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CRUSHED CONCRETE – QUALITY ISSUES OF CONCRETE RECYCLING

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Abstract: Structural concrete is designed to last for decades, and when a concrete structure reaches the end of its life cycle, it must be recycled according to the principle of the circular economic approach. The presented results expand the knowledge required for the re-use of recycled concrete aggregates produced from crushed concrete in concrete and the re-use of recycled concrete fines as cement additive. They represent the importance of selective preparation technology and the role played by the material characteristics of crushed concrete in the development of certain properties of concrete. Knowledge of these relationships is essential, in order for crushed concrete to become a valuable product, instead of ending up as waste.

***Keywords**: concrete recycling, recycled concrete aggregate, concrete durability, concrete fines, grindability of concrete*

1. INTRODUCTION

Concrete is actually an artificial stone. A composite material that traditionally consists of three components: aggregate (most often sanded gravel or crushed stone), cement and water. However, modern concrete can consist of up to five or six components. With admixtures, concrete additives (active or inert fine powders), fibers, etc. the properties of the concrete can be significantly influenced.

Due to its plasticity, versatile usability and durability, concrete has become the most used construction material in the world today, and after water, concrete is the second most used material. Commonly used concrete is designed to last at least 50 years, but the lifetime of more serious structures (bridges, tunnels, valley closing dams, marine structures, etc.) is more than hundred years.

When a building made of concrete reaches the end of its lifetime, it can be completely recycled with modern technologies available today. The processing of demolished concrete is very similar to that of natural aggregates: it is extracted, crushed and graded according to size (Figure 1). That's why concrete recycling is a perfect example of 'urban mining'. Based on its carefully examined characteristics, the field of use where these processed concrete wastes can be used as raw materials can be determined. By recycling, the accumulation of concrete waste can be avoided and natural raw material sources can be protected.

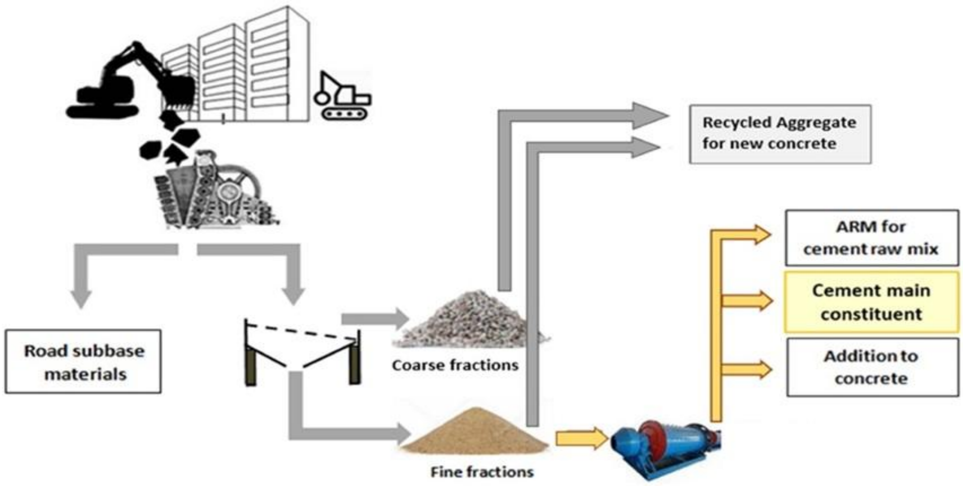


Figure 1

Recycling process of demolished concrete (CEN/TC 51 Document N 1500, 2021)

This approach, the idea of circular economy, waste reduction and more efficient use of resources have become basic requirements also in the construction industry, especially in the building materials industry (Marsh et al., 2022). Nowadays, there are no technical obstacles to the recycling of crushed concrete as aggregate and/or cement additive (Likes at al., 2022), we have sufficient experience (Rocha and Filho, 2023) and appropriate technical regulations (see the References: European standards signed EN, Hungarian national standard signed MSZ, Hungarian road technical specifications signed e-UT).

For decades, the construction industry has been striving for the largest possible proportion recycling of construction, demolition and construction material production waste, but this was not really successful for a long time because of the lack of guidance for concrete technologists that would have helped them to design the composition without a large number of mixes trialed.

