significantly lower than flexural strengths of tested SCCs. Testing is conducted on 15×15×15 cm cubic samples (Fig. 17). Results are presented in Table 3.

Figure 17. Crushed SCC sample after splitting tensile strength test.

Table 3. Results of the splitting tensile strength test.

Sample	SCC-A	SCC-B	SCC-C	SCC-D	SCC-E
TS (MPa)	3.6	2.4	3.6	4.2	4.0

Samples with coated RCA (SCC-C, SCC-D, SCC-E) show higher splitting tensile strength values than the sample with NRA (SCC-A). The lowest value of splitting tensile strength is obtained for SCC-B sample based on uncoated recycled concrete aggregate. Splitting tensile strength test reveals that treating RCA with water glass leads to considerable strength improvement. Increase is much more noticeable when RCA is combined with water glass, silica fume, or fly ash.

Static modulus of elasticity for experimental SCC samples measured is provided in Fig. 18. Results are obtained after 1, 3, 28, and 90 days of solidification. Values obtained for static modulus of elasticity (Eb) after the first day are similar: 30.1, 30.3, and 30.2 GPa for SCC-A, SCC-D and SCC-E. Samples with uncoated RCA (SCC-B) and coated RCA (SCC-C) prepared without mineral additives have somewhat lower Eb: 28.9 and 29.2 GPa. Similar disposition of peak values is kept up to the 28th day. Namely, the SCC-A shows maximal Eb as the referent sample prepared with NRA. Samples based on RCA exhibit lower Eb values regardless of applied water glass coating method and utilisation of fly ash and silica fume as mineral additives. However, the trend shows a change from the 28th to the 90th day of hardening. The Eb for SCC-A maintains maximal of 39 GPa. The Eb values for RCA-based samples are in the range from 36.1 GPa (SCC-E) to 39.1 GPa (SCC-D). The highest modulus of elasticity is obtained for the sample with silica fume addition. The highest increase in Eb values from 28th to the 90th day is noticed for SCC-C and SCC-D: 15 % and 16 %, in respect. Concretes with RCA treated with water glass exhibit comparable static modulus of elasticity values, while those of SCC-A are greater. However, it can be noted that silica fume contributes to the highest modulus of elasticity, whereas fly ash contributes to the lowest values in all combinations with partial replacement of aggregate.

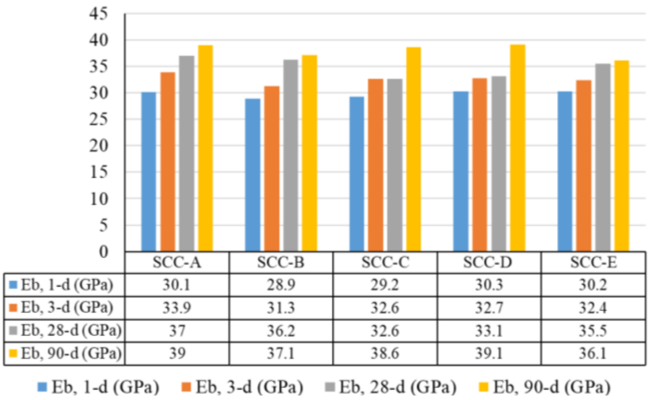


Figure 18. Static modulus of elasticity of hardened SCCs aged 1, 3, 28, and 90 days.

Results of the 'Pull-off' method (tensile strength of concrete and mortar, i.e., adhesion) are provided in Table 4.

Table 4. Results of the Pull-off test on SCC samples.

Sample	SCC-A	SCC-B	SCC-C	SCC-D	SCC-E
f_{ts} (MPa)	3.2	3.9	3.6	4.7	4.5

Samples with RCA (SCC-B, SCC-C, SCC-D, and SCC-E) show higher values of adhesion than with NRA (SCC-A). The lowest value of the adhesion is obtained for the

SCC-C sample based on coated recycled concrete aggregate. Cracking through the glue occurred during the testing of SCC-D sample. Results of Pull-off, i.e., adhesion tests, reveal that the mixture in which RCA is treated with water glass has a lower strength than the mixture developed with untreated RCA. Treating RCA with water glass and silica fume, or fly ash, results in considerable strength improvement. The RCA treated with water glass and silica fume demonstrates the highest adhesion values.

