CIVIL ENGINEERING JOURNAL

Article no. 23

THE CIVIL ENGINEERING JOURNAL 3-2025

HIGH-PERFORMANCE CONCRETE WITH RECYCLED CONCRETE AGGREGATES: EFFECTS OF PRODUCTION TECHNOLOGY ON MECHANICAL PROPERTIES AND SHRINKAGE

Bohdan Sousedík, Vlastimil Bílek and Oldřich Sucharda

VSB - Technical University of Ostrava, Faculty of Civil Engineering, Department of Building Materials and Diagnostics of Structures, Ostrava-Poruba, Ludvíka Poděště 1875/17, 70800, Czech Republic; bohdan.sousedik@vsb.cz, vlastimil.bilek@vsb.cz, oldrich.sucharda@vsb.cz

Received: 04.06.2024
Received in revised form: 18.03.2025
Accepted: 30.08.2025

ABSTRACT

This research project explores the potential of incorporating fine recycled concrete aggregates (RCA) into high-performance concrete (HPC). The primary objective of this study is to assess the mechanical properties, shrinkage behaviour, and production methodologies, with a particular emphasis on the approach to water dosing. A secondary objective is to assess the potential of internal curing using RCA. The experimental program encompasses concrete mixtures with varying proportions of recycled material and water content. The compressive and bending strength values of the samples were measured, and all samples were monitored for shrinkage over a period of 1 - 28 days. Contrary to the prevailing assumption that the replacement of natural aggregates with recycled ones results in a reduction in strength, this study proposes an alternative conclusion. Specifically, the study indicates that mixtures containing 15% natural aggregate, when substituted with RCA, demonstrate higher strength than those composed exclusively of natural aggregates.

KEYWORDS

High Performance Concrete, Recycled Concrete Aggregates (RCA), Shrinkage, Mechanical properties, Production technology

INTRODUCTION

In the contemporary field of materials engineering for construction, there is a growing emphasis on the use of high-strength and high-performance concrete (HPC) [1, 2]. This trend is driven by the recognition of the numerous advantages offered by HPC, including superior mechanical properties, excellent durability, and extended service life. Moreover, the use of HPC aligns with the increasing demand for innovative technological solutions in construction [3, 4].

A key criterion for the sustainable development of the construction industry is the reduction of energy consumption and the efficient use of available raw materials [5, 6]. Given the limited availability of natural resources, the incorporation of recycled materials plays a vital role in promoting sustainability. It is particularly relevant in the construction industry, which is a major producer of waste, especially construction and demolition waste.

The utilisation of recycled concrete aggregates (RCA) represents an important component of the circular economy and the sustainable development of concrete and concrete structures [7]. The need to preserve natural aggregate resources is becoming increasingly urgent, a concern that is also addressed through life cycle assessment (LCA) analyses [8].

RCA can serve as a partial replacement for natural aggregates; however, several challenges must be carefully considered [9, 10]. The quality of RCA is generally lower than that of high-grade natural aggregates, particularly in terms of mechanical performance. Additionally, RCA typically exhibits a higher water absorption capacity.

According to established standards [11, 12], it is generally acceptable to replace a portion of coarse natural aggregates with coarse RCA. However, the use of fine RCA fractions—such as the 0/4 mm size range—poses particular challenges [13, 14]. These fine particles tend to have high water absorption, irregular grain shapes, and rough surface textures, which often lead to reduced workability in fresh concrete.

Nevertheless, this high absorption capacity can also be leveraged in concrete mixtures, for example, to support internal curing.

As noted by Aïtcin [15], referring to the earlier work of Powers [16], water interacts with Portland cement through two distinct mechanisms:

- Chemically, by reacting with cement compounds to form calcium silicate hydrate (C-S-H) gel, portlandite, and other hydration products.
- Physically, by becoming incorporated as "gel water"—water molecules that are physically bound within the hydration products, yet do not participate in chemical reactions.

Furthermore, a reduction in the volume of hardened cement paste is observed during the hydration process. This volume contraction has been shown to result in an approximate 8% decrease relative to the initial paste volume. The phenomenon is accompanied by an increase in concrete porosity, characterised by the formation of numerous capillary pores.

It has been established that, if the water-to-cement ratio (w/c) is equal to or greater than 0.42, as referenced in [15], then concrete will contain sufficient water to facilitate hydration and the saturation of fine capillaries with water. The phenomenon of volume contraction is characterised by its diminutive scale. However, in the event of the water-to-cement ratio being less than 0.42, the stress exerted by the menisci in fine capillaries is known to induce the shrinkage of hardened cement paste [15-18].