Nowadays there are several technical guidelines and standards which prescribe the technical requirements of recycled concrete to use as concrete aggregate. European product standards for concrete aggregates (EN 12620+A1, EN 13139/AC, EN 13242+A1) also cover recycled aggregates from demolition waste and the Hungarian concrete standard (MSZ 4798) also contains limitations concerning the maximal proportion of recycled aggregate used in ready-mixed concrete but the technical specifications cannot give exact composition of these concrete mixtures because of the differences of original properties of concrete and because of the long-term environmental effects.

Despite detailed technical specifications, the rate of high-quality recycling of demolished concrete is still quite low (Rocha and Filho, 2023). In Hungary the majority of demolished concrete is placed in road sub-bases and landfills (OECD, 2023). However, with the increase in construction industry output, the amount of concrete waste increases, which, in contrast to gravel quarries, is mostly generated in densely populated areas where the greatest need for concrete use occurs. One of the reasons for the low rate of high-quality recycling is the misconception that concrete made from recycled aggregates has worse characteristics than concrete with conventional aggregates. The experiments presented here prove that with proper care, regular raw material tests and precise composition planning, concrete made with recycled aggregate can have the same or even better properties than concrete made with conventional additives. Moreover, if the natural sand and gravel additive with high transport costs can be replaced at least in part, then the cost of concrete production can be reduced in addition to protecting the environment.

However, there is another problem, the recycling of the fine (< 4 mm) part of crushed concrete. Coincidentally, to this, the EN 197-6 non-harmonized cement product standard offers an option. This standard allows the use of the fine fraction of crushed recycled concrete as a cement additive. Initial experiments aimed at determining the composition and technical parameters of cements containing concrete fines with appropriate quality and application properties are also in progress.

2. MATERIALS AND METHODS

The test materials were recycled aggregates from road concrete made with basalt aggregate, concrete paving stones and formwork elements produced with a laboratory jaw crusher and natural aggregates from eight Hungarian gravel quarries, as well as the concretes made with them (Figure 2).

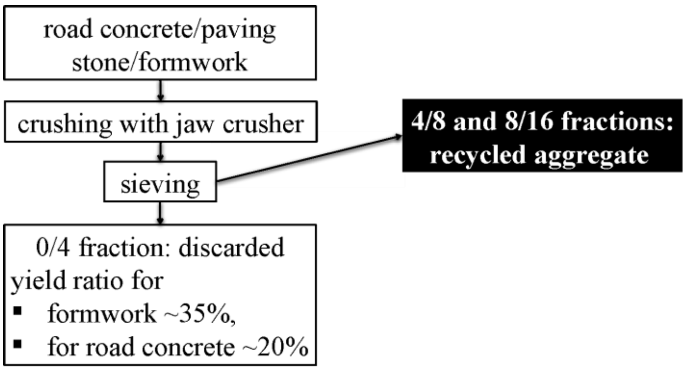


Figure 2

Production of experimental recycled aggregates

According to the technical specifications, only the part of the crushed concrete waste over 4 mm was used for concrete mixes as aggregate, classified into 4/8 and 8/16 fractions and 50 m/m% replacing the natural gravel fraction.

The following tests were performed on the crushed concrete and natural gravel fractions:

- particle density and water absorption according to EN 1097-6 standard;
- resistance to wear (micro-Deval test) according to EN 1097-1 standard;
- resistance to fragmentation (Los Angeles test) according to EN 1097-2 standard;
- resistance to freezing and thawing according to EN 1367-1 standard.

The test results of crushed concrete aggregates were compared with the average of the test results of natural gravel aggregates from eight different Hungarian quarries. Experimental concrete mixtures were prepared with crushed concrete aggregates from different types of concrete elements, which consisted of 50 m/m% natural gravel and 50 m/m% crushed concrete per fraction of aggregate over 4 mm. Concrete with recycled aggregate is commonly called <u>re-concrete</u>. The experimental concrete mixes were designed to have almost the same consistency (flow class F2), which was achieved by changing the amount of plasticizing admixture while maintaining the water/cement ratio of v/c = 0.55.

