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EXPERIMENTAL INVESTIGATION OF SCC WITH RECYCLED RUBBER AND RECYCLED CONCRETE AGGREGATE

Abstract

The replacement of natural aggregates (NA) with alternative aggregates in concrete can contribute to the sustainable development of the construction industry. This paper aims to present research investigating the effects of recycled concrete aggregate (RCA) and crumb rubber (CR) utilization on the performance of Self-Compacting Concrete (SCC) mixtures in both fresh and hardened states. For this purpose, SCC mixtures with three different replacement levels of CR - 0%, 20% and 30% by volume for fine aggregate and 100% coarse RCA were prepared along with the reference mixture containing NA only. To assess the effects of NA replacement, the physical and mechanical tests were conducted on prepared SCC mixtures and corresponding results were analysed and compared.

Keywords: Self-Compacting Concrete, rubber aggregate, recycled concrete aggregate

ЕКСПЕРИМЕНТАЛНА ИСПИТИВАЊА САМОУГРАЂУЈУЋЕГ БЕТОНА СА РЕЦИКЛИРАНОМ ГУМОМ И РЕЦИКЛИРАНИМ БЕТОНОМ У СВОЈСТВУ АГРЕГАТА

Сажетак

Замена природних агрегата (NA) алтернативним агрегатима у бетону може допринети одрживом развоју грађевинске индустрије. У раду је презентовано истраживање утицаја рециклираног бетонског агрегата (RCA) и дробљене гуме (CR) на перформансе мешавина самоуграђујућег бетона (SCC) у свежем и очврслом стању. Припремљене су SCC мешавине са три различита нивоа замене CR - 0%, 20% и 30% запремине ситнозрног агрегата и 100% крупног RCA заједно са контролном мешавином која садржи само NA. Да би се проценили ефекти замене NA, извршена су испитивања физичких и механичких карактеристика припремљених SCC мешавина и одговарајући резултати анализирани и упоређени.

Кључне ријечи: самоуграђујући бетон, гумени агрегат, агрегат од рециклираног бетона

1. INTRODUCTION

The construction industry is characterised by a considerable demand for energy and natural resources. In addition, the environmental impact is increased by the waste originated in the processes of construction and demolition. With more than a third of the total amount of the waste produced, construction and demolition waste (CDW) is the largest waste stream in the EU [1]. Bearing in mind, in addition to the environmental effects, the economic and social impact of the construction industry, achieving sustainability in this sector is crucial.

Concrete is the most widely produced and used construction material. The rapid growth of population and urbanization is reflected in the construction at an accelerating rate. Constantly increasing concrete production puts an immense strain on material resources such as natural aggregates (NA), leading to their depletion and causing damage to the environment. In addition to the rapid expansion of the built environment, an increased number of structures that are no longer serviceable has resulted in a huge amount of construction and demolition waste worldwide. Although the data presenting a composition of CDW vary depending on the source, it is unquestionable that concrete contribution is among the major. One of the sustainable and environmentally friendly solutions that address both waste disposal and natural aggregate depletion is the recycling of waste concrete as aggregate in recycled aggregate concrete (RAC).

The apparently unrelatable environmental concern involves the management of end-of-life rubber tyres. Most of the worn-out tyres are discarded or buried in landfills, left to decompose on their own over many decades or sometimes even burned. Discarded tyres are a type of harmful solid waste known as “black pollution”. Rubber tyres are not readily biodegradable and their burning releases poisonous smoke that stays in the air for a long period of time, with a hazardous effect on living creatures. Moreover, residue leftover in form of powder contaminates the soil. As a result of the growing demand for vehicles, the number of waste tyres is continually increasing, making them a global environmental eyesore. A potential solution to this issue and previously mentioned natural aggregate depletion is using recycled rubber as aggregate in concrete.

Recycling of CDW and waste tyres as a partial or total replacement of natural aggregate in concrete is in accordance with circular economy principles, offering a potential way for making the construction industry more sustainable. In addition to beneficial environmental impacts, it provides significant job creation possibilities [2].