High-performance concrete has a water-to-cement ratio (w/c) of less than 0.42, which results in a significant effect of self-desiccation. In certain cases, the use of internal curing has been employed as a solution to this problem [19, 20, 21]. The process entails the incorporation of porous aggregates that have been saturated with water into the concrete mixture. During the process of self-desiccation, water is consumed and subsequently replaced by water from porous aggregates. Water-saturated expanded clays are typically employed in the self-curing of concrete. However, the utilisation of RCA is a potential avenue for exploration. The strength values of RCA can exceed those of expanded clay, and RCA exhibits a high level of absorption. The use of a minute proportion of RCA can be regarded as a highly advanced method of employing waste and problematic materials.

METHODOLOGY FOR THE EXPERIMENTAL PROGRAM

This article presents three different methods of incorporating recycled concrete aggregates (RCA) into high-performance concrete (HPC) [22] and [23]:

Dry method

RCA has been used to replace a proportion of the natural aggregates in the mixture. This has been achieved by adding RCA to the dry mixture, without the need for water or an increase in the quantity of water used during the mixing process. It is evident that the water absorption capacity of porous aggregates will result in an effective w/c that is lower than that of concrete that does not incorporate porous aggregates. This is due to the fact that the water absorption capacity of the aggregates is greater than that of the natural sand. What will be the effect? Firstly, it is important to note that the workability of the mixture could be suboptimal. The strength values of HPC can be elevated (lower w/c), but the presence of inadequate water content within HPC can have harmful effects on hydration, resulting in shrinkage and the formation of cracks. Furthermore, the strength values of RCA could be lower than those of concrete with natural aggregates, which would also affect the resulting strength values. What will be the result?

Water method

In this approach, RCA is incorporated alongside an increased quantity of mixing water to achieve a workability comparable to that of a reference mixture composed solely of natural aggregates. During mixing, only a portion of the additional water is absorbed by the RCA, resulting in a higher effective water-to-cement ratio (w/c). Consequently, the degree of cement hydration is enhanced. This method of water addition is regarded as the most practical and convenient for application in real-world concrete production.

Pre-soaked method

Prior to incorporation into the concrete mixture, RCA was soaked in water for 24 hours. Although this method is regarded as the most precise in controlling the aggregate moisture content, it can pose practical challenges in implementation.

The objective of this study is to compare the aforementioned methods of incorporating RCA regarding their effects on both flexural and compressive strength values, as well as concrete shrinkage.

MATERIALS

Recycled concrete aggregates (RCA)

Recycled concrete aggregates (RCA) with a fraction size of 0/4 mm, produced by DESTRO company and illustrated in Figure 1, were employed as a replacement for natural sand. The RCA was characterised in accordance with the requirements of ČSN EN 12620+A1 (Aggregates for concrete) [12]. The performed tests included sieve analysis, bulk density determination, and water absorption capacity measurement. Prior to use, the RCA samples were oven-dried at a temperature of (105 ± 5) °C. Density and absorption capacity were measured using the pycnometric method [24]. Concrete samples were produced using both dried RCA and RCA pre-soaked in mixing water for 24 hours.

Fig. 1 – Fraction 0/4 RCA delivered by DESTRO.

A sieve analysis of the recycled concrete aggregates was conducted in accordance with the standard ČSN EN 933-1 (Determination of particle size — sieve analysis of aggregates) [25]. The results are presented as a grading curve in Figure 2.