The composition of the experimental concrete mixtures was as follows:

- 325 kg of CEM II/A-S 42.5 N type Portland-slag cement
- 179 kg of water
- 896 kg of 0/4 aggregate fraction
- 573 kg of 4/8 aggregate fraction
- 386 kg of 8/16 aggregate fraction
- 50-100-110-120 g of plasticizing concrete admixture

Cube test specimens with an edge length of 150 mm were prepared from the experimental concrete mixes for compressive strength and freeze-thaw resistance tests according to the requirements of the relevant standards. The compressive strength test specimens were stored under water at 20 ±2 °C until they were 28 days old, and the freeze-thaw resistance test specimens were also stored under water at 20 ±2 °C for 7 days, then in a climate chamber (at 20 ±2 °C and relative humidity ≥ 95%) until the beginning of the test.

The compressive strength was tested according to the EN 12390-3 standard. The freeze-thaw with de-icing salts resistance test was carried out according to the reference method of CEN/TS 12390-9 technical specification, which is called scaling.
The structure of hardened re-concretes, namely the interface between the cement matrix and aggregate particles was also examined by optical microscopy (Keyence VHX-7000 digital microscope).

The fine fraction (< 4 mm) of recycled concrete made from natural gravel was aimed to be tested as cement additive. However, the 1-4 mm fraction was discarded because of its high content of quartz. It was 70.5% according to the XRD measurement and didn't meet the requirements of carbonate content in accordance with the EN 197-6 standard (see below). The experimental concrete fine was made of the original < 0.090 mm fraction and of the ground 0.090-1 mm fraction of crushed concrete (Figure 3).

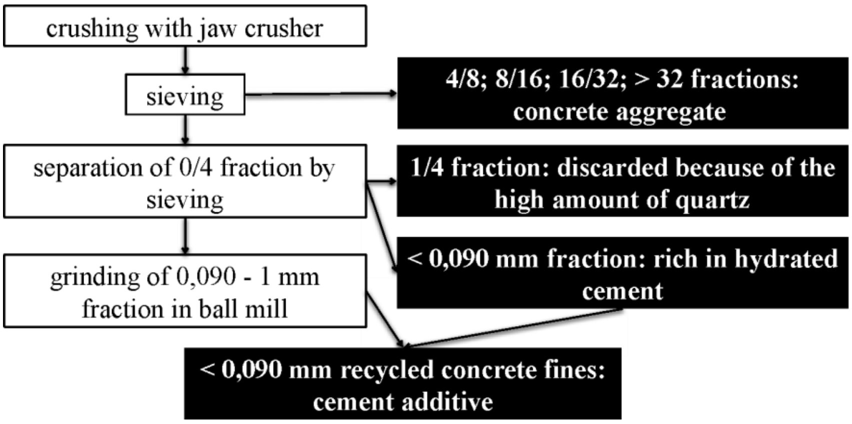


Figure 3

Production of concrete fines as cement additive

The yield ratio of concrete fines as cement additive was ~4.5 m/m%. Recycled concrete fine used for the experiments met the quality requirements in the relevant EN 197-6 standard:

- $R_{CU90} \geq 90$ m/m% concrete;
- total organic content (TOC) ≤ 0.8 m/m%;
- sulfate content (SO_3) ≤ 0.8 m/m%;
- clay content (methylene blue value) ≤ 1.20 g / 100 g;
- calcium carbonate ($CaCO_3$) ≥ 40 m/m%;
- sum of calcium carbonate and magnesium carbonate ($CaCO_3$+$MgCO_3$) ≥ 75 m/m%.

The grindability of the 0.090-1 mm fraction of crushed concrete was tested according to the Zeisel-method (Zeisel, 1953). Both (ground and non-ground) < 0.090 mm fractions of concrete fine were ground together to three different finenesses in laboratory ball mill without grinding aid and with TEA (triethanolamine). Experimental cements were made with ground concrete fines, 20 m/m% of them added to ordinary Portland cement (CEM I 42.5 N) and their standard strength on cement mortar was tested according to the EN 196-1 standard.

3. Results

The differences between the three different types of concrete (road concrete, paving stones and formwork elements) were already evident during crushing and classification. The yield of fractions produced in the same way depends significantly on the composition, strength, and porosity of the original concrete. The profitability of recycling mostly depends on the energy spent on crushing and the yield ratio of the 0/4 fraction to be further treated, which in this case was the highest for the formwork stone (~35 m/m%) and the lowest for the road concrete (~20 m/m%) (Figure 2).