Recycled concrete aggregates are fine or coarse aggregates produced by crushing and processing waste concrete originating from demolished old concrete structures. Due to its production process, RCA is a two-phase composite material consisting of original NA and residual cement paste. High porosity and the presence of micro-cracks in old cement paste significantly affects the physical and mechanical properties and performance of RAC. In addition to that, the production process of RAC can potentially contribute to internal cracking [3]. As the main consequence of the above-mentioned aspects, RCA has higher water absorption (WA), causing problems when designing RAC mixtures. Thus, fast and reliable measurement of WA is a highly significant part of the assessment of RCA properties before the production of a new concrete mixture [4, 5]. The amount of water that RCA absorbs during mixture preparation reduces the water-cement ratio, causing workability problems. This should be solved by presoaking RCA in water before mixing all ingredients or adding an extra amount of water calculated based on WA measurements [6]. Because of that, an effective water-cement ratio was conducted, taking into account only the amount of water available for cement hydration, ie the difference between the total amount of water in the mixture and water absorbed by RCA. Recycled aggregate concrete can be described as three-phase material, with the presence of two interfacial transition zones (ITZ) – the “new” between recycled aggregate and cement paste and the “old” within RCA – between residual mortar and original NA (Figure 1). High WA of RCA reduces the water available to react with the cement, affecting the quality of the new ITZ, leading to a decrease in mechanical properties. Tam et al. [7] proposed a new mixing approach in which the whole process is divided into two phases with half of the total water amount introduced in each of them. It was experimentally confirmed that the two-stage mixing approach (TSMA) improves the quality of the new ITZ, enhancing the mechanical properties of RAC.

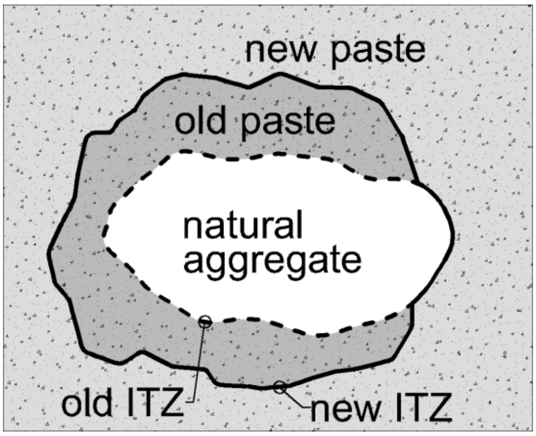

Figure 1. *Micro structure of the recycled aggregate concrete*

Rubber from recycled tyres can be used as a partial replacement of fine or coarse natural aggregate to produce the so-called “rubberized concrete”. Depending on the particle size, rubber aggregate can be classified as chips, crumb rubber and powder rubber [8]. Both fresh and hardened state properties of rubberized concrete are highly affected by the presence and the amount of rubber content. Hydrophobicity, surface roughness, and interlocking among rubber particles lead to higher porosity and entrapped air content in the mixture, potentially causing a workability problem [9]. Introduction of rubber in concrete mixture decrease compressive, flexural tensile and splitting strengths as well as modulus of elasticity, limiting structural application of crumb rubber concrete (CRC) [8–11]. Rubber particles are much more deformable than surrounding cement paste, which results in the development of microcracks in concrete under load. Because of the poor chemical interaction, the adhesion between rubber aggregate and the surrounding cement matrix is weak [8]. Porous ITZ with a lack of bonding reduces the strength values of CRC. The negative effects of NA replacement with rubber aggregates can be mitigated by optimizing the mix ratio and pretreatment of rubber particles with an aim to improve the ITZ. Along with previously mentioned negative effects, using the rubber aggregate can increase the sound insulation, frost resistance, ultimate strain, fatigue life, toughness and enhance the dynamic performance of concrete structures [8–11].

Self-compacting or self-consolidating concrete (SCC) is considered to be the concrete of the future [12]. SCC can be described as high-flowable concrete that is able to completely fill the formwork, encapsulating reinforcement even in congested arrangement, placed and consolidated under its own weight and without segregation or bleeding. Therefore, SCC doesn’t need vibration after pouring, improving the productivity and working conditions during construction. In comparison with normally vibrated concrete (NVC), SCC possesses higher strength and enhanced durability and provides an increasing degree of architectural freedom to carry out more complex geometries in structural design. One of the key factors enabling the development of SCC was the advancement of highly efficient cement dispersants - superplasticizers. The advancements of superplasticizers based on polycarboxylate technology provided the achievement of new capabilities in terms of the production, placement, and service life of high-quality SCC mixtures. Replacing materials from natural resources with industrial by-products can make SCC more sustainable. One of the examples is replacing NA with sustainable alternative aggregates such as RCA and CR. In this paper, the feasibility of such replacement is studied in terms of the performance of SCC mixtures in both fresh and hardened states.

