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Prof. dr Zoran Lazarević

President to the Society
for Renewable Electrical
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within the SMEITS
Prof Zoran Lazarević, Ph. D.

Urednik
V.prof. dr Aleksandar Savić

Editor
Assoc. prof Aleksandar Savić, Ph. D.

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EVALUACIJA SCC MEŠAVINA SA KOMBINACIJOM DROBLJENE GUME I RECIKLIRANOG BETONSKOG AGREGATA

EVALUATION OF SCC MIXTURES WITH THE COMBINED USE OF CRUMB RUBBER AND RECYCLED CONCRETE AGGREGATE

Marko POPOVIĆ[1], Branko BOROZAN[1], Mihailo ŠTAVLJANIN[1],
Aleksandar SAVIĆ[1], Marina LATINOVIC KRNDIJA
[1]University of Belgrade Faculty of Civil Engineering, Belgrade, Serbia,
[2]University of Banja Luka Faculty for Architecture Civil Engineering, and Geodesy,
Banja Luka, Republika Srpska, mpopovic@grf.bg.ac.rs

Usvajanje održivosti u građevinskoj industriji pokazalo se kao ključno za postizanje Globalnih ciljeva održivi razvoj Ujedinjenih nacija (SDGs). Brzi rast u građevinskom sektoru opterećuje resurse sirovina kao što su prirodni agregati (NA), što može dovesti do njihovog iscrpljivanja. Štaviše, rast otpada od građenja i rušenja (CDW) intenzivira globalni problem upravljanja otpadom kao jednog od najvećih tokova otpada širom sveta. Pošto beton čini glavni deo CDW-a, njegova reciklaža kao agregata (RCA) se pojavljuje kao istaknuto rešenje za gore navedene probleme. S druge strane, potencijalno hazardno odlaganje otpadnih guma (ELTs) je još jedan rastući problem otpada. Uključivanje agregata nastalog recilažom pneumatika u betonske mešavine kao zamene za prirodne agregate je jedno od mogućih rešenja. Ovaj rad ima za cilj da pruži uvid u mogućnost upotrebe drobljene gume (CR) i recikliranog betonskog agregata (RCA) kao alternativnih agregata u samougrađujućim betonskim mešavinama (SCC). U tu svrhu, ispitivanjima na svežem i očvrslom betonu procenjena su fizičko-mehanička svojstva pripremljenih SCC mešavina sa CR i RCA.

Ključne reči: *samougrađujući beton; drobljena guma; reciklirani betonski agregat*

Adopting sustainability in the construction industry emerged as crucial to achieving the United Nations Global Goals for Sustainable Development (SDGs). Rapid growth in the construction sector strains raw material resources such as natural aggregates (NA), possibly leading to their depletion. Furthermore, the growth of construction and demolition waste (CDW) intensifies the global issue of waste management as one of the largest waste streams worldwide. Since concrete is the main constituent of CDW, its recycling as aggregate (RCA) emerges as a prominent solution to the abovementioned problems. On the other hand, potentially hazardous disposal of end-of-life tyres (ELTs) is another increasing waste problem. Incorporating recycled tyre rubber in concrete mixtures as a substitute for natural aggregates is one possible solution. This paper aims to give some insights into the possibility of using crumb rubber (CR) and recycled concrete aggregate (RCA) as alternative aggregates in self-compacting concrete (SCC) mixtures. For that purpose, the physical and mechanical properties of prepared SCC mixtures with CR and RCA were evaluated by tests performed on fresh and hardened concrete.

Key words: *Self-Compacting Concrete; crumb rubber; recycled concrete aggregate;*

1 Introduction

Concrete is the most widely used construction material around the world with a comparable environmental footprint. Cement and concrete production is energy and emissions intensive process with a high demand for natural resources. In addition to that concrete is among the major contributors to one of the largest waste streams known as construction and demolition waste (CDW) [1]. The rapid urbanization along with economic growth reflected a significant increase in construction. Consequently, concrete production is constantly increasing which puts an enormous strain on natural resources and increases the overall impact on the environment.