Ultrasonic approach involves measuring the speed at which longitudinal ultrasonic waves propagate through concrete. Because the speed of ultrasound is directly proportional to the attained density of concrete and density is one of the fundamental criteria determining the compressive strength of concrete, this method is used to measure the strength of concrete in finished structures (*in situ*). The test is carried out according to the standard method. The ultrasonic pulse velocity test is performed on prismatic samples measuring 12×12×36 cm, aged 1, 3, 28, and 90 days. Test results are given in Fig. 19.

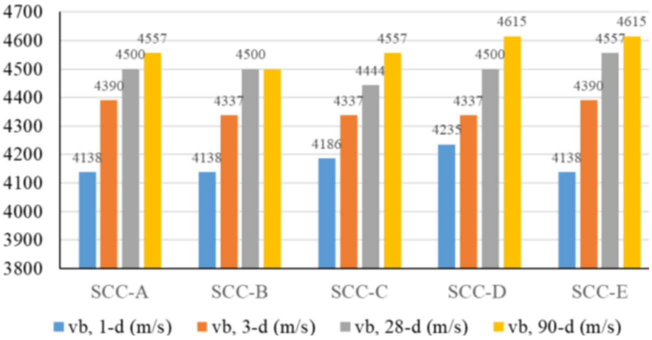


Figure 19. Ultrasonic pulse velocity (UPV) obtained for SCC samples at ages of 1, 3, 28, and 90 days.

UPV values increased over a 90-day period for all evaluated SCC samples. These findings are consistent with the results from the bulk density test (Fig. 14) and compressive strength examinations (Fig. 15). Microstructure of concrete samples grows denser over the period of 90 days with hydration and corresponding reactions taking place. Density of the examined material, and hence UPV values, are directly related to compressive strength. The slowest ultrasonic rates (4138 m/s) are found on SCC-A (reference sample), SCC-B, and SCC-E. The sample with coated RCA (SCC-C) had somewhat greater velocity, whereas the sample with coated RCA and silica fume had the greatest UPV (4235 m/s). At 28 days, SCC-A, SCC-B, and SCC-D had UPV values of 4500 m/s each. SCC-C had a lower UPV than the other samples at 28 days, while SCC-E had the highest value. UPV values increased for all samples collected between 28 and 90 days, with the exception of SCC-B, where values remained stable. This indicates that the hydration route was completed by day 28. The highest UPV values are found in SCC-D and SCC-E samples, indicating that the combination of RCA coating and addition of silica fume, or fly ash, caused the increase in density of the concrete microstructure.

The waterproofing test was conducted on cubical samples (15 cm) and began on the 28th day. Samples are placed under a 5 bar pressure for three days before being broken to determine the depth of water penetration (Fig. 20). Table 5 shows the measured values for water penetration (h).

Figure 20. Depth of water penetration on experimental SCC sample.

Table 5. Results of water permeability test on SCC samples.

Sample	SCC-A	SCC-B	SCC-C	SCC-D	SCC-E
h (mm)	18.3	21.7	17.5	9.0	17.5

Samples prepared with coated RCA without and with mineral addition (fly ash), i.e., SCC-C and SCC-E, had lower h values than reference concrete SCC-A prepared with NRA. It can be concluded that water glass and the addition of fly ash reduced porosity and thus water penetration. On the other hand, the sample with uncoated RCA (SCC-B) had higher levels of water penetration than the reference sample. Finally, the sample including coated aggregate and silica fume (SCC-D) demonstrates exceptionally minimal water penetration.

The depth of water penetration reveals that water glass has a good impact on concrete water resistance. In particular, because recycled aggregate has a lower compactness than natural aggregate, the depth of water penetration in the combination in which natural aggregate is partially replaced with recycled has increased noticeably. SC-concretes with better water resistance than SCC with natural aggregate are obtained by treating recycled aggregate with water glass, as well as water glass and fly ash. Treatment with water glass and silica fume produces much better water resistance than other mixes.

In general and based on the results of physical and mechanical properties, it is possible to conclude that water glass is suitable for the treatment of recycled concrete aggregates.

CONCLUSIONS

Presented study investigates the possibility of incorporating recycled concrete aggregate (RCA) into self-compacting concrete (SCC). Research addresses a significant gap in the existing literature by examining the effects of RCA impregnated with a water glass solution on the physical and mechanical properties of both fresh and hardened SCC.