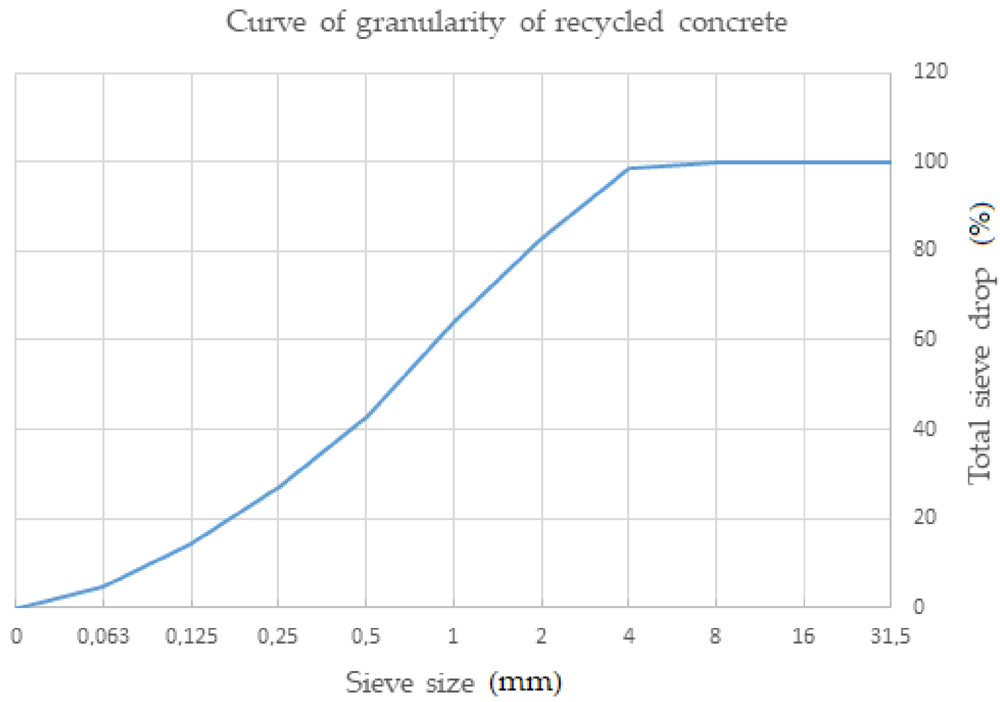

Fig. 2 – Grading curve of recycled concrete aggregates (RCA)

Basic raw materials for concrete production

The concrete was composed of fine natural aggregates, specifically sand 0/4 mm, sourced from the Polešovice gravel plant. This sand meets the requirements for use in concrete and mortar applications [24-25]. Prior to use, the aggregate was oven-dried at (105 ± 5) °C to achieve near-zero moisture content. The absorption rate of this sand was determined to be 1.5%.

Ordinary Portland cement CEM I 42.5 R, manufactured at the Cement Hranice cement factory, was employed in the concrete production.

Potable water from the municipal water supply was used as the mixing water.

Superplasticiser BASF MasterGlenium ACE 300, based on polycarboxylate ethers, was employed to improve the workability of the concrete.

Metakaolin Metaver I (NEWCHEM) was incorporated as a pozzolanic admixture, while finely ground limestone was serving as a second admixture.

Composition of concrete mixes

Eight high-performance concrete mixtures were carefully designed and prepared. Two reference mixtures were produced: one using oven-dried natural sand and the other employing natural sand pre-soaked in water. The use of RCA in both dried and soaked forms address concerns related to its potential deterioration.

A series of alternative mixtures were formulated by partially replacing natural sand with RCA at replacement levels of 10% and 15%. Initially, the dry method was applied, where RCA was added without additional water. Subsequently, two mixtures containing the same proportions of RCA were prepared with increased mixing water to achieve workability similar to the reference mixes. In the final set of mixtures, natural sand was replaced by RCA at 10% and 15%, respectively, with the RCA having been soaked in water for 24 hours prior to mixing.

The compositions of these concretes are shown in Table 1.

Tab. 1 - Composition of high-performance concretes

1 m³	Designation of mixes			
	Reference	10% Recycled	10% Recycled + water	10% Soaked recycled + water
Sand Polešovice 0–4 [kg]	960	864	864	864
Cement CEM I 42.5 R [kg]	650	650	650	650
Metakaolin [kg]	75	75	75	75
Limestone [kg]	60	60	60	60
Recycled concrete 0–4 [kg]	0	96	96	96
Water [kg]	165	165	175	175
Plasticizer Glenium 300[kg]	8	8	8	8

1 m³	Designation of mixes			
	Sand	15% Recycled	15% Recycled + water	15% Soaked recyclated + water
Sand Polešovice 0–4 [kg]	960	816	816	816
Cement CEM I 42.5 R [kg]	650	650	650	650
Metakaolin [kg]	75	75	75	75
Limestone [kg]	60	60	60	60
Recycled concrete 0–4 [kg]	0	144	144	144
Water [kg]	180	165	180	180
Plasticizer Glenium 300 [kg]	8	8	8	8

Testing procedure

Following the mixing process, the concrete was cast into steel moulds measuring 40 × 40 × 160 mm. The moulds were compacted, and a glass plate was placed on top to ensure a flat surface. Subsequently, the specimens were cured for 24 hours in a climate chamber maintained at a temperature with relative humidity exceeding 95%. After demoulding, the specimens were wrapped in polyethylene (PE) foil. To verify the absence of water evaporation during curing, the specimens were weighed both before wrapping and after removal of the aluminium foil at the end of the curing period.