On the other side, apparently unrelatable, another environmental concern is driven by urbanization and economic growth. The increased number of vehicles has led to enormous growth in the volume of end-of-life tyres (ELTs). The ELTs waste management is a global sustainability issue – they are usually discarded and left to decompose in landfills for decades, contaminating the soil with various toxic substances, or sometimes even being burned. The discarded rubber tyres are a type of “black pollution”. They are highly flammable and if they catch fire they release hazardous smoke that stays in the air for a long time, leaving behind the toxic residue that ends up in the soil.

A promising and sustainable solution to the previously mentioned over-exploitation of natural aggregate and CDW and ELTs disposal problem is the use of recycled concrete and crumb rubber as aggregate. This way recycled aggregate concrete (RAC) and crumb rubber concrete (CRC) are produced.

Recycled concrete aggregate (RCA) is produced from the debris from demolished structures by crushing and processing waste concrete. The RCA is a two-phase composite material consisting of original natural aggregate and leftover cement paste as a result of its manufacturing process. This is the reason why there could be workability problems when designing mixtures with RCA. The porosity and micro-cracks in old cement paste and potential internal cracking caused by the crushing process result in high water absorption (WA) of the recycled concrete aggregate. As a result, during the mixture production, the RCA absorbs the part of the water amount provided for hydration of the new cement paste, reducing the water-cement ratio. Recycled aggregate concrete (RAC) is considered a three-phase material – the original natural aggregate, adhered old mortar and new cement paste. As a cement composite, RAC’s properties are dependant on the quality of two interfacial transition zones (ITZs). The “old” ITZ is the one within RCA – it is between adhered old mortar and natural aggregate, while the “new” ITZ is between RCA as a whole and new cement paste (Figure 1). The high water absorption capacity of the recycled concrete aggregate reduces the amount of water available for cement hydration, affecting the quality of the new ITZ. This problem could be solved either by pre-soaking the RCA before mixing or by increasing the quantity of water by the amount calculated based on WA measurement [2] and increasing the total water-cement ratio (w/c) but maintaining the effective water-cement ratio (w/c_{eff}) that considers only the free water, ie the total amount of water reduced by absorbed.

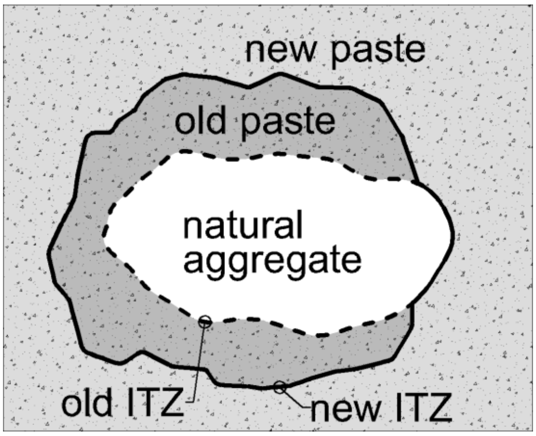

Figure 1: Recycled concrete aggregate micro structure – three-phase composite material with two interfacial transition zones (ITZs)

The crumb rubber concrete is made by replacing the natural aggregate with crumb rubber particles. The CRC performance in both fresh and hardened states is highly affected by the presence of rubber particles and their amount. Similarly to RAC, the properties of CRC are the consequence of the inherent properties of rubber particles as well as the quality of ITZ.

Rubber particles are characterised by lower density making them attractive for the production of lightweight concrete. Fresh state performance is affected by particles hydrophobicity, surface roughness and interlocking, resulting in the increase of air voids, which might cause the workability problem [3]. Because of hydrophobicity and poor chemical reaction, crumb rubber particles don’t participate in the cement hydration process so the bond between them can be described as physical resulting in ITZ with a lack of bonding. Weak ITZ and lower stiffness of CR particles compared to other compounds of concrete mixtures reduce the strength values of CRC. However, the CR particles have the potential to enhance some concrete properties such as thermal and sound insulation, toughness, dynamic performance, frost resistance and fatigue life [3-6].