Results highlight that the influence of water glass varies depending on the co-constituent with which it is combined. Flowability tests confirm that all mixtures maintain acceptable levels of workability, with minor variations attributable to aggregate treatment and content. It is also revealed that the water glass impregnation of RCA significantly influences mechanical properties of SCC. Specifically, the combination of water glass with fly ash results in the most notable improvement in compressive strength over 90 days, suggesting a synergistic effect that enhances microstructure and the bonding within the concrete matrix. Conversely, the mixture incorporating silica fume demonstrates comparatively lower strength gains, potentially due to differences in particle packing and pozzolanic reactions. Water-permeability assessments indicate that impregnated recycled aggregates contribute positively to long-term stability of concrete, likely due to reduced porosity and enhanced interfacial bonding. The chemical nature of bonding reactions remains to be investigated by instrumental methods in the following research.

This study proves that impregnation of recycled concrete aggregates with water glass solutions can effectively influence mechanical and durability properties of SCC. Findings particularly highlight the beneficial effects when combined with supplementary cementitious materials like fly ash that synergistically improve strength development over extended curing periods. The research underscores the potential for utilising waste raw materials in sustainable concrete production, contributing to environmental conservation efforts and resource efficiency. Future investigations should also explore long-term durability, environmental impact, and economic feasibility of such approaches to facilitate their adoption in mainstream construction practices.

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REFERENCES

1. Kamal, M.M., Safan, M.A., Bashandy, A.A., Khalil, A.M. (2018), *Experimental investigation on the behavior of normal strength and high strength self-curing self-compacting concrete*, J Build. Eng. 16: 79-93. doi: 10.1016/J.JOBE.2017.12.012
2. Inqiad, W.B., Dumitrascu, E.V., Dobre, R.A. (2024), *Forecasting residual mechanical properties of hybrid fibre-reinforced self-compacting concrete (HFR-SCC) exposed to elevated temperatures*, Heliyon, 10(12): e32856. doi: 10.1016/j.heliyon.2024.e32856
3. Alnebhan, K.M., Shallal, M.A. (2020), *Composite concrete and concrete filled steel tube (CFST) truss girders*, Struct. Integr. Life, 20(2): 103-112.
4. Yang, Z., Liu, S., Yu, L., Xu, L. (2021), *A comprehensive study on the hardening features and performance of self-compacting concrete with high-volume fly ash and slag*, Materials, 14(15): 4286. doi: 10.3390/ma14154286
5. Bui, N.K., Satomi, T., Takahashi, H. (2018), *Mechanical properties of concrete containing 100% treated coarse recycled concrete aggregate*, Constr. Build. Mater. 163: 496-507. doi: 10.1016/j.conbuildmat.2017.12.131
6. Jiang, Y., Chen, L., Wang, D., et al. (2024), *Mechanical properties and acoustic emission characteristics of soft rock with different water contents under dynamic disturbance*, Int. J Coal. Sci. Technol. 11(1): 36. doi: 10.1007/S40789-024-00682-0
7. Wang, J., Zhou, J., Kangwa, J. (2023), *12 - Self-compacting concrete adopting recycled aggregates*, In: Woodhead Publishing Series in Civil and Structural Engineering, Multi-Functional Concrete with Recycled Aggregates, pp.267-288. doi: 10.1016/B978-0-323-89838-6.00007-4