Of course, in the case of concrete with a heterogeneous composition, such as road concrete with crushed basalt aggregate, the crushed concrete fraction above 4 mm contained a much higher proportion of basalt fraction 11/22 than in the original concrete aggregate, and in addition, the different crushing technologies result different grain shapes, which affect the properties of both fresh and hardened concrete.

3.1. Results of aggregates

As expected, crushed concrete aggregates have lower particle density than natural gravel (Figure 4), which mostly consists of low-porosity quartz grains and fragments of volcanic rocks. It is also reflected in the results of water absorption of aggregates (Figure 5).

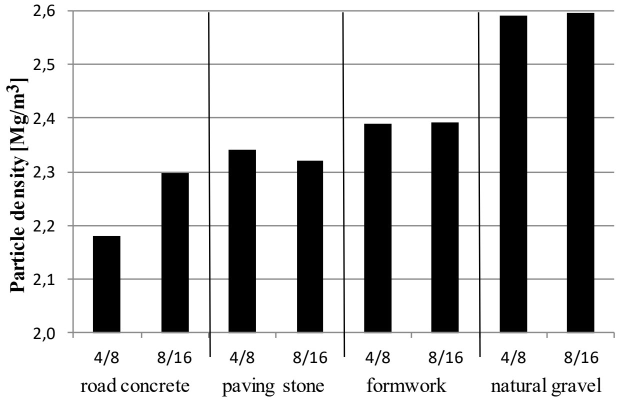


Figure 4

Particle density of different recycled concrete and natural gravel aggregate fractions

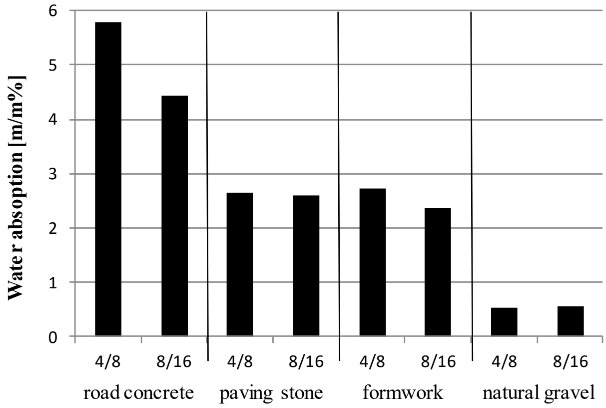


Figure 5

Water absorption of different recycled concrete and natural gravel aggregate fractions

The resistance to wear and fragmentation of the crushed, recycled concrete aggregate was worse than that of the harder natural quartz gravel (Figure 6).

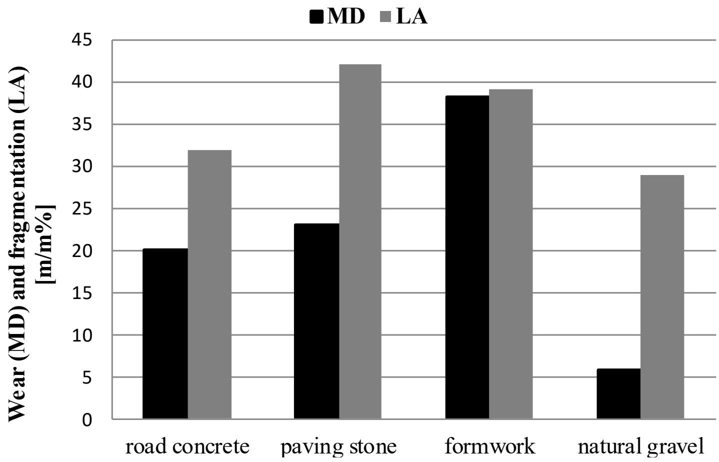


Figure 6

Mechanical properties of different recycled concrete aggregates and natural gravel

As a result, the recycled aggregates are not suitable for use as the wear layer of roads and paving and their use is also not recommended for making high-strength concrete. Concerning freeze-thaw, only the recycled aggregate made of formwork elements had extremely bad results (Figure 7), that's why, it is not recommended for making concrete with requirement of freeze-thaw resisting.