The use of RCA and CR as an improvement of self-consolidating concrete (SCC) sustainability was studied. Unlike conventional concrete, the SCC is placed and consolidated under its own weight so it doesn't need vibration for pouring thanks to its ability to completely fill the formwork without segregation, bleeding or honeycombing even in case of complex geometry and dense reinforcement. As a result, SCC has enhanced mechanical properties and durability, increases architectural freedom and provides an improvement in productivity and working conditions because of a lack of external compaction. The performance of SCC with CR as a fine NA replacement and coarse RCA was evaluated based on the experimental campaign carried out on fresh and hardened state mixtures.

2 Experimental campaign

2.1 Scope and objective

The aim of the ongoing research partially presented in this paper is to study the influence of the recycled concrete aggregate and untreated crumb rubber on the physical and mechanical properties of SCC mixtures, so the possibilities and limitations of using these mixtures in structural elements could be estimated. With that intention, fresh and hardened state tests were conducted on several mixtures with varying replacement levels of fine and coarse natural aggregates.

2.2 Materials

The constituent materials of prepared SCC mixtures are presented in Figure 2.

Three types of aggregate – natural river aggregate (NA), crumb rubber (CR) and recycled concrete aggregate (RCA) were separated into three standard fractions in accordance with EN 933-1:2012: 0/4mm (fraction I), 4/8mm (fraction II) and 8/16mm (fraction III).

Figure 2: SCC components used in this research – natural aggregate fractions I, II and III (NA I, NA II, NA III), crumb rubber (CR) and recycled concrete aggregate fractions II and III (RCA II, RCA III), limestone powder (LP), portland-composite cement CEM II/A-M(S-L)42,5R, superplasticizer (SP) and water from the city water-works

Crumb rubber produced by grinding end-of-life tyres (ELTs) was used as a partial replacement for fine natural aggregate (fraction I) and incorporated in concrete mixtures without pre-treatment.

Coarse recycled concrete aggregate (fractions II and III) was obtained by crushing concrete debris collected from the demolition of concrete foundation slab for tram tracks. According to tests that are performed at the time of crushing, around thirty years old concrete satisfied the conditions for class C35/45. The RCA was composed of original concrete (98%), asphalt (1.2%), and brick fragments (0.8%). Considering the high water absorption of fine RCA and the linked negative impact on SCC workability and strength, only coarse RCA with WA values of 3% for fraction II and 4.1% for fraction III was used in the mixtures considered in this research.

Natural aggregate was commercially available gravel from the Danube river, provided by a local aggregate supplier. As powder materials, Portland-composite cement CEM II/A-M(S-L)42,5R and fine-grained limestone filler with particle size under 0.125 mm were used.

2.3 Mixtures

Three SCC mixtures with three aggregate replacement levels are considered in this study – REF stands for the reference mixture, while the numbers in the labels of R_0C_{100} and $R_{20}C_{100}$ stand for the percentage of volumetric replacement of fine NA by CR (the number after "R") and the percentage of mass replacement of coarse NA by RCA (the number after "C"). Mixture composition is presented in Table 1.

Table 1: Composition of SCC mixtures (kg/m^3)

Mixture	CR %	RCA %	CEM	LP	Fraction I (0/4 mm)		Fraction II (4/8 mm)		Fraction III (8/16 mm)		W	SP
					NA	CR	NA	RCA	NA	RCA		
REF	0	0	380	250	860	0	530	0	310	0	171.0	4.4
R_0C_{100}	0	100			860	0	0	530	0	310	199.6	
$R_{20}C_{100}$	20	100			688	71.3	0	530	0	310	199.6	

All three mixtures were designed with the same amount of water provided for cement hydration, making the value of the so-called effective water-cement ratio equal – $w/c_{eff} = 0.45$. However, because of the higher WA of recycled concrete aggregate, an additional amount of water was added in the case of the R_0C_{100} and $R_{20}C_{100}$ mixtures, resulting in a difference in the total amount.

