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POSSIBILITIES OF REPLACING NATURAL SAND IN CONCRETE

Kristina Fořtová*, Tereza Pavlů, Diana Mariaková, Jakub Řepka, Tomáš Vlach

Czech Technical University in Prague, University Centre for Energy Efficient Buildings, Třinecká 1024, 273 43 Buštěhrad, Czech Republic

* corresponding author: kristina.fortova@cvut.cz

Abstract. This study explores the potential of using fine recycled aggregate (FRA) to replace natural sand in concrete production. The research was divided into two parts. In the first part, natural aggregate's complete fine fraction (0–4 mm) was replaced with FRA in conventional concrete for two strength classes. In the second part, individual fine components of high-performance concrete (HPC) were substituted with a similar fraction of fine recycled HPC and concrete aggregate. The physical and mechanical properties of these mixtures with recycled aggregate were evaluated against reference mixtures that contained only natural aggregate, following European standards. Results showed that while most of the concrete and HPC mixtures with recycled aggregate showed slight decreases in properties compared to the reference mixes, the most significant reduction in mechanical properties was observed in the flexural tensile strength of the concrete mixture with FRA, which decreased by over 50 %. The absorption by immersion increased by up to 85 %. The deterioration in properties must be considered during the design stage and only used in applications where it will not affect the functionality of the structures.

Keywords: Fine recycled aggregate, highperformance concrete, natural sand replacement.

1. Introduction

Concrete is one of the construction industry's largest consumers of natural aggregate, relying heavily on primary resources such as river sand, gravel, cement, and water. The excessive extraction of natural sand (fNA) can result in serious ecological problems, including changes in water direction, coastal erosion, and dead-end diversions. One solution to reduce the negative environmental impact of concrete production is replacing natural aggregate (NA) with recycled aggregate (RCA). The aggregate accounts for about 70 % of the largest component of concrete [1]. Still, from a climate change perspective, it is a minor contributor to emissions, accounting for only about 15 % of the emissions generated by concrete production and transportation [2–7]. The environmental impact of RCA can be influenced by its transportation, so it is important to find ways to use all fractions of recycled aggregate, such as using it as a substitute for natural sand in concrete mixtures, at the demolition site.

The use of recycled aggregate (RA) in concrete is often associated with a decrease in mechanical properties and durability compared to conventional concrete (NAC). To mitigate this reduction, cement or supplementary cementitious material (SCM) is added [8]. Recycled concrete aggregate (RCA) is made of natural aggregate particles combined with adhered cement mortar, with quality depending on the demolition and recycling process, including the method, speed, and a number of crushing and sieving steps [9–13]. The properties of RCA are affected by the type and size of the natural aggregate in the parent concrete, as well as the strength of the parent concrete. RCA often presents challenges such as an irregular and angular shape and a porous, rough particle structure [14–16]. The use of fine recycled aggregate (fRA) in concrete is even more complicated, as the measurement of its water absorption has not been clearly developed, with large variations in evaluation methods, and its absorbability during concrete manufacturing is also unknown. Due to these factors, using fRA (< 4 mm) in concrete is challenging, leading to standards worldwide that do not allow it as a substitute for natural aggregate.

The properties of the mixtures produced and tested in the laboratory are described in each of the two parts of this research. While the first part deals with ordinary concrete, the second part follows up the high-performance concrete. These mixtures have very diverse properties, starting with the granulometry of the aggregate used in the mixture and ending with the values of the mechanical properties. Therefore, different properties of the aggregate, which are important in individual cases, must also be taken into account during the design. However, the same properties of the mixture for both cases were investigated (only on different types of samples, corresponding to the character of the mixture). The results are further described in tables and graphs in the Results and Discussion part.

2. Materials and methods

This paper deals with the properties of conventional concrete with the replacement of fine natural aggregate (fNA) with fine recycled aggregate. There is a complete replacement of fNA with two types of recycled aggregate (RA) – fine recycled concrete aggregate (fRCA) and fine recycled masonry aggregate (fRMA) up to a grain size of 4 mm described in the first part of this research. The second part of the research consists of the complete replacement of individual fine-grained components of HPC with the fine recycled aggregate of two types – fine recycled high-performance concrete aggregate (fRHPCA) laboratory prepared by crushing up to grain size of 1 mm and the same type fRCA as in the first part of this research.

