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UNIQUE AND INNOVATIVE TECHNOLOGY FOR SUSTAINABLE AND EFFICIENT STRUCTURAL CONCRETE MADE OF 100% RECYCLED AGGREGATE FROM CDW

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Abstract. For supporting an environmental and social approach to the construction industry, the authors are bringing a new unique technology for maintaining the production of sustainable and efficient structural concrete made of 100% of recycled aggregate from construction demolition waste (CDW) as a replacement of natural aggregate. A wide range of laboratory testing of concrete with a grade up to C 30/37 using brick and concrete recycled aggregate as well as pilot projects will be presented with very successful results. This has been done by taking a different approach to the concrete mix design and production using new modern materials as well as new methods. Then full-scale production testing proved the new concept with only a minor adjustment in concrete plant technology. This new solution has very positive environmental impact and cost optimization shows its great potential for use as a structural concrete supporting a circular economy, saving natural sources, minimizing dumping and landfilling of CDW as well as reducing the CO_2 footprint. This innovative technology makes the reuse of CDW possible in concrete with higher added value in the construction production chain (upcycling) compared to conservative CDW downcycling. This unique concrete production together with proper CDW management brings with it a quite cost-effective contribution to the building industry and market.

Keywords: Concrete, demolition waste, recycled aggregate.

1. Introduction

The substitution of natural aggregates in concrete by recycled ones brings both environmental and economic benefits. In terms of environmental protection, it involves the utilization of rarely used, yet recyclable raw materials, which are largely deposited in landfills or dumps, while maintaining these landfilling capacities for materials that cannot be further used. At the same time, it is saving natural aggregate resources for applications where irreplaceable. The reduction of the traffic exposure is another benefit of this method, as the resources of CDW coming from the demolition of old buildings are usually closer to concrete mixing plants than quarries and sand borrow pits usually located far outside of urban areas. In business terms, this method reduces material costs in tens of percent by replacing expensive natural aggregates by what is basically considered a cheap waste.

The results of this paper were compared with other research results, where is used 100 % of recycled aggregates. In [1] are compared influences of bricks recycled aggregate on properties of concrete, there is one relevant mixture RMAC D with 100 % of recycled aggregates. In mixture RMAC D is used 70 kg more CEM I 42.5 R than in mixture in Table 5. The most significant difference is in used RA, in [1] were used three fractions of RA 0/4, 4/8, 8/16 mm, in this paper is used only mono fraction 0/22 mm, which saves economical and ecological costs during recycling of CDW. The other difference is in parameters of concrete with RA, water absorption is 10 % lower with this technical solution.

2. Principles of the technical solution

Partial substitution of the natural aggregate in concrete by recycled one has been a standard procedure. However, our research and development focused on the production of concrete made solely from the recycled aggregate (RA) including fine fractions of up to 4 mm (100% replacement of natural aggregate including sand). Several years of laboratory testing have been finalized with success and new technology has been developed that was patented both in the Czech Republic as well as internationally.

The patented solution used for the production of concrete from CDW has been launched in the Czech Republic under the registered trademark of Rebetong®. The technical solution starts with the proper preparation of RA with demanded granulometry prescribed by technical specifications. The main technical know-how then continues in the production process of concrete mixing using "nanofiller", the particles of which reinforce the structure of aggregates itself. The final concrete mixture, in general, achieves similar performance properties as conventional concrete made of natural aggregates, with a strength class of up to 30 MPa including waterproof and frost resistant properties.

The use of nanofiller, as well as the reactivation of the binding components contained in recycled aggregate, allows to use the same or even lower cement dose as with quality natural aggregate. Due to the softer nature of recycled aggregate, the modulus of elasticity is lower which has to be taken into account in structural design. The used additive ensures the durability of concrete products while allowing for their full recyclability thus completely eliminating future environmental burdens and meeting the strictest views of a circular economy in the construction industry [2, 3].