Cement and filler dosage was kept constant for all mixes. High quantities of powder content and low water-powder ratio (w/p) are common for all three mixtures categorising them as powder-type SCC.

2.4 Concrete mixing and specimen preparation

The water absorption (WA) capacity of RCA is linked with the presence of old mortar content. Water absorption of old mortar leads to a lack of water provided for hydration of new cement, affecting the quality of bond properties between RCA and new cement paste. To overcome this problem, a two-stage mixing approach (TSMA) [7] was conducted. More water was added to the amount provided for cement hydration, based on the WA testing of RCA done in previous research. The mixing procedure was divided into two parts (Figure 3). At first, aggregate and limestone powder are premixed with half of the total water amount in order to form a slurry that penetrates and fills the pores, and seals the surface of RCA, thus preventing excessive WA. In the second stage, the rest of the water and cement were introduced into the mixture and mixed. As the final constituent, a superplasticizer was added. This way, TSMA improves the quality of new ITZ, leading to enhanced mechanical properties of RAC.

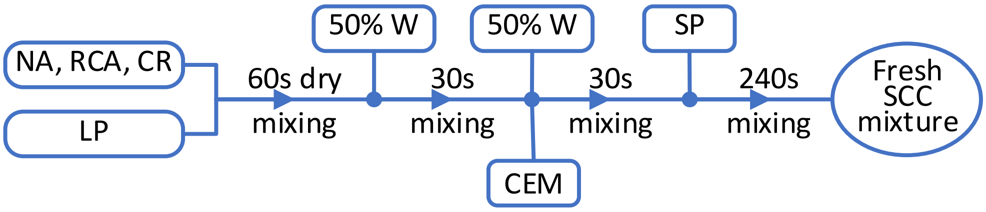

Figure 3: Two-stage mixing approach (TSMA)

2.5 Testing methods

Fresh and hardened state performance of prepared SCC mixtures was evaluated to compare the influence of CR and coarse RCA inclusion.

In the fresh state, bulk density was measured (EN 12350-6:2019), flowability and viscosity were assessed based on the results of the slump flow test (EN 12350-8:2019), while the L-box test (EN 12350-10:2019) was utilized to determine the passing ability of mixtures.

The influence of different aggregates on several mechanical properties and durability was determined based on the tests conducted on cubic, prismatic and cylindric specimens.

Cube specimens with 150 mm sides were used for compressive strength testing (EN 12390-3:2019).

On prismatic specimens (120×120×360 mm) three tests were conducted. At first, the ultrasonic pulse velocity (UPV) test was conducted to assess the quality and homogeneity of mixtures (EN 12504-4:2021). The tensile strength was determined based on three-point-bending test (3PBT) with a 300 mm span (EN 12390-5:2019). After that, pull-off adhesion test was carried out on broken prisms (EN 1542:1999).

The durability performance of mixtures was rated based on the water permeability test (SRPS U.M1.015:1998). The penetration depth was measured on the Ø/H=150/150 mm cylinders under water pressure to assess the water tightness of mixtures.

3 Results and discussion

3.1 Fresh mix properties

The results of fresh mixture tests are summarized in Table 3. Because of the crumb rubber intrusion, bulk density was the smallest for the $R_{20}C_{100}$ mixture – 2244 kg/m^3, while the biggest value was in the case of the reference mixture – 2405 kg/m^3.