The most critical mechanical-physical properties of both groups of samples, in the first part samples of conventional concrete and in the second part HPC mixtures, were tested and evaluated according to the relevant standards. As has already been stated many times, the main properties of concrete that affect its durability are its porosity and water absorption [17]. Water absorption by immersion, which describes the transport behaviour of the material, was obtained on cube samples 100×100×100 mm (for conventional concrete) and beam fragments 100 × 100 × aprox. 80 mm (for HPC), respectively, according to ASTM C1585-20. Cubes with dimensions of 150 × 150 × 150 mm (for conventional concrete) and 100 × 100 × 100 mm (for HPC), respectively, stored for 28 days during solidification and maturation in a permanent laboratory environment, were used for compressive strength testing according to EN 12390-3 (2003). Prismatic samples with dimensions of 100 × 100 × 400 mm and 40 × 40 × 160 mm, respectively, cured in water for 28 days, were used to test the flexural tensile strength according to EN 12390-5 (2009). The static modulus of elasticity was tested according to EN 12390-13 (2014), and the dynamic modulus of elasticity according to EN 12504-4 (2005). For both tests, prismatic specimens with dimensions of 100 × 100 × 400 mm (for conventional concrete) and 40 × 40 × 160 mm (for HPC) were used, respectively.

3. Complete replacement of fNA in conventional concrete mixtures

In total, six concrete mixtures were produced and tested to verify the possible replacement of fNA with fRA. For comparison, the concrete strength class with a compressive strength of 20 MPa, which is used for plain concrete, and the strength class with a compressive strength of 30 MPa, which is often used for structural concrete (reinforced concrete), were chosen. In each strength class, one reference mixture (NAC 1, NAC 2) is produced, which contains only natural aggregate with a grain size of 0–16 mm. In all other mixtures, natural gravel is used as coarse aggregate (4–16 mm), and fine natural aggregate (0–4 mm) is replaced by fine recycled aggregate from construction and demolition waste (CDW) of two types concrete aggregate (mixtures fRCAC 1, fRCAC 2) and masonry aggregate (mixtures fRMAC 1, fRMAC 2). Basic physical properties (density, water absorption) and mechanical properties (compressive strength, flexural strength, and modulus of elasticity) were verified and compared.

3.1. Fine recycled aggregate 0–4 mm for complete replacement

This part of the paper presents the possibility of replacing the complete fine fraction of natural sand (fNA) with fine recycled aggregate (fRA). One type of coarse NA (grain size 4–8 mm and 8–16 mm) and natural mined sand (fNA 0–4 mm), one type of fRCA, and one type of fRMA (grain size 0–4 mm) were used. A cooperating recycling company prepared both types of RA originating from CDW. The aggregate was sorted, and unwanted components and impurities were separated – the aggregate was also washed during the recycling process. According to valid European standards, the properties of aggregates, which are essential for the design of the mixture, were tested in the laboratory. First, particle size distribution tests were performed according to the EN 933-1 standard, and then density and water absorption were determined by a pyknometric test according to the EN 1097-6 standard. Since the methodology for determining the density and water absorption of the fine fraction still needs to be precisely defined [17] only the results for the coarse aggregate fraction with grain sizes of 4–8 and 8–16 mm are presented. Furthermore, the current moisture in the aggregate was measured for the design of the mixture, which is essential in terms of the amount of water added to pre-soak the aggregate during the first phase of mixing the concrete mixture. The properties of NA and RA used in this part of the paper are given in Table 1.

The mixtures are marked according to the type of aggregate used (natural aggregate concrete – NAC, fine recycled concrete aggregate concrete – fRCAC, or fine recycled masonry aggregate concrete – fRMAC). Number 1 indicates the amount of cement for the concrete strength class with a compressive strength of 20 MPa and number 2 with 30 MPa.