2. EXPERIMENTAL CAMPAIGN

2.1. SCOPE AND OBJECTIVE

The aim of this study is to provide an overview of the ongoing insights in research exploring the influence of the recycled concrete aggregate and crumb rubber on physical and mechanical properties of self-compacting concrete mixtures. In order to examine the feasibility of natural aggregate replacement with recycled aggregate, several concrete mixtures with different replacement levels were prepared.

Aggregate was divided into three standard fractions: I (0/4 mm), II (4/8 mm) and III (8/16 mm). Natural fine aggregate (fraction I) was replaced by CR at three levels of volumetric replacement - 0%, 20% and 30%, while natural coarse aggregate (fractions II and III) was replaced by RCA with replacement ratio of 0% and 100%. A total of four SCC mixtures were defined and their designation and content of aggregate fractions are presented in Table 1.

To compare the impact that combinations of various RCA and CR replacement ratios have on SCC properties, testing of fresh and hardened concrete was carried out and determined properties of studied mixtures were compared to reference concrete.

Table 1. Labels of studied mixtures

	REF	R_0C_{100}	$R_{20}C_{100}$	$R_{30}C_{100}$
CR %	0	0	20	30
RCA %	0	100	100	100

2.2. MATERIALS

Three types of aggregate were used in the concrete mixtures (Figure 2):

- Natural river aggregate separated in three fractions: 0/4 mm, 4/8 mm, 8/16 mm
- Coarse recycled concrete aggregate separated in two fractions - 4/8 mm and 8/16 mm
- Crumb rubber as fine aggregate - 0/4 mm.

Separation of aggregate into fractions was done according to EN 933-1:2012 [13].

Recycled concrete aggregate used in this study was obtained by crushing a 30-year-old base structure for tram tracks. Based on the results of performed tests it was concluded that the original concrete satisfied the conditions for class C35/45 at the moment of crushing. The RCA composition was as follows: 98% base concrete, 1.2% asphalt and 0.8% brick debris. High water absorption of RCA has a negative impact on SCC workability and strength that might be considerable. This is especially the case with fine RCA which has led to it being largely not recommended. According to the above mentioned, only coarse RAC was used in mixtures considered in this experimental campaign with WA values of 3% for fraction II and 4.1% for fraction III.

Crumb rubber - a recycled rubber produced from scrap tires was used as fine aggregate. CR particles were not pre-treated before incorporation into the concrete mixture.

The cement used in this study was Portland-composite cement CEM II/A-M(S-L)42,5R, consisting of 80–94% Portland cement clinker, 6–20% ground slag and limestone and 0–5% gypsum and mineral fillers.

Powder type SCC mixtures were prepared using the fine-grained limestone filler with particle size under 0.125 mm, superplasticizer and water from the city water-works.

Figure 2. *Constituents of studied SCC mixtures – limestone powder (LP), 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)*

2.3. MIXTURES

Four SCC mixtures were defined with the equal effective water-cement ratio – $w/c_{eff} = 0.45$. Due to the higher water absorption of recycled concrete aggregate, mixtures containing RCA had an additional amount of water in comparison with reference concrete. All mixtures are classified as powder type SCC as they were made with high powder content and low water-powder ratio. The quantities of powder materials were kept constant - 630 kg/m^3 of which 380 kg/m^3 of cement and 250 kg/m^3 of filler. Superplasticizer was also applied in the same amount for all mixtures, so similar values of slump flow were expected. The composition of studied mixtures is presented in Table 2 and illustrated in Figure 3.