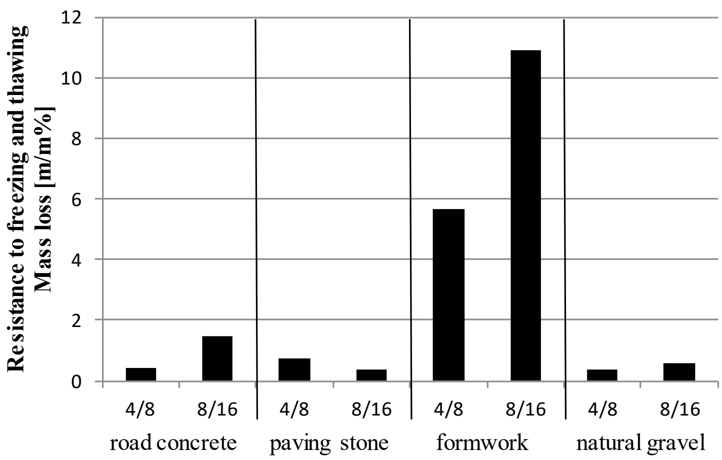


Figure 7

Weathering properties of different recycled concrete and natural gravel aggregate fractions

3.2. Results of concretes

The properties of both fresh and hardened concretes were examined, from which only the most important ones are presented here.

In the case of using crushed, recycled concrete as an aggregate, due to its significantly higher water absorption, in order to achieve the planned consistency of the fresh concrete, it is necessary to use a higher w/c ratio or to use a larger amount of plasticizing admixture (Figure 8).

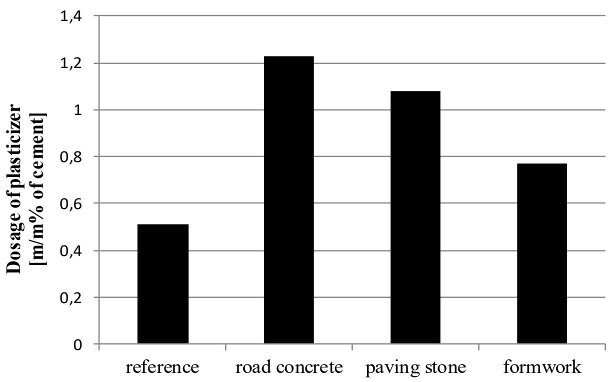


Figure 8
Demand of plasticizing admixture to the same consistency of re-concretes and reference concrete

Figure 9 shows the average compressive strength at the age of 28 days of experimental concretes made with a gravel fraction and different types of crushed concrete aggregates (50-50 m/m%), and the reference concrete made with only natural gravel aggregates.