3.2. Fine recycled aggregate concrete mixtures

To verify the properties, six concrete mixtures with aggregates with a grain size of up to 16 mm were produced, in which the content of cement CEM I 42.5 R was approx. 260 kg m^{-3} and water-cement (W/C) ratio 0.65 for mixtures marked 1 and 300 kg m^{-3} and W/C ratio approx. 0.55 for mixtures marked 2. The composition of individual mixtures, designed according to Bolomey's particle size distribution curve, is shown in Table 2. Two control mixtures of conventional concrete (NAC 1 and NAC 2) were produced, which contained only natural mined sand. Furthermore, two mixtures corresponding to the amount of cement of strength class 20 MPa (one with replacement

Type of Aggregate	Grain Size [mm]	Finest Particles Content f [%]	Oven-dried Particle Density ρRD [kg m^{-3}]	Water Absorption Capacity WA24 [%]	Saturation Level [%]
Natural aggregate (NA)	0–4	4–8	2 570 ± 81	1.0 ± 0.0	0.0
	4–8	0.3	2 530 ± 12	1.7 ± 0.3	0.0
	8–16	0.4	2 540 ± 12	1.9 ± 0.2	0.0
Fine recycled concrete aggregate (fRCA)	0–4	0.6	2 430 ± 60	3.6 ± 0.8	1.6
Fine recycled masonry aggregate (fRMA)	0–4	1.0	2 320 ± 130	6.6 ± 0.8	4.7

TABLE 1. Measured properties of NA and RA used in this part of the research.

Concrete Mixture	Cement [kg m^{-3}]	Mixing + Additional Water [kg m^{-3}]	W/C Ratio [-]	Natural Aggregate Fine 0–4 mm [kg m^{-3}]	Natural Aggregate Coarse 4–16 mm [kg m^{-3}]	Recycled Aggregate Fine 0–4 mm [kg m^{-3}]
NAC 1	260	169 + 0	0.65	709	1 130	0
fRCAC 1	260	169 + 17	0.71	0	949	843
fRMAC 1	260	169 + 18	0.72	0	766	971
NAC 2	300	165 + 0	0.55	671	1 167	0
fRCAC 2	300	165 +16	0.60	0	994	800
fRMAC 2	300	165 + 17	0.61	0	822	920

TABLE 2. Composition of concrete mixtures used in this part of the research.

fRCA – fRCAC 1 and one with replacement fRMA – fRMAC 1) and two mixtures corresponding to 30 MPa (again one with replacement fRCA – fRCAC 2 and one with replacement fRMA – fRMAC 2).

Due to the high absorbency of the recycled aggregate, a two-phase mixing system was used, wherein in the first phase, the aggregate is mixed with water intended for pre-soaking (it is labelled as additional water in Table 2 and it is determined based on the physical properties of the aggregate and the current amount of water contained in the aggregate) and 2/3 of mixing water. After 10 minutes of mixing, all other components are added in the second phase. No plasticiser or other additives were added to the mixtures. Replacement ratios and grain size are shown in Table 2.

4. Replacement of individual fine-grained components of HPC

In this part of the research, seven HPC mixtures with complete replacement of individual fine-grained components were prepared and tested in the laboratory. fRA from the reference HPC (fRHPCA) and regular waste concrete from the recycling centre (fRCA) were used as substitute materials. Natural quartz powder (QP) and quartz sand (QS) were replaced by recycled fRHPCA and fRCA corresponding to the grain size of individual components, respectively QP 0–0.06 mm was replaced by fRHPC (mixture fRHPCA.HPC.QP) and fRCA (mixture fRCA.HPC.QP) of fraction 0–0.063 mm, QS 0.1–0.6 was replaced by fRHPCA (fRHPCA.HPC.QS1 mixture) and fRCA (fRCA.HPC.QS1 mixture) of fraction 0.125–0.5 – in which the compensation of total amount of QS is 60 %. And finally, QS 0.6–1.20 mm was replaced by fRHPCA (fRHPCA.HPC.QS2 mixture) and fRCA (fRCA.HPC.QS2 mixture) with a grain size of 0.5–1.0 mm – in this case, the total amount of compensated QS is 40 %. A reference HPC mixture based on previous investigations by the research team, just with a slightly modified recipe, was designated as NA.REF, and was used as a control mixture. Therefore, the results do not meet the requirements for UHPC – compressive strength up to 120 MPa according to ASTM C1856, and tensile strength varies from 6 to 12 MPa according to ACI 239R-18. Hardened concrete's basic physical and mechanical properties were verified and compared in this part of the paper.