Table 2: Properties of SCC mixtures in fresh state

Mixture label	Slump flow diameter [mm]	Slump flow t500 [s]	L-box PA [/]	Bulk density [kg/m^3]
REF	840	2,2	0,99	2405
R_0C_{100}	790	2,4	0,88	2353
$R_{20}C_{100}$	770	3,1	0,88	2244

According to the slump flow test and L-box test results, the concrete fresh state performance declined with the increase of the NA replacement rate. Nevertheless, all three mixtures fulfilled the requirements for SCC in terms of workability [8].

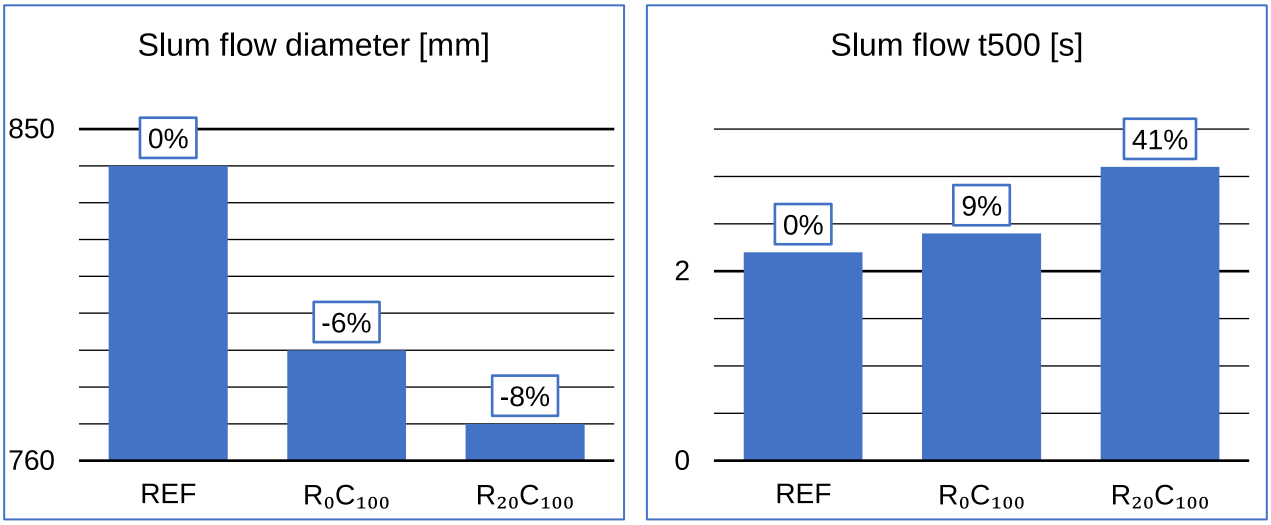

Figure 4: Slump test results: diameter (left) and t500 time (right)

The flowability of mixtures was assessed based on the slump flow diameter values (Figure 4). The average diameter across the spread of concrete varied between 840 mm for REF and 770 mm for $R_{20}C_{100}$ mixture, so all mixtures were categorised as the highest – SF3 class. The t500 slump time is a measure of flow rate that is linked to plastic viscosity – the lower the t500 time, the lower the viscosity. The lowest t500 value had the reference mixture (2.2 s), while $R_{20}C_{100}$ had the highest (3.1 s). All t500 values were above 2 s, so all mixtures were classified as VS2. Therefore, with the increment of NA replacement, flowability showed decreasing trend, while it was the opposite in the case of viscosity.