The evaluation of volume alterations was conducted utilising the FORMTEST Mituloyo apparatus, as depicted in Figure 3. In this device, the deformation of the joists is measured on steel spikes that are concreted into the joist during the casting process. The use of steel spikes as measuring bases within the forms during the casting process facilitates the measurement of deformations from the initial day of mixing, thereby providing a reference point for comparison with previous values. Subsequent measurements were conducted on the same days as for ordinary concrete, i.e. at the ages of 2, 3, 4, 7, 11, 18, 25 and 28 days. The measurement was therefore carried out on beams with dimensions of 40x40x160 mm3, with the measurement being taken on three specimens in each case. The measurement of each specimen was conducted in both directions, i.e. twice. The instrument's sensitivity, as evidenced by its capacity to detect a deformation of one micrometer, necessitated meticulous calibration with a wooden standard following each measurement to ensure accuracy and reliability. During the entirety of the measurements, the temperature and humidity levels in the laboratory environment were meticulously regulated. However, these parameters exhibited minimal fluctuations throughout the measurement process, with all values being recorded at a temperature of (23 ± 2) °C and a humidity level of (50 ± 5) %.

Fig. 3. – FORM+TEST strain gauge.

RESULTS

Consistency of high-performance concrete

The consistency values of the concretes are shown in Table 2. Mixtures without additional water tend to exhibit reduced workability, as seen in mixtures A, B, D, and F. This reflects a real-world scenario where the water absorption capacity of recycled concrete aggregate (RCA) is not properly accounted for. In addition to absorption, the coarser surface texture of RCA compared to sand further contributes to the decline in workability. The issue was addressed by adding water to achieve a consistency comparable to the reference mixture (see mixtures A, C, E, and F). However, due to the rougher surface of RCA, more water had to be added than the amount indicated by laboratory-determined absorption. While the measured absorption of RCA was 10%, the effective water addition corresponded to 20%. Concrete made with pre-saturated RCA also showed inferior workability compared to the reference mix F, likely due to the angular shape and rough surface of RCA particles.

Tab. 2 - Workability of high-performance concretes

	Cone flow [mm]		Mean value [mm]
(A) Reference	250	250	250
(B) 10% Recycled	160	170	165
(C) 10% Recycled + water	250	250	250
(D) 15% Recycled	120	130	125
(E) 15% recycled + water	230	250	240
(F) Reference to soaked	250	250	250
(G) 10% Recycled + water soaked	170	170	170
(H) 15% Recycled + water soaked	180	190	185

Strength of high-value concretes

Table 3 presents the average bending and compressive strength values of the concretes, which are graphically illustrated in Figure 4.

Tab. 3 - Strengths of high-performance concretes

	[MPa]		[kg/m³]
	Bending strength	Compressive strength	Volume density
(A) Reference	10.7	102.4	2373
(B) 10% Recycled	10.6	93.6	2364
(C) 10% Recycled + water	10.4	99.3	2385
(D) 15% Recycled	10.7	88.8	2402
(E) 15% recycled + water	10.1	95.7	2385
(F) Reference to soaked	10.9	99.3	2294
(G) 10% Recycled + water soaked	10.2	94.5	2325
(H) 15% Recycled + water soaked	9.9	96.4	2320