4.1. Fine recycled aggregate 0–1 mm for replacement of individual components of HPC

This part of the paper deals with the individual fractions of fine-grained aggregates of the fraction up to 1 mm, i.e. it is a much finer grain size than in the first part of the research. Therefore, different aggregate properties important for HPC mixture design were tested. However, it is mainly the chemical composition and specific surface area of the finest component of aggregates with a grain size of 0–0.63 mm. The measured properties of all types of aggregate used in this part of the paper are given in Table 3.

4.2. Fine recycled aggregate HPC mixtures

To verify the properties of hardened HPC, seven concrete mixtures were produced with the same amount of cement CEM I 42.5 R 680 kg m^{-3} and a W/C ratio of 0.25. The mixtures were designed using packing density optimisation. Although additional water is usually added due to the higher water absorption of

Type of Aggregate	**Grain Size**	**Chemical Composition [%]**					**Specific Surface**
	[mm]	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**CaO**	**LoI**	**Area [$cm^2\,g^{-1}$]**
Cement	0–0.063	17.6	5.9	2.1	66.4	8.0	3 640
Microsilica	0–0.063	97.0	0.2	0.1	0.3	2.4	-
Quartz powder (QP)	0–0.063	99.7	0.2	0.0	0.0	0.1	3 760
Quartz sand (QS)	0–0.063	94.1	2.6	1.0	0.9	1.04	2 820
Fine recycled HPC (fRHPCA)	0–0.063	45.5	3.6	2.9	41.9	6.1	3 390
Fine recycled concrete aggregate (fRCA)	0–0.063	41.1	11.8	4.0	33.4	9.7	4 450

TABLE 3. The basic properties of the finest fractions of aggregate used.

HPC Mixture	**Cement**	**Mixing + Additional Water**	**W/C Ratio**	**Super-plasticiser**	**Micro-silica**	**Natural Aggregate**		**Recycled Aggregate**	
						QP 0–0.06 mm	**QS 0.1–1.2 mm**	**Powder 0–0.063 mm**	**Sand 0.125–1 mm**
	[$kg\,m^{-3}$]	**[$kg\,m^{-3}$]**	**[-]**	**[$kg\,m^{-3}$]**	**[$kg\,m^{-3}$]**	**[$kg\,m^{-3}$]**	**[$kg\,m^{-3}$]**	**[$kg\,m^{-3}$]**	**[$kg\,m^{-3}$]**
NA.HPC	680	168 + 0	0.25	19	75	225	960	-	-
fRHPCA.HPC.QP	680	168 + 0	0.25	19	75	-	960	225	-
fRHPCA.HPC.QS1	680	168 + 0	0.25	19	75	225	384	-	576
fRHPCA.HPC.QS2	680	168 + 0	0.25	19	75	225	576	-	384
fRCA.HPC.QP	680	168 + 0	0.25	19	75	-	960	225	-
fRCA.HPC.QS1	680	168 + 20	0.25	19	75	225	384	-	576
fRCA.HPC.QS2	680	168 + 0	0.25	19	75	225	576	-	384

TABLE 4. Composition of HPC mixtures used in this part of the research.

fRA (see previous text), in this case, except for one mixture (see Table 4), no additional water was added to the mixtures. To improve the workability of the mixtures, a superplasticiser based on polycarbonate was added. The composition, replacement ratios and grain size of all HPC mixtures are shown in Table 4.