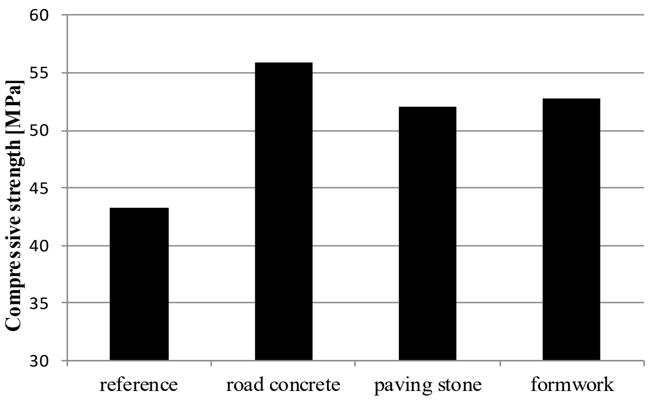
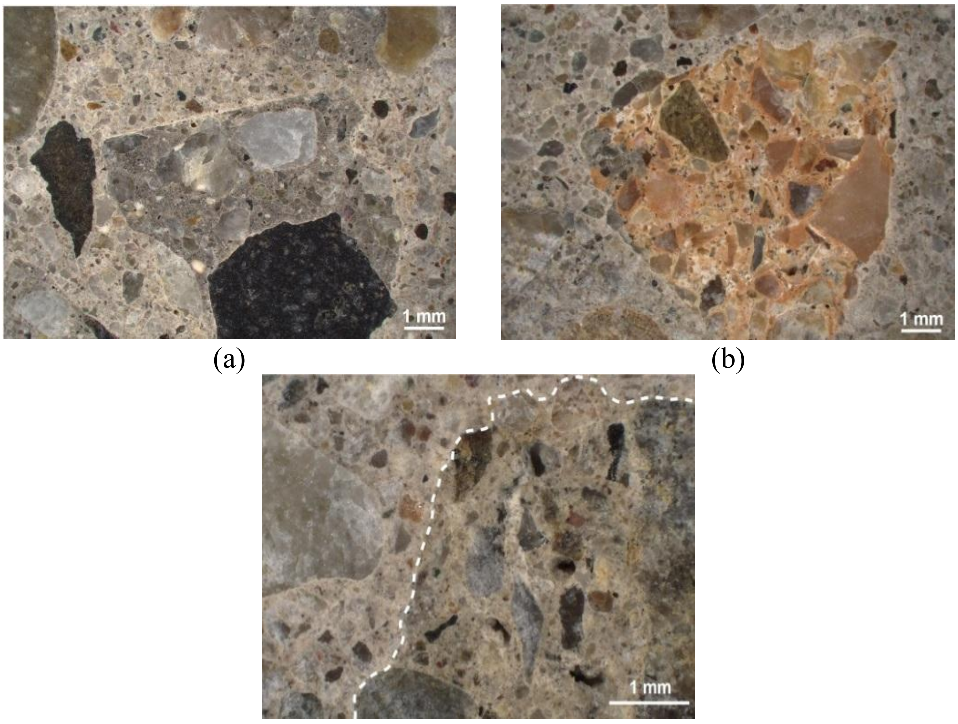


Figure 9
Compressive strength of the re-concretes made with 50 m/m% recycled concrete aggregate and the reference concrete without recycled concrete aggregate

The compressive strength of all experimental concretes was higher than that of the reference concrete, which, by the way, contained only natural gravel aggregate with higher particle strength based on its resistance to wear and fragmentation. In the case of the test specimens made with crushed concrete containing basalt, we measured a significant strength increase of almost 30% compared to the reference concrete.

Figure 10 shows the structure of re-concretes with different recycled concrete aggregates.



(a) (b)

(c)

Figure 10

Microscopic images of concretes made with different recycled concrete aggregates a) road concrete, b) paving stone, c) formwork element

Compared to natural gravel, crushed concrete particles come into contact with the cement paste on a larger surface area. It must be considered when calculating the necessary paste content of concrete. During crushing, the concrete waste broke along the cracks and weak joints, cracks inside the grains were not typical.

These results indicate that the size of the surface of the aggregate binding to the cement paste plays an important role in the development of the compressive strength of concrete.

Figure 11 shows the results of the freeze-thaw test (the specific amount of material scaled from the surface exposed to the salt solution during freezing) of the re-concretes made using different types of crushed concrete aggregates (50 m/m% in the gravel fraction) and the reference concrete after 7, 14, 21 and 28 freeze-thaw cycles (days).

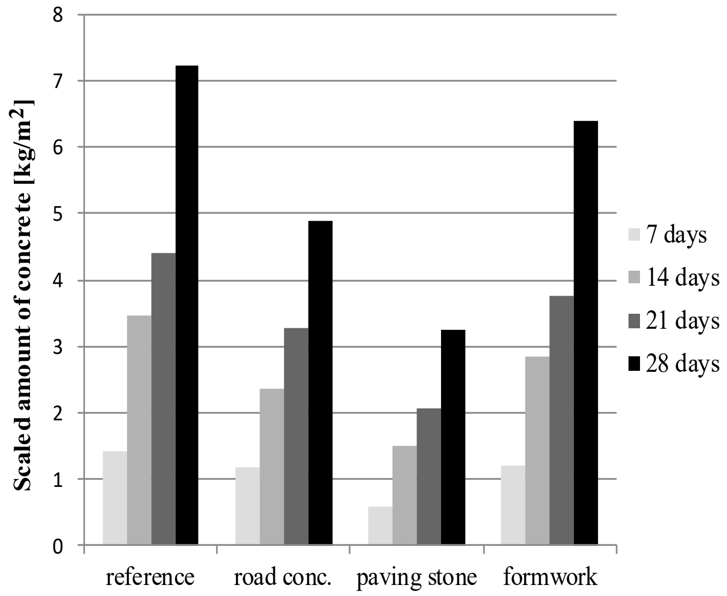


Figure 11

Freeze-thaw resistance of the re-concretes made with 50 m/m% recycled concrete aggregate and the reference concrete without recycled concrete aggregate