Table 2. Composition of mixtures (kg/m^3)

Mixture		REF	R_0C_{100}	$R_{20}C_{100}$	$R_{30}C_{100}$
Cement		380			
Limestone powder		250			
Fraction I (0/4 mm)	NA	860	860	688	602
	CR	0	0	71,3	107
Fraction II (4/8 mm)	NA	530	0	0	0
	RCA	0	530	530	530
Fraction III (8/16 mm)	NA	310	0	0	0
	RCA	0	310	310	310
Water		171,0	199,6	199,6	199,6
Superplasticizer		4,4			

Figure 3. *Specimen fracture surface of SCC mixture made with CR as partial replacement of fine aggregate and 100% coarse RCA*

2.4. CONCRETE MIXING AND SPECIMEN PREPARATION

Porosity and water absorption capacity of RCA have significant impact on SCC mixture performance in fresh and hardened states.

The presence of attached old mortar in the RCA consumes more water leading to a lack of water required for hydration of new cement, affecting the quality of ITZ between RCA and new cement paste. In order to improve the new ITZ, two-stage mixing approach (TSMA) was conducted. In TSMA, as the name suggests, the whole mixing process is divided into two parts and the required water is split accordingly into two parts that are added at different timing (Figure 4). At the beginning, fine and coarse aggregates are mixed for 60 seconds. After that, half of the required water is added and mixed for another 60 seconds. In the next stage, the total quantity of cement is introduced into the mixture and mixed for 30 seconds before the remaining half of water is added and final mixture mixed for 120 seconds. The water incorporated in the first stage can generate a thin layer of cement slurry on the RCA surface that penetrates and fills up the pores and cracks in the residual mortar, resulting in denser and stronger ITZ and therefore enhanced mechanical properties of concrete made with RCA. Limestone filler was introduced in the first stage, along with aggregates.

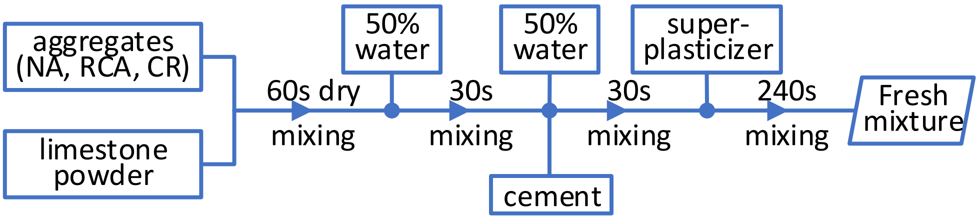

Figure 4. *Mixtures preparation using two-stage mixing approach (TSMA)*

2.5. TESTING METHODS

Performance of four prepared SCC mixtures, both in fresh and hardened state, was evaluated and compared [14].

The filling ability and stability of studied mixtures in the fresh state was determined according to three tests. Flowability and viscosity were quantitatively evaluated by the slump flow and t500 slump time test [15] and V-funnel test [16], while the L-box test [17] was used to measure the passing ability of mixtures.

In hardened state, the following mechanical properties were determined by tests carried out: compressive strength [18], flexural tensile strength [19], static and dynamic modulus of elasticity [20, 21], ultrasonic pulse velocity [22].

Influence of different aggregates on durability of prepared mixtures was assessed based on depth of penetration of water under pressure (concrete water impermeability) [23].

3. RESULTS AND DISCUSSION

3.1. FRESH MIX PROPERTIES

Results of conducted fresh concrete tests are summarized in Table 3.

Bulk density of fresh SCC [24] ranged between 2207 kg/m^3 (mixture $R_{30}C_{100}$ with the highest aggregate replacement ratio) and 2405 kg/m^3 (REF - reference mix). All presented mixtures satisfied both filling ability and passing ability of SCC. However, it was observed that the replacement of coarse NA with RCA (mixture R_0C_{100}), as well as additional replacement of fine NCA with crumb rubber (mixtures $R_{20}C_{100}$ and $R_{30}C_{100}$), decreased the concrete fresh state performance.

Table 3. Properties of mixtures in fresh state

Mixture	Slump flow		V-funnel	L-box
	diameter (mm)	t500 (s)	time (s)	PA (/)
REF	840	2,2	9,3	0,99
R_0C_{100}	790	2,4	12,4	0,88
$R_{20}C_{100}$	770	3,1	13,4	0,88
$R_{30}C_{100}$	730	3,5	16,6	0,85

The slump flow test [15] was performed to assess flowability and flow rate of prepared SCC mixtures in the absence of obstructions. Based on the slump flow diameter values (varied between 730 mm and 840 mm), mixtures were classified in terms of flowability - $R_{30}C_{100}$ mix was classified as SF2, while all the other mixtures as SF3 class. The plastic viscosity is associated with speed of flow, and therefore can be assessed by the t500 slump time. Time t500 ranged between 2,2 s and 3,5 s, so all mixtures are categorized as VS2. V-funnel test [16] results were correlated with t500 values - all mixtures satisfied VF2 class requirements. To notice, with the increment of RCA and CR content flowability showed decreasing trend, while trend of increase was observed in the case of viscosity.