The mixtures are marked according to the type of aggregate used (natural aggregate – NA, fine recycled HPC aggregate – fRHPCA, or fine recycled concrete aggregate – fRCA), followed by the information that the mixture is HPC. The last part indicates which component of HPC is replaced with the recycled aggregate of the corresponding grain size.

5. RESULTS AND DISCUSSION

This part of the paper compares and presents the essential mechanical and physical properties of both types of investigated mixtures, conventional concrete and HPC. All properties were investigated on three samples, the arithmetic averages of the values, including standard deviations, are shown in the tables and graphs.

6. COMPLETE REPLACEMENT OF fNA IN CONVENTIONAL CONCRETE MIXTURES

6.1. PHYSICAL PROPERTIES

The table (see Table 5) shows dry density and water absorption by immersion of the investigated samples. A slight decrease in density can be observed for all RAC mixtures compared to NAC, with the highest reduction of 7 % for both mixtures with fRMA. Furthermore, it was found that the water absorption by immersion of concrete with fRA is higher than that of mixtures with only NA. A maximum increase of 85 % was observed for the fRMAC 1 mixture. This is caused by the fRMA aggregate that contains highly porous materials such as bricks, aerated concrete, and mortar.

6.2. MECHANICAL PROPERTIES

Compressive strength results, a critical mechanical property of concrete, are shown in the additional graph in Figure 1. The chart shows the flexural tensile strength for all evaluated conventional concrete mixtures. The green columns are for the concrete strength class with a compressive strength of 20 MPa and the blue 30 MPa. The columns for the mixtures with complete replacement of the fine fraction of natural aggregate are distinguished by their different texture – see the legend below the graph. The orange marks above the columns indicate the value of the compressive strength of a particular mixture compared to the reference mixture for the given strength class, expressed as a percentage.

The effect of using fRMA in the concrete mixture is similar for both strength classes – it reduces compressive strength by 10 and 15 %, respectively. In contrast, the complete replacement of NA with fRCA has minimal impact on compressive strength. For a concrete strength class of 30 MPa, there is a decrease of only 4 %, and for a lower strength class, even an increase in strength of 3 % is observed compared to the reference mixture. Flexural tensile strength results and comparison of all mixtures are shown in

Concrete Mixture	Dry Density	Water Absorption by Immersion	Compressive Strength	Flexural Tensile Strength	Modulus of Elasticity	
					Static	Dynamic
	[kg m^{-3}]	[%]	[MPa]	[MPa]	[GPa]	[GPa]
NAC 1	2 241 ± 18	5.89 ± 0.35	33.3 ± 2.5	6.2 ± 0.2	36.7 ± 1.4	38.2 ± 1.8
fRCAC 1	2 195 ± 11	7.68 ± 0.25	34.4 ± 1.7	5.8 ± 0.3	29.6 ± 0.4	34.5 ± 0.7
fRMAC 1	2 080 ± 14	10.89 ± 0.38	30.0 ± 2.2	5.5 ± 0.4	22.4 ± 1.0	27.3 ± 1.4
NAC 2	2 269 ± 13	5.03 ± 1.11	44.8 ± 0.9	7.6 ± 0.9	35.9 ± 0.5	38.2 ± 0.8
fRCAC 2	2 206 ± 5	7.70 ± 0.06	42.8 ± 0.8	6.5 ± 0.4	31.4 ± 1.0	35.7 ± 0.6
fRMAC 2	2 115 ± 12	10.30 ± 0.32	38.0 ± 0.9	6.8 ± 0.6	25.3 ± 0.2	30.0 ± 0.9

Table 5. Basic mechanical-physical properties of ordinary concrete mixtures with replaced sand.