3. The development process from the laboratory to industrial production in the concrete plant

The performance parameters of concrete made of 100% recycled aggregate are the outcome of the long-term development and laboratory testing in the Czech Republic with final results in Table 1. That was followed by the joint development with the construction company for further industrial optimization and upscale. The first laboratory tests in their laboratories made with concrete mix design in 3 basic modifications using 100% concrete recycled aggregate (RC-C), 100% brick recycled aggregate (RC-B), or mixed recycled aggregate (RC-M) showed surprisingly good results - see Table 2. This confirmed the high potential of RA concrete for commercial use on construction and development projects. Therefore, operational tests have been started immediately at the pilot concrete mixing plant, again with very good results (see Table 3). The joint development brought among others the further optimization of production processes, the verification of feasibility in the conditions of industrial production at the concrete plant, and the verification of technological as well as rheological properties of concrete from RA during the production, transport, and casting. Based on this good experience the production of concrete made of 100% RA has been certified and since September 2019 branded the certified production Rebetong has started. It offers ready-mix concrete in strength classes up to C 25/30, exposure class up to XC4, XF1, and prefabricated wall blocks with the Reblok trademark. It focuses on the production of the concrete made of 100% RA mono-fraction 0-22 mm from brick CDW, which makes leftovers in the market and the use of which has a greater economic as well as environmental effect.

4. Results of the testing

Within the framework of research and development, laboratory tests have been performed both on fresh and hardened concrete. As a standard, consistency, air content in fresh concrete, compressive strength of concrete, bulk density of fresh and hardened concrete, have all been performed. On selected samples, concrete bending tensile strength and transverse tensile strength, frost resistance, concrete resistance to de-icing solutions, static modulus of elasticity, water absorption, volume changes of concrete, depth of pressure water infiltration and alkali-silica reaction tests have all been tested. The results of laboratory and production tests show good performance properties of concrete with 100% recycled aggregate made of concrete and bricks.

Table 1 shows final laboratory result during development phase and Table 2 indicate the results of laboratory tests made prior to the industrial production.

After laboratory testing, industrial production tests were carried out on the BHS DKXS mixing plant with the mixer volume of 1.67 m^3. Recipes for concrete strength classes C20/25 and C25/30 with 100% recycled brick aggregate were tested during the first production tests. The test results are indicated in Table 3.

Other concrete parameters tested during certification are shown in Table 4, the example of the most commonly used concrete recipes is shown in Table 5.

One of the success factors is the production of the recycled aggregate from CDW. It took some time and several steps to set up optimize production process, select most suitable equipment and proper set up of each machine in the production chain. Development of the concrete made of 100% RA started with 2 fractions 0-8 and 8-16 mm. After some steps of optimization of the RA production the mono-fraction 0-22 mm with similar granulometry was managed. This was an important step for efficient production at concrete plants as they usually lacking of storage space for more fractions of aggregate.

Also a source of the CDW is important and the best possible way is to manage the whole process starting with selective demolition and create a large storage of the recycled aggregate with similar properties.

The final recycled aggregate is tested according EN12620 + A1 and furthermore a prescribed limited gradation curve for granulometry is specified - see Figure 1.

Storage of the recycled aggregate is similar to natural one. The sensitivity test for the moisture in aggregates between 0 % to full saturation have been done with no significant differences.

During the operational tests, the workability of concrete made of recycled aggregate, its behavior, transportability and possibilities of placement have been verified. The behavior of recycled fresh concrete has been found to be similar to conventional natural aggregate concrete.

Sample No.	Type of RCA	Consistency	Strength class	Compressive strength [MPa]		
				7 days	14 days	28 days
1	RC-C	S4	C25/30	18.8	28.4	35.0
2	RC-B	S4	C25/30	19.8	27.8	35.3
3	RC-M	S4	C25/30	22.5	31.0	38.0
	Bulk density [kg/m^3]	Tensile bending strength [MPa]	Tensile splitting strength [MPa]	Water absorption [%]	Static modulus of elasticity [GPa]	Depth of penetration of water [mm]
1	2150	4.7	2.8	3.5	18.6	22.0
2	1920	3.7	2.4	3.2	12.9	16.0
3	2100	4.4	2.5	4.4	14.8	18.0

TABLE 1. Results of final laboratory tests during initial development.

Strength class	Type of RCA	Consistency	Sample No.	Compressive strength on cubes [MPa]				Bulk density [kg/m^3]	Coefficient of frost resistance
				2 d	7 d	28 d	92 d		
C25/30	RC-C	S3	1	11.5	27.2	41.1	45.0	2115	–
C25/30	RC-B	S4	2	12.2	29.7	44.2	48.5	1913	0.98
C25/30	RC-C	S4	3	10.6	25.9	40.0	42.0	2132	1.00
C25/30	RC-B	S4	4	13.5	29.3	44.7	48.8	1928	–
C25/30	RC-M	S4	5	14.4	32.7	46.5	51.7	2043	0.99
C25/30	RC-M	S4	6	13.3	30.4	44.4	49.8	2027	–

TABLE 2. Results of laboratory tests prior start of industrial production.