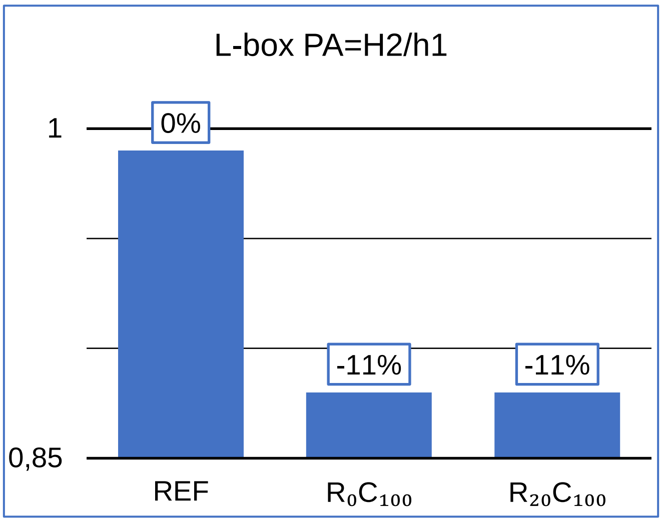

Figure 5: L-box test results – passing ability PA

The ability of prepared SCC mixtures to flow through narrow openings and confined spaces such as dense reinforcement without blocking or segregation was evaluated based on the L-box test with 3 rebars (Figure 5). All PA values were between 0.88 ($R_{20}C_{100}$) and 0.99 (REF) with no blocking effect observed, satisfying PA2 class requirements. Similar to flowability, the passing ability decreased with the RCA and CR intrusion.

3.2 Hardened concrete properties

The influence of the natural aggregate replacement with crumb rubber and recycled concrete aggregate on the mechanical properties and durability of SCC mixtures was investigated by testing the cubic and prismatic specimens after 28 days. The results of tests conducted on hardened concrete are summarized in Table 4.

Table 3: Hardened concrete properties of SCC mixtures

Mixture label:	REF	R_0C_{100}	$R_{20}C_{100}$
Compressive str. [MPa]	56.3	54.8	41.8
Flexural tensile str. [MPa]	8.4	7.9	5.7
Ultrasonic pulse velocity (UPV) [m/s]	4639	4447	4194
Water permeability test – penetration depth [mm]	12	27	28
Pull-off test – bond str. [MPa]	3	2.7	2.6

The results of the strength tests are presented in Figure 6. Both the compressive and flexural tensile strength showed similar relationships with the NA replacement. The highest strength values were obtained in the reference mixture, the total replacement of coarse NA with RCA resulted in slightly lower values (R_0C_{100}), while the more noticeable decline was in the case of the combined intrusion of RCA and CR ($R_{20}C_{100}$) – 26% and 32% in the cube test and 3PBT, respectively.

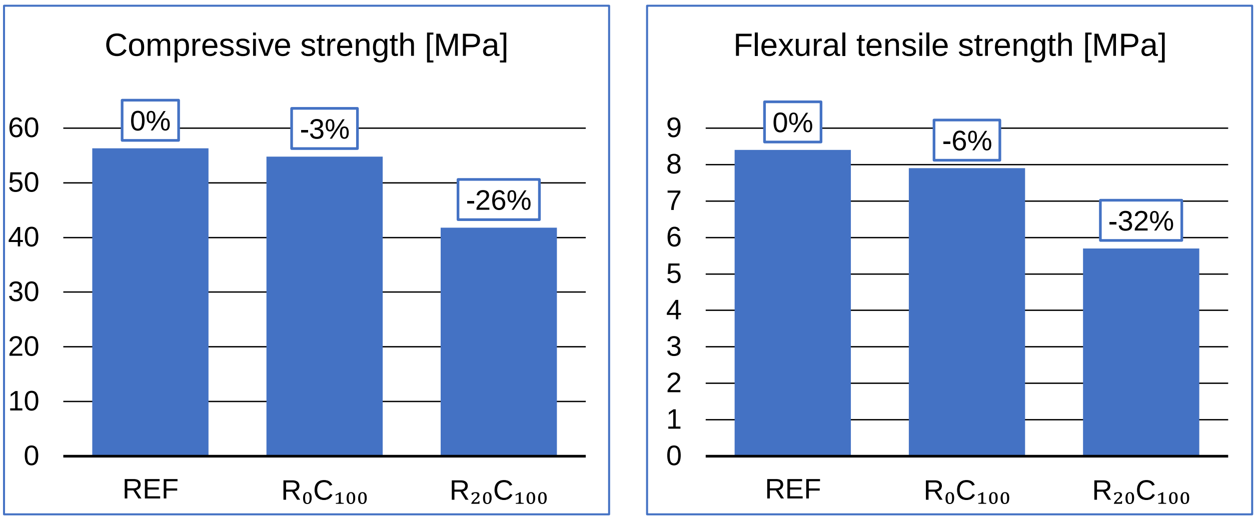

Figure 6: Compressive strength (left) and flexural tensile strength (right)