8. Geiker, M., Jacobsen, S. (2019), *10 - Self-compacting concrete (SCC)*, In: Sidney Mindess (Ed.), Woodhead Publishing Series in Civil and Structural Engineering, Developments in the Formulation and Reinforcement of Concrete (Second Ed.), Woodhead Publishing, pp.229-256. doi: 10.1016/B978-0-08-102616-8.00010-1
9. Zheng, S., Liu, Q., Han, F., et al. (2024), *Basic mechanical properties of self-compacting concrete prepared with aeolian sand and recycled coarse aggregate*, Buildings, 14(9): 2949. doi: 10.3390/buildings14092949
10. Uysal, M., Yilmaz, K., Ipek, M. (2012), *Properties and behavior of self-compacting concrete produced with GBFS and FA additives subjected to high temperatures*, Constr. Build. Mater. 28(1): 321-326. doi: 10.1016/j.conbuildmat.2011.08.076
11. Asteris, P.G., Kolovos, K.G. (2019), *Self-compacting concrete strength prediction using surrogate models*, Neural Comput. Appl. 31(Suppl. 1): 409-424. doi: 10.1007/s00521-017-3007-7
12. Asteris, P.G., Kolovos, K.G., Douvika, M., Roinos, K. (2016), *Prediction of self-compacting concrete strength using artificial neural networks*, Europ. J Environ. Civil Eng. 20(Suppl. 1): s102-s122. doi: 10.1080/19648189.2016.1246693
13. Soleimani, F., Si, G., Roshan, H., Zhang, J. (2023), *Numerical modelling of gas outburst from coal: a review from control parameters to the initiation process*, Int. J Coal Sci. Technol. 10(1): 81. doi: 10.1007/S40789-023-00657-7
14. Ali, Z., Karakus, M., Nguyen, G.D., Amrouch, K. (2022), *Effect of loading rate and time delay on the tangent modulus method (TMM) in coal and coal measured rocks*, Int. J Coal Sci. Technol. 9(1): 81. doi: 10.1007/s40789-022-00552-7
15. Li, F., Shen, W., Ji, Y., et al. (2024), *Pressure-based analysis of rheological equilibrium distances of pumped self-consolidating concrete (SCC)*, Constr. Build. Mater. 411: 134517. doi: 10.1016/j.conbuildmat.2023.134517
16. Moghaddam, H.H., Lotfollahi-Yaghin, M.A., Maleki, A. (2025), *Comprehensive analysis of mechanical characteristics in self-compacting concrete (SCC) with aluminum oxide (Al_2O_3) nanoparticles and glass fibers: An experimental and analytical investigation*, Case Studies Constr. Mater. 22: e04095. doi: 10.1016/j.cscm.2024.e04095
17. Sanchez, F., Sobolev, K. (2010), *Nanotechnology in concrete - A review*, Constr Build Mater. 24(11): 2060-2071. doi: 10.1016/j.conbuildmat.2010.03.014
18. Hosseini, P., Afshar, A., Vafaei, B., et al. (2017), *Effects of nano-clay particles on the short-term properties of self-compacting concrete*, Eur. J Environm. Civ. Eng. 21(2): 127-147. doi: 10.1080/19648189.2015.1096308
19. Varela, H., Barluenga, G., Palomar, I. (2020), *Influence of nanoclays on flowability and rheology of SCC pastes*, Constr. Build. Mater. 243: 118285. doi: 10.1016/j.conbuildmat.2020.118285
20. Sadoun, A., Ibrahim, A., Abdallah, A.W. (2020), *Fabrication and evaluation of tribological properties of Al_2O_3 coated Ag reinforced copper matrix nanocomposite by mechanical alloying*, J Asian Ceram. Soc. 8(4): 1228-1238. doi: 10.1080/21870764.2020.1841073
21. Sadoun, A.M., Meselhy, A.F., Abdallah, A.W. (2021), *Microstructural, mechanical and wear behavior of electroless assisted silver coated Al_2O_3-Cu nanocomposites*, Mater. Chem. Phys. 266: 124562. doi: 10.1016/j.matchemphys.2021.124562
22. Ahmadian, H., Fouly, A., Zhou, T., et al. (2024), *Investigating the valence balance of adding Nano SiC and MWCNTs on the improvement properties of copper composite using mechanical alloying and SPS techniques*, Diam. Relat. Mater. 145: 111113. doi: 10.1016/j.diamond.2024.111113