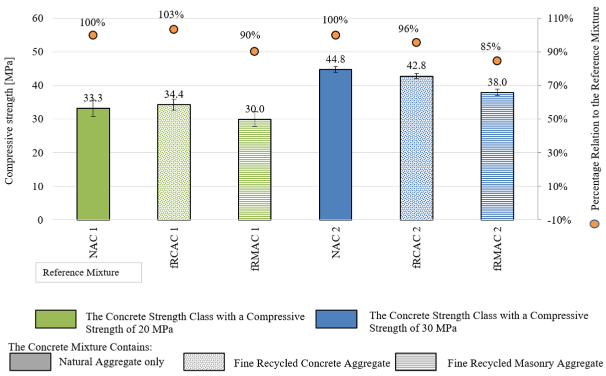

Figure 1. Compressive strength of all evaluated conventional concrete mixtures.

Table 5. The flexural tensile strength decreased for all concrete mixes with fRA compared to the mixture with NA. The most significant reduction – of 13 % is observed in the mixture with NA replacement with fRCA in the strength class with a concrete strength of 30 MPa (fRCAC 2). The static and dynamic moduli of elasticity show the same trend (see Table 5). All mixtures with fRA show a decrease in properties compared to mixtures with NA, while the decline for mixtures with fRMA is more significant (39 and 31 %) than for mixtures with fRCA (19 and 14 %). The dynamic modulus values are slightly higher than the static modulus values, with a maximum difference of 18 % for the fRMAC 1 mixture.

7. Replacement of individual fine-grained components of HPC

7.1. Physical properties

The use of RA in HPC shows (see Table 6) a decrease in dry density of 3–6 %, which is insignificant. In contrast, water absorption by immersion is 3 % lower – 5 % higher (for mixtures with NA replacement with fRHPCA) and 6 % lower – 35 % higher (for mixtures with fRCA), respectively. From the results, it can be observed that the mixtures with QP replacement have lower water absorption. On the contrary, the mixtures with the most extensive QS replacement have higher water absorption than the HPC control mixture with natural aggregate. This could be related to the high water absorption of fRCA originating from conventional concrete.

7.2. Mechanical properties

The graph in Figure 2 shows the compressive strength values for all investigated HPC mixes. The red column represents the HPC reference mixture with a natural aggregate only. In the following columns, one entire HPC component (QP, QS1 or QS2) is completely replaced in each case. Blue columns represent replacement with fine recycled HPC aggregate, and green columns describe replacement with the fine recycled concrete aggregate of the corresponding grain size. The orange marks above the columns again indicate the value of the compressive strength of the specific mixture compared to the reference mixture, expressed as a percentage.

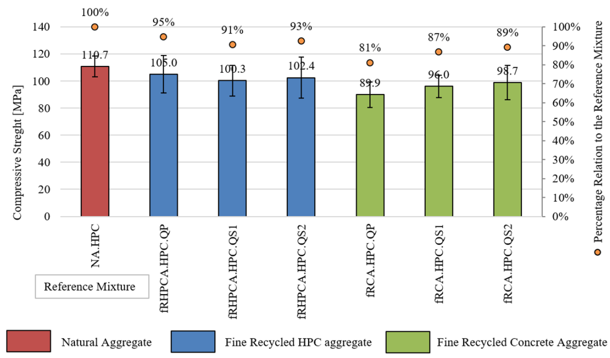

Figure 2. Compressive strength of all investigated HPC mixtures.

The compressive strength of HPC containing replacement NA with fRCA decreases more (11–19 %) than that of HPC containing fRHPCA (5–9 %). Samples with the replacement of QP with fRCA show the maximum drop in compressive strength. The highest deterioration of properties can be observed in the flexural tensile strength (see Table 6). For mixtures with fRCA, a decrease of 2–32 % was observed, and for mixtures with fRHPCA, even a 50–55 % reduction. All mixtures show similar values for static and dynamic moduli of elasticity (Table 6). A slight decrease compared to the reference mixture can be observed for all mixtures with RA, with the most significant