Ultrasound pulse velocity is very sensitive to the presence of discontinuities in concrete, so the test was carried out to assess the impact that CR and RCA can have on the homogeneity and quality of concrete. The results of the UPV test (Figure 7) were in line with the characteristics of used aggregates, as well as their bond with cement paste. Adhered old mortar and crushing production process are the cause of discontinuities in RCA, leading to a 4% drop in UPV value. The increase of air void content caused by CR and its low elastic modulus resulted in a 10% UPV decline. According to the classification given in Table 5, the REF mixture was classified as "excellent", while the quality of R_0C_{100} and $R_{20}C_{100}$ mixtures, although UPV decreased, can be categorised as "good", far away from the lower limit value (3500 m/s) [9].

Table 4: Classification of concrete quality according to UPV [9]

UPV (m/s)	Concrete quality
> 4500	Excellent
3500 – 4500	Good
3000 – 3500	Medium
< 3000	Doubtful

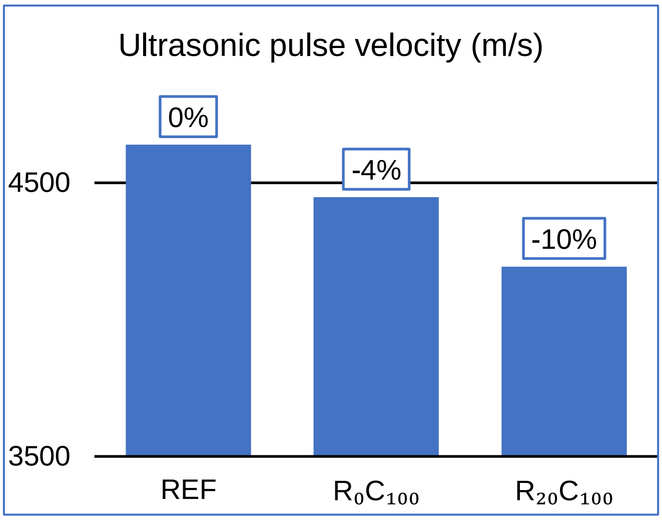

Figure 7: Ultrasonic pulse velocity (UPV)

To assess the durability performance of mixtures the water permeability (WP) test was conducted. The water penetration depth is an indicator of freeze-thaw and chemical attack resistance. High water absorption of RCA has the potential to decrease the water tightness of concrete. The cement gel produced in the TSMA procedure that seals the RCA surface improves the WA hence the durability performance of concrete made of RCA [10]. The weak bond between crumb rubber as aggregate and surrounding cement paste makes it easier for pressurized water to penetrate deeper. The water permeability test results were in line with the previously said – the coarse NA total replacement with RCA resulted in the WP depth increase from 12 mm to 27 mm, while additional partial replacement of fine NA with CR caused a minor increase to 28 mm (Figure 8). Although this change in WP depth seems significant, it is noteworthy to state that all three mixtures can be classified as “impermeable under aggressive conditions” as their WP depths are under 30 mm [11].