23. Ahmadian, H., Zhou, T., Alansari, A., et al. (2024), *Microstructure, mechanical properties and wear behavior of Mg matrix composites reinforced with Ti and nano SiC particles*, J Mater. Res. Technol. 31: 4088-4103. doi: 10.1016/j.jmrt.2024.07.125
24. Ahmadian, H., Sadoun, A.M., Fathy, A. Zhou, T. (2023), *Utilizing a unified conceptual dynamic model for prediction of particle size of duel-matrix nanocomposites during mechanical alloying*, Powder Technol. 418: 118291. doi: 10.1016/j.powtec.2023.118291
25. Hussein, I.A., Ghalehnovi, M. (2025), *The impact of colloidal nano silica (CNS) and polypropylene fibers (PP) on the properties of recycled concrete aggregate self-compacting concrete (SCC)*, Case Stud. Constr. Mater. 22: e04424. doi: 10.1016/j.cscm.2025.e04424
26. El Marzak, M., Serroukh, H.K., Benaicha, M., et al. (2025), *Rheological and mechanical analysis of self-compacting concrete incorporating rubber aggregates*, Case Stud Constr. Mater. 22: e04564. doi: 10.1016/j.cscm.2025.e04564
27. Bahmani, H. Mostofinejad, D. (2025), *Innovative fiber-reinforced self-compacting concrete using activated slag from sugar factory lime waste*, Case Stud Const Mater, 22: e04752. doi: 10.1016/j.cscm.2025.e04752
28. Pavithra, A., Murali, K. (2023), *Crushed-stone sand for use in the development of self-compacting concrete (SCC)*, Mater. Today: Proc. doi: 10.1016/j.matpr.2023.03.571
29. Shenbagam, N.K., Siddharth, M.A., Kannan, V., Dhanusree, C. (2023), *Experimental investigation of self-compacting concrete (SCC) using fly ash*, Mater. Today: Proc. doi: 10.1016/j.matpr.2023.04.582
30. Bheel, N., Awoyera, P., Shar, I.A., Kırgız, M.S. (2024), *16 - Self-compacting concrete blended with fly ash and ground granulated blast furnace slag*, In: Woodhead Publishing Series in Civil and Structural Engineering, Advance Upcycling of By-Products in Binder and Binder-Based Materials, Woodhead Publ. pp.309-334. doi: 10.1016/B978-0-323-90791-0.00001-9
31. Aadi, A.S., Hilal, N., Hama, S.M., et al. (2024), *Mechanical performance of eco-friendly self-compacting concrete (SCC) mixtures and two-way slabs partially containing cement kiln dust as cement replacement and internally reinforced with waste plastic mesh*, Structures 66: 106864. doi: 10.1016/j.istruc.2024.106864
32. Li, N., Jin, Z., Shen, K., et al. (2023), *Strategies to improve the impact resistance of self-compacting concrete (SCC) after freeze-thaw cycles*, J Build. Eng. 66: 105854. doi: 10.1016/j.jobe.2023.105854
33. Indriyantho, B.R., Prasetya, B.H., Hidayat, B.A., et al. (2025), *Tensile behavior of self-compacting geopolymer concrete considering tension stiffening*, J Build. Eng. 105: 112402. doi: 10.1016/j.jobe.2025.112402
34. SRPS EN 933-1:2013, Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method
35. SRPS EN 933-2:2009, Tests for geometrical properties of aggregates - Part 2: Determination of particle size distribution - Test sieves, nominal size of apertures
36. SRPS ISO 6782:1999, Aggregates for concrete - Determination of bulk density
37. SRPS ISO 7033:1999, Fine and coarse aggregates for concrete - Determination of the particle mass-per-volume and water absorption - Pycnometer method
38. Superplasticizer Cementol Hiperplast 463 (https://beta-b.rs/proizvod/5506-cementol-hiperplast463-10-1 last accessed 01.06.2025)
39. Autischer, M., Mülleder, T., Prskalo, S., et al. (2024), *Improved rheological characterisation of self-compacting cementitious pastes and concrete by advanced slump flow test analysis*, Constr. Build. Mater. 452: 138857. doi: 10.1016/j.conbuildmat.2024.138857
40. SRPS EN 12350-8:2019 Testing fresh concrete - Part 8: Self-compacting concrete – Slump-flow test
41. SRPS EN 12350-9:2012 Testing fresh concrete - Part 9: Self-compacting concrete - V-funnel test
42. SRPS EN 12350-12:2012 Testing fresh concrete - Part 12: Self-compacting concrete - J-ring test
43. SRPS EN 12350-1:2019 Testing fresh concrete - Part 1: Sampling and common apparatus
44. SRPS EN 12350-6:2019 Testing fresh concrete - Part 6: Density
45. SRPS EN 12350-7:2010 Testing fresh concrete - Part 7: Air content - Pressure methods
46. SRPS EN 12390-3:2019 Testing hardened concrete - Part 3: Compressive strength of test specimens
47. SRPS ISO 12390-5:2019 Testing hardened concrete - Part 5: Flexural strength of test specimens
48. SRPS EN 12390-6:2024 Testing hardened concrete - Part 6: Tensile splitting strength of test specimens
49. SRPS ISO 6784:2000 Concrete - Determination of static modulus of elasticity in compression
50. SRPS EN 1542:2010 Products and systems for the protection and repair of concrete structures - Test methods - Measurement of bond strength by pull-off
51. SRPS U.M1.042:1998 Concrete, hardened - Determination of ultrasonic pulse velocity
52. SRPS U.M1.015:1998 Concrete - Concrete, hardened - Determination of the depth of penetration of water under pressure
53. SRPS EN 206-1:2011 Concrete - Part 1: Specification performance, production and conformity