Ability of SCC mixes to flow through tight openings between obstructions like reinforcing bars without segregation or blocking was estimated using the L-box three bar test [17]. Passing ability of studied mixtures was classified as PA2 and no blocking effect was observed. The highest PA value was estimated for REF mix, while mixtures with 100% coarse RCA had similar values, meaning that the decrease of passing ability showed negligible for CR replacement levels up to 30% of fine aggregate volume.

3.2. HARDENED CONCRETE PROPERTIES

Testing on hardened concrete was conducted for all four mixtures after 28 days to determine the compressive and flexural strength, static and dynamic modulus of elasticity, ultrasonic pulse velocity (UPV) and impermeability.

Compressive strength tests were performed on 150 mm cube specimens in accordance with EN 12390-3 [18]. The relationship between mixtures and estimated compressive strength is presented in Figure 5. Mixture R_0C_{100} had slightly lower compressive strength than reference (3%), while mixtures $R_{20}C_{100}$ and $R_{30}C_{100}$ had 26% and 45% lower values respectively.

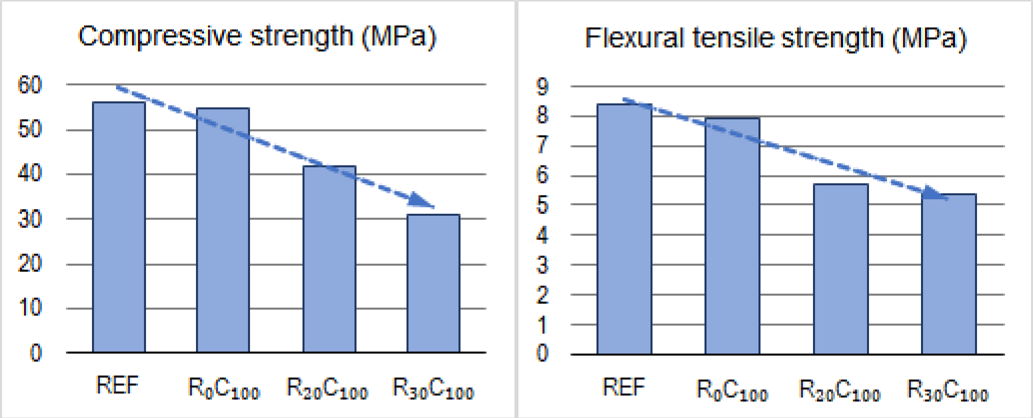

Figure 5. *Compressive strength and flexural tensile strength of prepared SCC mixtures*

Tensile strength of concrete was indirectly measured by three-point-bending test on prismatic specimens (120x120x360 mm, 300 mm span) [19]. Mixture containing natural aggregate only had highest strength, while the total replacement of coarse NA with RCA decreased strength value by 6%. Additional partial replacement of fine NA with CR had much bigger impact on flexural strength – the reduction was up to 36% for mixture with 30% fine CR and 100% coarse RCA.

It is well known that there is general correlation between compressive strength and modulus of elasticity of concrete [25]. Therefore, in accordance with previously presented results, it is expected that the replacement of NA with RCA and CR has significant impact on the elastic modulus of SCC. Static and dynamic modulus of elasticity were obtained for prepared mixtures. Static modulus of elasticity test was carried out in accordance with EN 12390-13 [20], while dynamic modulus was determined based on resonant frequency method [21]. As can be seen from the Figure 6, dynamic and static modulus of elasticity showed similar decreasing trend with the increase of CR and RCA content. In comparison with the reference mixture, mixture R_0C_{100} had 12% lower static modulus and 10% lower dynamic modulus, while $R_{30}C_{100}$ had decrease of 40% and 35% respectively.