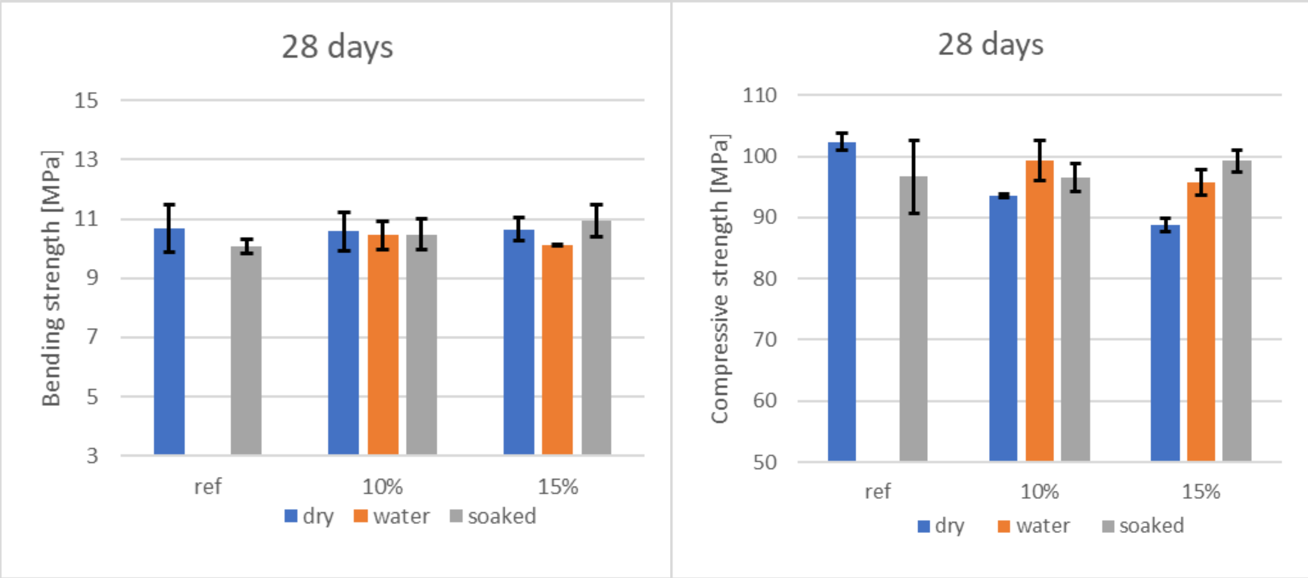

Fig. 4 – Bending and compressive strength values of prepared fine-grained high-performance concretes with error bars representing standard deviation.

The bending strength values are similar regardless of the method used to dose RCA, which is an interesting observation. This may be attributed to the high-water absorption capacity of RCA. Consequently, there is no significant difference between dosing with pre-soaked RCA and adding water to dry RCA. Furthermore, bending strength values remain nearly constant across different RCA dosages. This suggests that the intrinsic strength of RCA likely does not play a significant role in bending strength. Instead, the self-curing ability of RCA may be more influential. A similar trend is observed for compressive strength. While dry RCA reduces compressive strength as its dosage increases, concretes with RCA and added water, as well as those with pre-soaked RCA, exhibit comparable compressive strengths. This may be interpreted as a positive effect of RCA's self-curing properties.

The compressive strength of concrete without added mixing water is slightly lower than that of the reference mix A. This is likely due to the lower strength of the RCA combined with poorer compaction caused by the reduced consistency. Concrete with a higher amount of mixing water shows increased strength, suggesting that the extra water is absorbed by the RCA and does not affect the effective water-to-cement ratio. Similarly, concretes with pre-soaked RCA exhibit strength values comparable to the reference concrete F.

Shrinkage of high-performance concrete with RCA

The results of relative deformation for the individual mixtures are presented in Figures 5 and 6. The graphs are divided according to the recycled material content, with each including a comparison to the reference mixture.

As shown in the graphs, the addition of RCA did not significantly reduce shrinkage, with the smallest shrinkage observed in the reference mix. This outcome may be influenced by several factors: (1) a substantial portion of shrinkage likely occurs during the first day of curing, which was not captured by the measurements; (2) the shrinkage primarily involves changes in absolute volume, while macroscopic dimensional changes are less pronounced; and (3) differences in the water-to-cement ratio (w/c) due to added water are insufficient to cause notable variations in shrinkage.

The shrinkage of concretes containing pre-soaked RCA is presented in Figure 7. The values are nearly identical to those observed in the previous cases of concretes without additional water or with increased mixing water. The concrete with 15% pre-soaked RCA exhibited slightly higher initial shrinkage; however, at 28 days, the shrinkage was slightly lower than that of the reference concrete.