Strength class	Type of RCA	Consistency	Number of samples	Compressive strength [MPa]		Bulk density [kg/m^3]	Depth of water penetration [mm]
				7 d	28 d		
C 20/25	RC-B	S4	20	22.0	32.4	1990	19 (6 samples)
C 20/25	NA	S3	11	20.5	28.1	2260	–
C 25/30	RC-B	S4	6	25.6	36.9	1990	18 (4 samples)

TABLE 3. Average results of operating tests during industrial production.

Age of samples [day]	Compressive strength [MPa]	Flexural tensile strength [MPa]	Bulk density [kg/m^3]	Tensile splitting strength [MPa]	Frost resistance (100 cycles) [–]	Water absorption [%]	Static modulus of elasticity [GPa]	Depth of water penetration [mm]	Shrinkage [%]
C 25/30 with 100 % RC-B									
7	24.1	4.3	2020	2.7	0.92	4.1	17.6	16	0.428
14	31.8								0.697
28	37.8								0.977
56	41.0								1.188
C 25/30 with 100 % RC-C									
7	19.7	3.9	2110	2.4	0.99	3.9	20.9	21	0.558
14	22.8								0.854
28	35.1								1.119
56	37.5								1.307

TABLE 4. Results of concrete parameters during certification.

Component	Quantity [kg/m^3] 100% RC-B	100% NA
CEM I 42,5 R	250	270
ground limestone / or fly ash	50	50
Nanofiller (microsilica)	25	–
Natural sand 0-4 mm	–	870
Natural crushed aggregate 4-8 mm	–	250
Natural crushed aggregate 8-16 mm	–	700
Brick recycled aggregates 0-22 mm	1500	–
Admixture (plasticizer)	5,5	2,0
water	210	165

Table 5. Comparison of concrete mix design for C 20/25 with RA and NA.

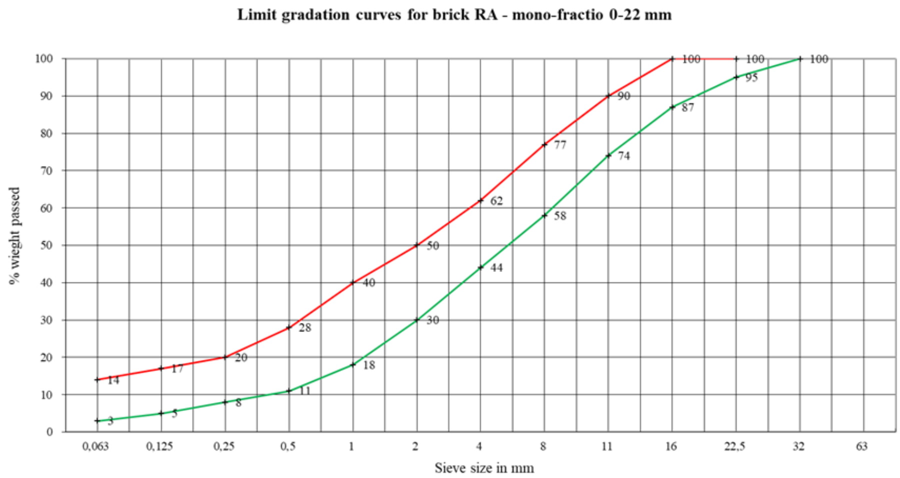

Figure 1. Stress diagram of a strengthened beam. Source: Adapted from Silveira [4].

Strength class	Type of RA	Time [min]	Air content [%]	Slump test [mm]	Temperature of concrete [°C]
C25/30	RC-B	0	4.4	210	23.3
		30	4.2	210	23
		60	4.0	160	22.5

Table 6. Results of workability testing in time.

Figure 2. Pictures from bond strength test.

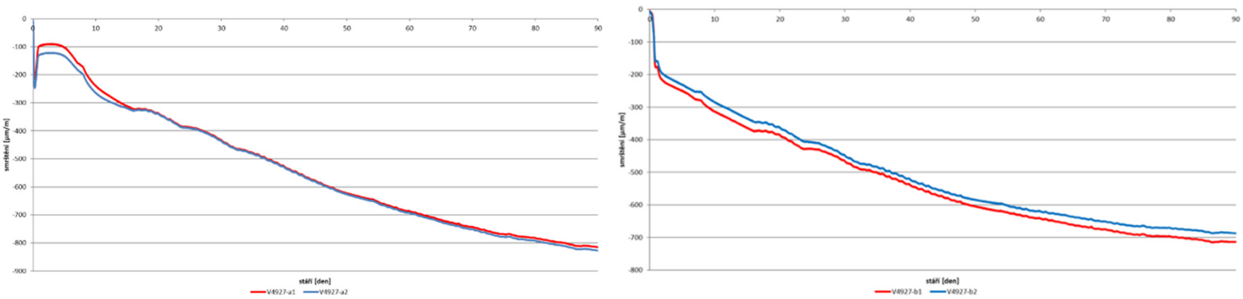

Figure 3. Shrinkage development test: left - 100% brick RA, right - 100% NA.