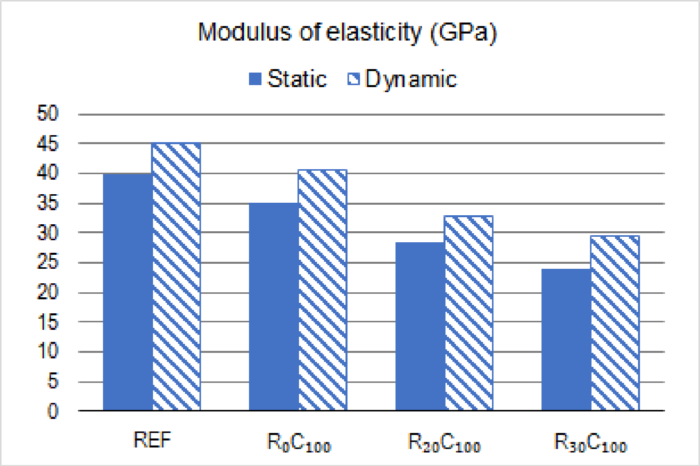

Figure 6. *Static and dynamic modulus of elasticity of studied mixtures*

In order to assess the quality and homogeneity of mixtures containing recycled aggregate, ultrasonic pulse velocity (UPV) test [22] was carried out. The UPV value is very sensitive to the presence of discontinuities in concrete like cracks and voids. As said before, recycled concrete aggregate contains old mortar which has high porosity. Therefore, it is expected that mixtures with replacement of natural aggregate with recycled concrete aggregate have lower values of UPV. The crumb rubber aggregate has a low value of elastic modulus and the addition of CR to mixture increases the air content, which all leads to pulse velocity reduction. The results of UPV measurement conducted on specimens made of considered mixtures are in line with previous considerations (Figure 7). The UPV values varied between 4073 m/s and 4639 m/s; the control mixture had the highest UPV value that decreased by 4% for mixture R_0C_{100}, 10% and 12% for mixtures $R_{20}C_{100}$ and $R_{30}C_{100}$ respectively. In accordance with the UPV classification criterion for concrete quality grading given in Table 4, the REF mixture was classified as “excellent”, while the rest fell within the range of “good”.

Table 4. Classification of concrete quality according to UPV [26]

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

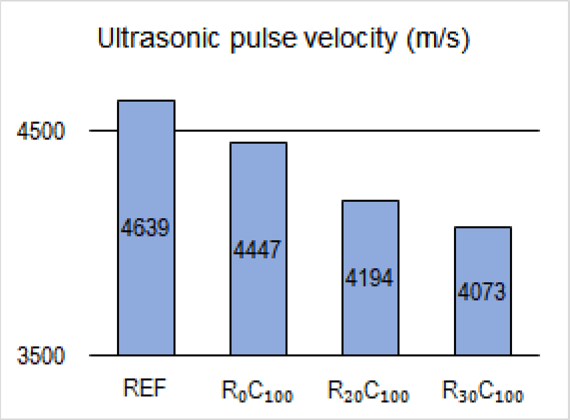

Figure 7. *Ultrasonic pulse velocity (UPV) of prepared mixtures*

The water permeability is a significant indicator of concrete performance regarding durability – increased water tightness is of critical interest for freeze-thaw and chemical attack resistance. The influence of NA replacement with RCA and CR on water permeability of SCC mixtures was assessed on cylindrical specimens (150 mm x 150 mm) based on the depth of penetration of water under pressure. Porosity and high water absorption of RCA have a substantial influence on permeability, making it directly related to the RCA replacement level [3, 6]. However, in the case of the TSMA, the cement gel surrounding the RCA reduces the porosity of old adhered mortar and provides impermeability improvement [27]. The incorporation of crumb rubber as aggregate increases water permeability [8]. Because of the weak bond between CR and surrounding cement paste, voids and micro-cracks in ITZ, the depth of pressurized water penetration into the concrete increases. The conducted testing (Figure 8) showed that coarse RCA and fine CR aggregates usage increases penetration depth. Based on these results, mixtures were classified with respect to their water permeability (SRPS U.M1.206 [28]): the reference mixture belongs to highest class – “V-III”, R_0C_{100} and $R_{20}C_{100}$ to class “V-II”, while the average value of penetration depth for $R_{30}C_{100}$ slightly exceeds the 30 mm threshold, classifying it as “V-I”. Despite the decrease in water permeability, all mixtures had penetration depths of less than 50 mm which classifies them as “impermeable”, while R_0C_{100} and $R_{20}C_{100}$ can be classified as “impermeable under aggressive conditions” thanks to depths under 30 mm [25].