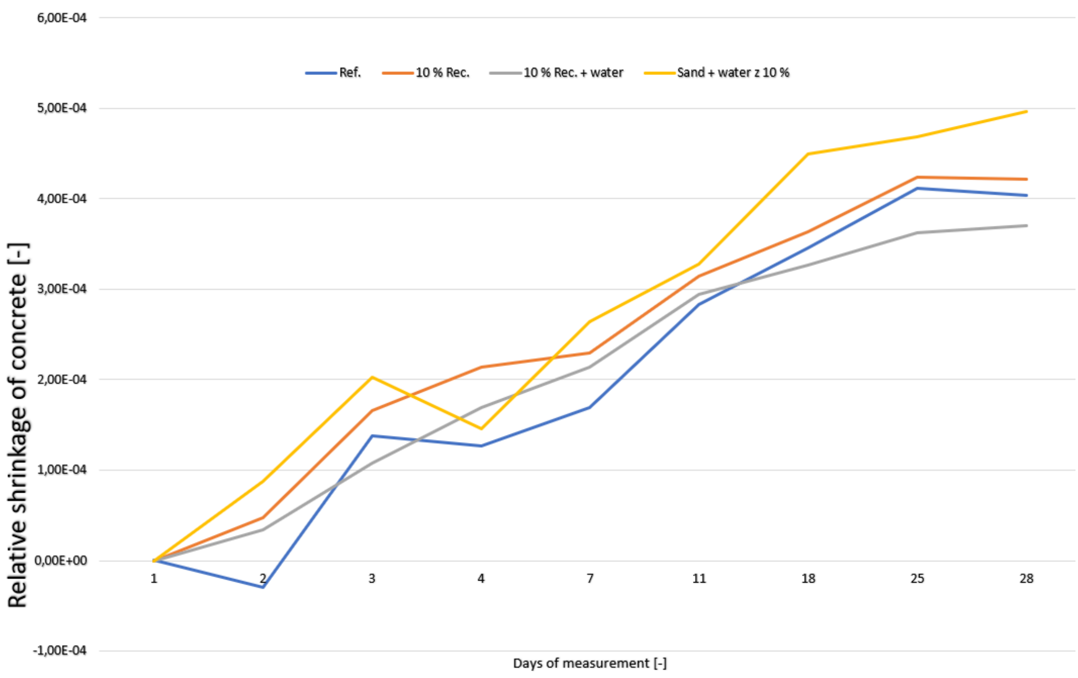

Fig. 5 – Relative shrinkage of concretes with 10% RCA.