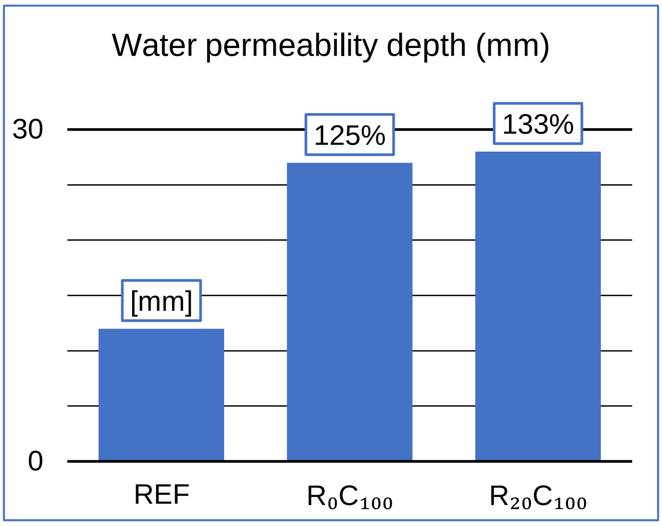

Figure 8: Water permeability test – penetration depth of water under pressure

The pull-off test was conducted to assess the impact that RCA and CR could have on adhesion capacity. The bond strength values varied between 3.0 MPa for REF and 2.6 MPa for $R_{20}C_{100}$ (Figure 9).

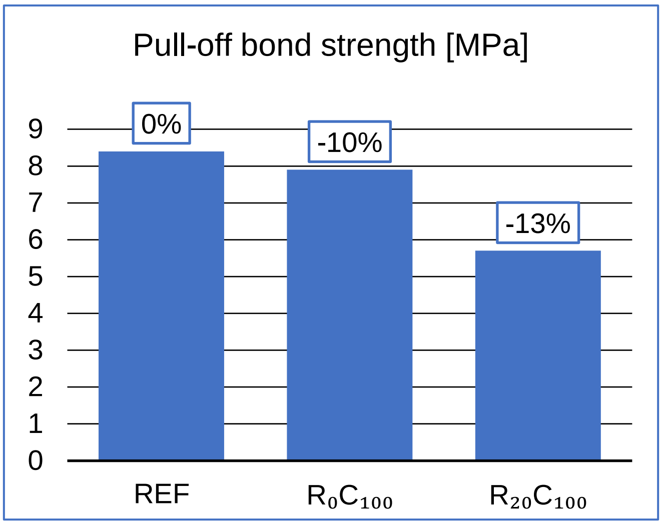

Figure 9: Pull-off test – bond strength

4 Summary and conclusions

The research work presented in this paper is conducted with the aim to investigate the utilisation potential of untreated crumb rubber and recycled concrete aggregate in SCC mixtures. The natural aggregate replacement is a prominent solution not only for possible depletion of natural resources but for CDW and ELTs management as well. Three mixtures were prepared to study the influence that partial replacement of fine NA (0/4 mm) with CR and total replacement of coarse NA (4/8 mm and 8/16 mm) with RCA have on the physical and mechanical properties of self-compacting concrete. The mixtures were made using the two-stage mixing approach to minimize the adverse impacts of

RCA intrusion on fresh and hardened SCC. Untreated crumb rubber was used to replace 20% of fine NA by volume.

Fresh and hardened SCC test results that are presented and discussed in the previous chapter were used to form the following conclusions:

- Both filling and passing ability decreased by replacing the NA with coarse RCA and CR as fine aggregate. However, the mixtures with RCA and CR intrusion satisfied the workability requirements for SCC and reached the same classification as the reference mixture. All three mixtures were classified as SF3 for flowability, VS2 for viscosity and PA2 in terms of passing ability.
- The usage of coarse RCA had a negligible effect on strength values, while the incorporation of CR had decreased compressive and flexural tensile strength values by 26% and 32%, respectively.
- The mixtures with replacement aggregates had up to 10% smaller values of UPV, but far above the lower limit for concrete homogeneity and quality to be classified as "good".
- The pull-off test results showed that bond strength decreased up to 13% for mixtures with RCA and CR intrusion.
- The water tightness of prepared SCC mixtures was tested as a durability indicator – the usage of RCA and CR increased the penetration depth by 133%, but still had values under 30 mm, meaning that mixtures can be classified as "impermeable under aggressive conditions".

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