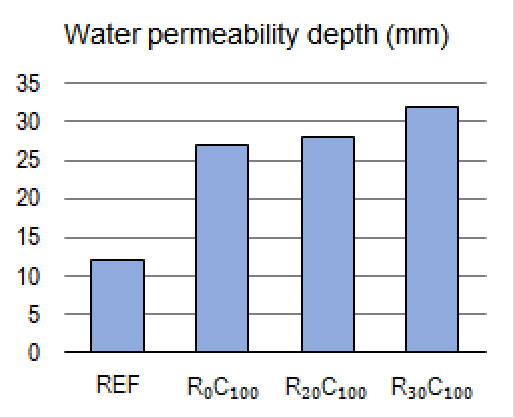

Figure 8. *Water permeability test – depth of penetration of water under pressure*

4. SUMMARY AND CONCLUSIONS

This study was aimed to investigate the influence of coarse recycled concrete aggregate and untreated crumb rubber as a partial fine aggregate replacement on SCC properties. The series of tests was conducted on specimens made from four different SCC mixtures: the reference mixture prepared with only natural aggregates and three mixtures with 100% coarse RCA and volumetric replacement of fine NA with CR at three levels – 0%, 20% and 30%. The mixtures were made using the two-stage mixing approach (TSMA), with the addition of limestone filler in premix and the equal effective water-cement ratio of 0.45 and the maximum aggregate particle size set at 16 mm. To compare the impact of two natural aggregate substitutions on fresh as well as hardened concrete, a range of measurements were carried out on prepared mixtures in fresh and hardened state. Based on the results and discussion presented in previous chapter, the following conclusions can be drawn:

- By replacing the coarse NA with RCA and with the increment of CR content, the flowability decreased while viscosity increased. Mixture $R_{30}C_{100}$ reached SF2 flowability class, while the other mixtures were classified as SF4. According to flow time values measured during the slump flow and V-funnel tests, all mixtures belonged to VS2/VF2 class.
- In terms of passing ability, the replacement of NA had an acceptable impact - all mixtures achieved the PA2 level. The mixture with coarse RCA had passing ability decreased by 11%, while the incorporation of CR had negligible results on the performance.
- The coarse RCA replacement had a minor effect on the values of compressive and flexural tensile strength. Contrary to that, untreated rubber aggregate considerably decreased both strength values.
- The static modulus of elasticity decreased with RCA and CR content increment up to 40%. Similar decreasing trend was observed in case of dynamic modulus of elasticity.
- According to UPV values, all three mixtures containing replacement aggregate showed quality graded as “good” with velocities high above the threshold, while the reference mixture had “excellent” quality.
- The usage of RCA and CR significantly increased the water permeability – up to 167% for highest level of replacement. The biggest change was obtained for mixture with 100% coarse RCA – penetration depth increased by 125%. Therefore, in terms of water permeability, RCA and CR can negatively impact the durability of concrete. However, mixtures with CR replacement levels up to 20% were classified as “impermeable under aggressive conditions” and $R_{30}C_{100}$ as “impermeable”.

LITERATURE

[1] “Waste statistics.” Internet: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics, [10.02.2022.].

[2] European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, *3rd Raw Materials Scoreboard : European innovation partnership on raw materials*, Publications Office, 2021, Available: https://data.europa.eu/doi/10.2873/680176, [10.02.2022.].

[3] M. Pepe, A Conceptual Model for Designing Recycled Aggregate Concrete for Structural Applications. Springer Theses, 2015.

[4] N. Tošić, A. Savić, and V. Carević, “A method for the continuous measurement of water absorption of coarse recycled aggregates,” in *Proceedings of the ASES Symposium 2016*, Zlatibor, Serbia, Sep. 2016, pp. 1023-1030.

[5] A. Savić, M. Aškrabić, B. Kovačević, and D. Pavlović, “Properties of SCC Mixtures with Coarse Recycled Aggregate,” in *Proceedings of 15th Conference hosted by Association of Structural Engineers of Serbia - ASES*, Zlatibor, Serbia, Sep. 2018, pp. 265-274.