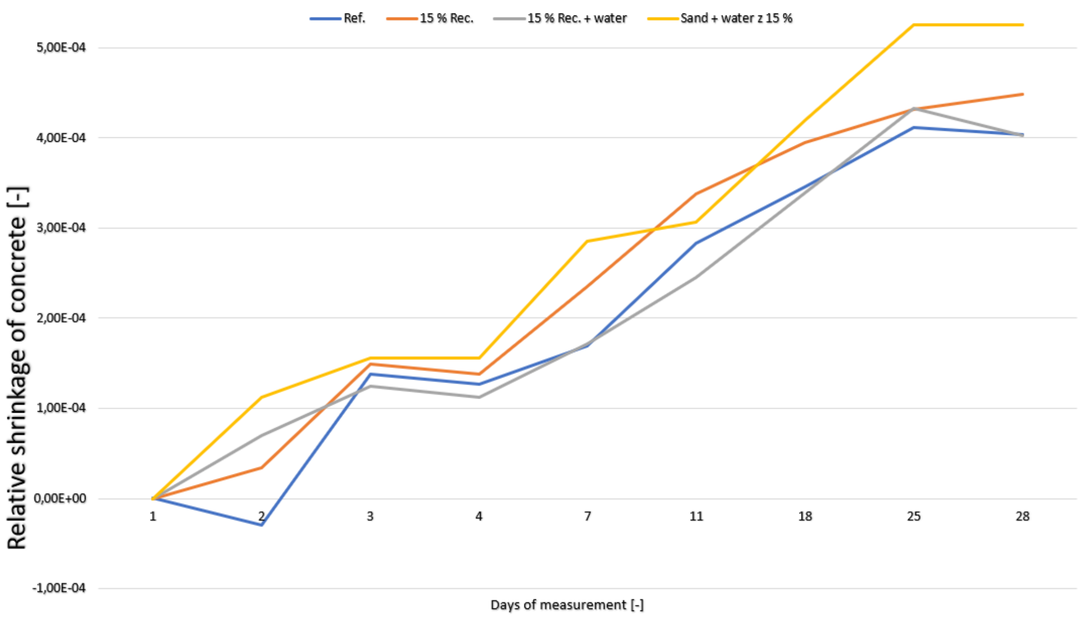

Fig. 6 – Relative shrinkage of concrete with 15% RCA

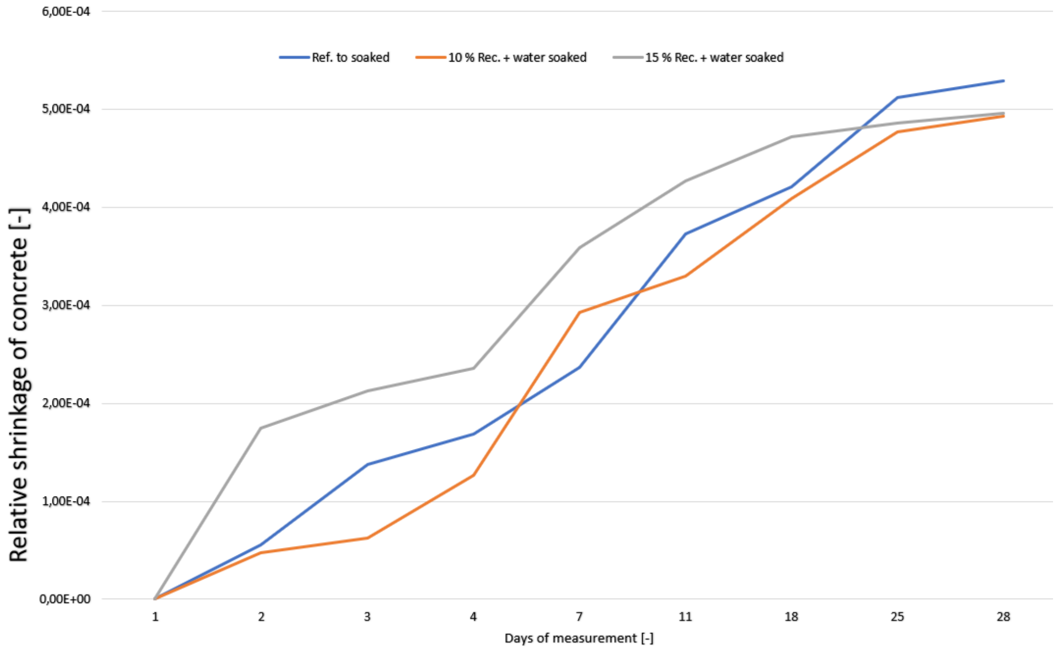

Fig. 7 – Relative shrinkage of concrete with soaked RCA.

CONCLUSION

The aim of this work was to determine whether the addition of recycled concrete to high-performance concrete, as a partial replacement for natural aggregate, affects concrete shrinkage as well as its flexural and compressive strength.

The results of the analysis of the 0/4 fraction of recycled concrete showed that its use in interior applications has no significant effect on shrinkage, regardless of the method of water dosing. Surprisingly, the influence remains very small even when RCA is used in a saturated state or with excess water of up to 21%. It should be noted that shrinkage was not measured during the first day of curing. The results may vary considerably depending on the volume change that occurs during this early stage.

The effect of replacing 10% and 15% of natural aggregates with RCA on compressive and flexural strength is not significant. The dependence of strength on the method and amount of added water is unexpectedly low.

The properties of RCA, particularly its fine fractions, can vary considerably. However, it is not appropriate to automatically consider fine RCA fractions (maximum aggregate size < 4 mm) as poor-quality material unsuitable for use in concrete, especially high-performance concrete, as suggested in ČSN EN 206+A2, Annex E [26].

Further research will focus primarily on measuring shrinkage during the first day of curing and on assessing the impact of RCA on concrete durability. It is also necessary to use and compare a range of different RCA sources.

ACKNOWLEDGEMENTS

This article has been achieved with the financial support of the Ministry of Education, specifically by the Student Research Grant Competition of the Technical University of Ostrava under identification number SP2025/094. This paper was created also as part of the project No. CZ.02.01.01/00/22_008/0004631. Materials and technologies for sustainable development within the Jan Amos Komensky Operational Program financed by the European Union and from the state budget of the Czech Republic.

REFERENCES

[1] Aitcin, P.C. High Performance Concrete; CRC Press: Boca Raton, FL, USA, 2018; ISBN 978036786598.

[2] Moravcik, M.; Bujnakova, P.; Bahleda, F. Failure and damage of a first-generation precast prestressed bridge in Slovakia. Struct. Concr. 2020, 21, 2353–2362.

[3] Fiala, C.; Hejl, J.; Tomalová, V.; Bílek, V.; Pavlů, T.; Vlach, T.; Volf, M.; Novotná, M.; Hajek, P. Structural Design and Experimental Verification of Precast Columns from High Performance Concrete. Adv. Mater. Res. 2015, 1106, 110–113.