Concrete Mixture	Dry Density [kg m^{-3}]	Water Absorption by Immersion [%]	Compressive Strength [MPa]	Flexural Tensile Strength [MPa]	Modulus of Elasticity Static [GPa]	Modulus of Elasticity Dynamic [GPa]
NA.HPC	2 358 ± 28	3.76 ± 0.20	110.7 ± 7.6	15.3 ± 1.1	45.5 ± 1.1	46.3 ± 1.6
fRHPCA.HPC.QP	2 271 ± 15	3.72 ± 0.12	105.0 ± 13.7	7.1 ± 0.5	45.0 ± 0.7	43.8 ± 0.5
fRHPCA.HPC.QS1	2 237 ± 13	3.94 ± 0.09	100.3 ± 11.3	7.0 ± 0.6	41.9 ± 1.0	41.0 ± 0.8
fRHPCA.HPC.QS2	2 288 ± 15	3.65 ± 0.07	102.4 ± 15.2	7.6 ± 0.9	44.2 ± 1.4	44.0 ± 0.5
fRCA.HPC.QP	2 277 ± 6	3.52 ± 0.16	89.9 ± 9.3	15.0 ± 0.5	45.3 ± 0.5	43.2 ± 0.4
fRCA.HPC.QS1	2 215 ± 7	5.08 ± 0.28	96.0 ± 8.1	10.5 ± 2.6	38.6 ± 0.6	39.4 ± 0.4
fRCA.HPC.QS2	2 268 ± 14	4.19 ± 0.21	98.7 ± 12.6	11.7 ± 0.8	43.6 ± 2.6	42.5 ± 0.5

Table 6. Basic mechanical-physical properties of HPC mixtures with the partially replaced quartz sand.

decline (15 %) again perceptible for the mixture with the highest replacement of QS with fRCA.

8. Conclusions

In this study, two cases of possible replacement of natural sand were experimentally verified and discussed. In the first case, the study focuses on completely replacing natural sand with fine recycled aggregate from two types of construction and demolition waste (conventional concrete and masonry) in conventional concrete. The second part of the study describes the complete replacement of quartz sand and quartz powder with fine recycled aggregate from two sources (HPC and conventional concrete) in HPC. The established properties of fRA were verified by testing the physical and mechanical properties of concrete and HPC containing fRA. The following conclusions can be drawn.

- Although the density of fRA is lower in comparison with natural sand, in both cases, there was only a slight decrease in the density of the resulting mixtures. From this point of view, using RA to replace NA in conventional concrete and HPC mixtures should not cause any unexpected complications.
- Water absorption by immersion of conventional concrete and HPC containing fRA increased, which could negatively affect the durability of concrete and HPC, respectively. Durability properties should therefore be verified in further tests.
- For conventional concrete mixtures, the compressive strength mostly decreases slightly when replacing NA with fRA. Due to the fact that natural sand is completely replaced, it can be stated that during further research of similar mixtures, it is possible to include the decrease in strength properties already at the mixture design stage. In the case of HPC, it turns out that RA's type and original properties influence the compressive strength of HPC with fRA. Therefore, the reduction in strength properties must be considered when designing mixtures with aggregates originating from conventional concrete. When using recycled HPC for replacement, the compressive strength drop is insignificant.
- For the flexural tensile strength of the HPC mixtures, the most significant decrease was found out of all the investigated properties. However, when using HPC in practice, it is assumed that the material will be reinforced with fibres or other reinforcement. For the future use of HPC with fRA, the decrease in flexural tensile strength should not be essential. However, it would be appropriate to directly verify the properties of reinforced HPC with fRA in subsequent research. Flexural tensile strength results for conventional concretes with the replacement of NA with RA show a similar trend to compressive strength results for individual mixtures.
- The results of this study align with previous research that observed a decline in the static modulus of elasticity of concrete when fine recycled aggregate is used as a replacement for natural sand, this can be observed for both types of studied concrete types.

The study showed that, in addition to being used in conventional concrete, a fine recycled aggregate could partially replace natural aggregate in high-performance concrete. However, a reduction in properties compared to the control conventional concrete and HPC must be expected and verified for both types of mixtures. At the same time, it is necessary to emphasise the quality and properties of the input raw materials used (particularly fine recycled aggregate of lower strength classes), which can significantly influence the properties of the resulting mixtures. Indeed, other possibilities of replacement ratios as well as properties of reinforced concrete and HPC with fNA replacement, are the subject of further research.

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