[6] M. C. Rao, S. K. Bhattacharyya, and S. V. Barai, *Systematic Approach of Characterisation and Behaviour of Recycled Aggregate Concrete*. Springer Transactions in Civil and Environmental Engineering, 2019.

[7] V. W. Y. Tam, X. F. Gao, and C. M. Tam, “Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach,” *Cement and Concrete Research*, vol. 35, no. 6, pp. 1195–1203, 2005.

[8] J. Xu, Z. Yao, G. Yang, and Q. Han, “Research on crumb rubber concrete: From a multi-scale review,” *Construction and Building Materials*, vol. 232, pp. 117282-117306, 2020.

[9] S. Raffoul, R. Garcia, K. Pilakoutas, M. Guadagnini, and N. F. Medina, “Optimisation of rubberised concrete with high rubber content: An experimental investigation,” *Construction and Building Materials*, vol. 124, pp. 391–404, 2016.

[10] Y. Li, S. Zhang, R. Wang, and F. Dang, “Potential use of waste tire rubber as aggregate in cement concrete – A comprehensive review,” *Construction and Building Materials*, vol. 225, pp. 1183–1201, 2019.

[11] H. Liu, X. Wang, Y. Jiao, and T. Sha, “Experimental Investigation of the Mechanical and Durability Properties of Crumb Rubber Concrete,” *Materials*, vol. 9, no. 3, 2016.

[12] S. Mindess, “Self-compacting concrete (SCC)” in *Developments in the formulation and reinforcement of concrete*, 2nd edition. Woodhead Publishing, Duxford, United Kingdom, 2019.

[13] EN 933-1:2012 - Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method. CEN, Brussels, 2012.

[14] EFNARC. (2005.). *The European Guidelines for Self-Compacting Concrete; Specification, Production and Use.* [On-line]. Available: www.efca.info/download/european-guidelines-for-self-compacting-concrete-scc/?wpdmdl=652 [10.02.2022.]

[15] EN 12350-8:2019 - Testing fresh concrete - Part 8: Self-compacting concrete - Slump-flow test. CEN, Brussels, 2019.

[16] EN 12350-9:2010 - Testing fresh concrete - Part 9: Self-compacting concrete - V-funnel test. CEN, Brussels, 2010.

[17] EN 12350-10:2010 - Testing fresh concrete - Part 10: Self-compacting concrete - L box test. CEN, Brussels, 2010.

[18] EN 12390-3:2019 - Testing hardened concrete - Part 3: Compressive strength of test specimens. CEN, Brussels, 2019.

[19] EN 12390-5:2019 - Testing hardened concrete - Part 5: Flexural strength of test specimens. CEN, Brussels, 2019.

[20] EN 12390-13:2021 - Testing hardened concrete - Part 13: Determination of secant modulus of elasticity in compression. CEN, Brussels, 2021.

[21] SRPS U.M1.026:1993 - Concrete - Determination of the dynamic modulus of elasticity and Poisson’s ratio. Institute for standardization of Serbia, Belgrade, Serbia, 1993.

[22] EN 12504-4:2021 - Testing concrete in structures - Part 4: Determination of ultrasonic pulse velocity. CEN, Brussels, 2021.

[23] EN 12390-8:2019 - Testing hardened concrete - Part 8: Depth of penetration of water under pressure. CEN, Brussels, 2019.

[24] EN 12350-6:2019 - Testing fresh concrete - Part 6: Density. CEN, Brussels, 2019.

[25] A. M. Neville, *Properties of concrete, 5th ed.* Harlow, England: Pearson, 2011.

[26] British Standards Institution, Specification for testing concrete. Part 203. Part 203. British Standards Institution, London, 1986.

[27] V. W. Y. Tam and C. M. Tam, “Assessment of durability of recycled aggregate concrete produced by two-stage mixing approach,” Journal of Materials Science, vol. 42, no. 10, pp. 3592–3602, 2007.

[28] SRPS U.M1.206:2013 - Specification, performance, production and conformity - Rules for the implementation of SRPS EN 206-1. Institute for standardization of Serbia, Belgrade, Serbia, 2013.