[4] Mateckova, P.; Bilek, V.; Sucharda, O. Comparative Study of High-Performance Concrete Characteristics and Loading Test of Pretensioned Experimental Beams. Crystals 2021, 11, 427

[5] Kashino, N., Ohama, Y., RILEM International Symposium Environmental Conscious Materials and Systems for Sustainable Develop-ment, pp.179-186, 2004Schokker A., J., et. al., The Sustainable Concrete Guide Applications, US GREEN CONCRETE COUNCIL, page 183, 2010. ISBN: 978-0-87031-401-8

[6] Schokker A., J., et. al., The Sustainable Concrete Guide Applications, US GREEN CONCRETE COUNCIL, page 183, 2010. ISBN: 978-0-87031-401-8

[7] Xiao, J. Zh., Li, JB, Zhang, Ch., On relationship between the mechanical properties of recycled aggregate concrete: On over-view, Materials and Structures, 39, pp. 655-664, 2006.

[8] Finnveden G., Hauschild MZ, Ekvall T., Guinée J., Heijungs R., Hellweg S., Koehler A., Pennington D., Suh S. Recent devel-opments in Life Cycle Assessment. Journal of Environmental Management, 91 (1), pp. 1 - 21, 2009. DOI: 10.1016/j.jenvman.2009.06.018

[9] Collepardi, M, The New Concrete, Grafiche Tintoretto, p. 436. 2010. ISBN 8890377720.

[10] Aïtcin, P.-C.; Mindess, S. Sustainability of Concrete. Spon Press: New York, NY, USA, 2011.

[11] Pavlů, T., Kočí, V., Hájek, P. Environmental Assessment of Two cycles of Recycled Aggregate Concrete, Sustainability 2019, 11, 6185, doi: 10.3390/su11216185.

[12] ČSN EN 12620+A1. Aggregate for concrete. Prague: Czech Standardization Institute, 2008

[13] Florea, M.V.A., Browers, H.J.H. Properties of Various Size Fraction of Crushed Concrete Related to Process Conditions and Re-USE, Cem. Concr, Res. 2013, 52, 11-21, doi:10.1016/j.cemconcres.2013.05.005

[14] Fan, C.-C, Huang, R., Hwang, H., Chao, S.-J. The Effect of Different Fine Recycled Concrete Aggregates on the Properties of Mortar, Materials 2015, 8, 2658-2672, doi:10.3390/ma8052658.

[15] Aïtcin, P.-C., The Problems with High Strengths and Low w/c Ratio Concretes, Cement-Wapno-Beton, 2/2014, pp.127-137

[16] Powers, T.C. The properties of fresh concrete, John Wiley and Sons, New York 1968, 664p

[17] Jensen, O.M., Hansen, P.E., Water-entrained cement-based materials I. Principles and theoretical background, Cement and Concrete Research 31, 2001 pp.647-654

[18] Tazawa, E. Autogenous shrinkage of concrete, F FN Spon, London, 1998, 406p

[19] Aïtcin, P.-C. Internal Curing, Proceedings of 3rd Int.Symposium Non.Traditional Cement Concrete, Bilek and Kersner (eds) 2008, Brno (Czech Republic) ISBN 978-80-214-3642-8

[20] Mahmoodi,S., Sadeghian,P. Self-Healing Concrete: A Review of Recent Research Developments and Existing Research Gaps, 7th International Conference on Engineering Mechanics and Materials, CSCE Annual Conference, 2019, Laval, QC, Canada, MA11-1 – MA11-10

[21] Al Saffar, D.M., Al Saad, A.J.K., Tayeh, B.A. Effect of internal curing on behavior of high performance concrete: An overview, Case Studies in Construction Materials 10, 2019. doi./10.1016/j.cscm.2019.e0022

[22] Experimental program (https://zenodo.org/) doi:10.5281/zenodo.11475054

[23] Soudedik, B. A possibility of internal curing of HPC using recycled concrete or bricks, diploma thesis, VSB - Technical University of Ostrava, 2018

[24] EN 1097-6 Tests for mechanical and physical properties of aggregates, Part 6: Determination of particle density and water absorption, Prague, Czech Standardization Institute, 2014

[25] EN 933-1. Testing of geometric properties of aggregates - Part 1: determination of grain size - mesh analysis. Prague: Czech Standardization Institute, 2012.

[26] CSN EN 206+A2, Concrete - Specifications, properties, production and compliance. Prague: Czech Standardization Institute 2021.