Figure 4. Concrete placement during the first semi-operational tests and concrete blocks.

Figure 5. The first ready mix concrete placement.

Figure 6. Residential project Devil's Hill in Prague and first concrete wall.

Due to the higher fluctuation of the absorption of RA, especially the one consisting of bricks, it is necessary to pay attention to the workability time of the fresh concrete and to use special additives to ensure good workability for at least 60 minutes. Within the testing, consistency using the slump test was determined over a time horizon of sixty minutes on brick recycled concrete to verify the workability and transportability of recycled concrete. The results are displayed in Table 6.

After satisfactory standard test results some additional over-standard tests, according to [5], were carried out for concrete made of 100% brick recycled aggregate. For example reinforcement bars bond test according to [4] with final bond strength of 5,2 MPA compare to reference result of 5,4 MPa for a concrete made fully of natural aggregate (NA). Pictures from the test see in Figure 2.

Other additional test was the shrinkage development test according to [6]. Resulting graphs are in the Figure 3.

5. Pilot projects, application examples

The concrete made from 100% RA has performance properties similar to the conventional concrete made from natural aggregates. Therefore, it can be used for common plain and reinforced concrete structures. When designing horizontal load-bearing structures, consider the lower modulus of elasticity (see chap. 4.). Customers have become soon interested in the prefabricated wall blocks, of which almost 2000 pcs have already been produced - see Figure 4. As a presentation of the pilot production, these precast units were used for the construction of the parkour playground at "Cukrkandl" in Prague.

The first pilot project of a ready-mix concrete made of 100% RC-B was executed for a base concrete for a commercial multi storey project in Olomouc in a volume of 350 m^3 - see Figure 5.

The next complex pilot project was a residential project called Devil's Hill in Prague, where 2000 m^3 of 100% RC-B were placed for base slabs and reinforced concrete walls - see Figure 6.

6. Technical legislation

Currently, not only within the Czech Republic but throughout the EU, there are significant barriers in technical regulations that significantly reduce the use of recycled aggregates in concrete. Although properties of RA are specified in European standard EN12602 + A1, the European standard for concrete EN206 + A1 recommends the use of coarse recycled aggregate in concrete only up to a maximum of 50% for types A and B, and only for the X0 exposure class, and even less for other exposure classes. To support wider use of RA in concrete, it is necessary to change this conservative normative approach and focus on proving the final properties of the concrete without limiting the RA content. In the Czech Republic, this process, thanks to significant support from the Ministry of the Environment, and Ministry of Industry and Trade, started in September 2019 and its aim is to create a revised national standard for concrete with up to 100% of RA (ČSN P 73 2404).

At the time being the only possible way to apply 100% recycled aggregate in concrete is the procedure according to the National Act No. 163 i.e. certification of the system of production control of concrete from RA and introducing the product to the market on a basis of building technical approval (STO). Unfortunately, this procedure cannot be applied to projects where the contractor is contractually bound by applicable national and European standards. At the moment, this applies for the majority of public procurement projects. However the situation is slowly but surely changing as public investors are increasingly becoming aware of the importance of having a sustainable construction in public procurement and a circular economy. Recently they are coming up with requirements in their projects for construction products made from secondary, recycled raw materials.

7. Conclusion

The parameters determined during laboratory and operational testing show a great potential of concrete made from 100% recycled aggregate, since its performance properties are comparable with conventional concrete in most indicators. The patented solution is in full compliance with the principles of a circular economy, where all inert CDW can be converted back into the building material with excellent properties, which is in addition fully recyclable using the same technological process. Considering the ever-decreasing stocks of natural aggregates, the use of alternative resources is economically and environmentally beneficial. The use of a patented technological process also results in a reduction in the carbon footprint by more than 10%, as less cement is used for the production of concrete and the otherwise rarely used CDW are used as a replacement of natural aggregates.

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