Air entraining admixture, which is required for freeze-thaw resistant concrete, was not added to the concrete mixtures, so it was expected that none of the concretes would meet the requirements of the standards. However, it is clear from the test results that the crushed road concrete and paving stones (which were originally designed to be freeze-thaw resistant) significantly improved the freeze-thaw resistance of the experimental concretes made with them compared to the reference.

3.3. Results of concrete fines as cement additive

As it was already mentioned, according to the currently valid technical specifications, the use of fine (< 4 mm) recycled concrete as aggregate is not allowed in Hungary. But fortunately, there is another possibility, thanks to a new European cement standard issued 2023: the non-harmonized product standard of cements with recycled building materials (EN 197-6:2023). The quality requirements of recycled concrete fines are quite similar to that of limestone cement additive.

However, there is an important difference between concrete fines and limestone, namely their grindability. Based on the results of grindability tests according to the

the Zeisel-method, concrete fines need three times more energy to reach a common cement fineness than does limestone (Figure 12).

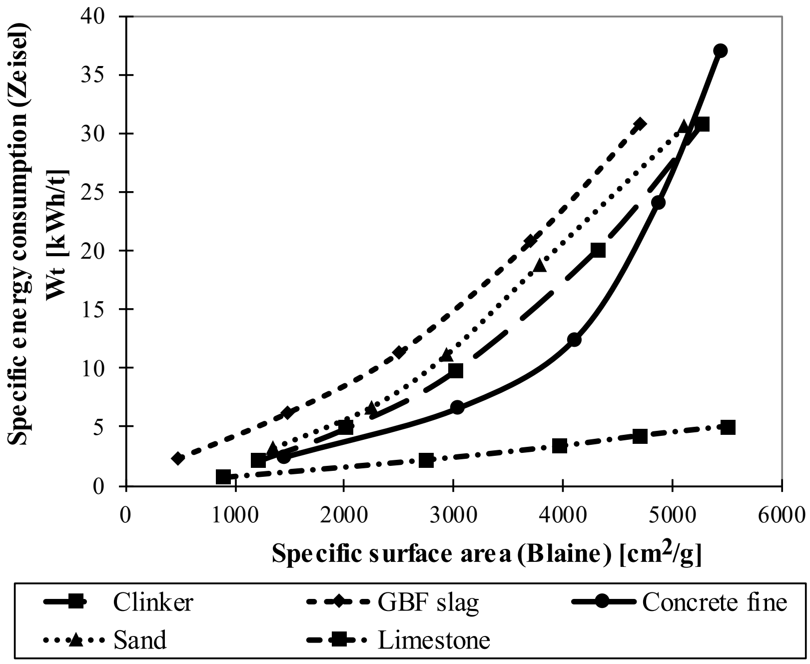


Figure 12
Grindability of recycled concrete fines and different raw materials of cement/concrete

For further experiments, the concrete fine was ground to three different finenesses in a laboratory ball mill without grinding aid (F01 and F02) and with TEA (F03). According to the grinding experiments, with the use of grinding aid (TEA) the agglomeration of concrete fines can be reduced and its fineness can be increased (Table 1).

Table 1
Finenesses of ground recycled concrete fines as cement additive

Mark	Grinding in ball mill	Specific surface area (Blaine) [cm^2/g]
F01	to a common cement fineness	~4200
F02	until agglomeration	~5700
F03	added grinding aid	~7700

Laboratory cements (K01, K02, K03) were made with of the ground concrete fines at 20 m/m% being added to ordinary Portland cement (K00) and their standard strength on cement mortar at the age of 28 days was tested. The test results show that the concrete fines decreased the compressive strength compared to that of the reference cement, yet all cements still met the requirements of standard strength according to the relevant standard (Table 2).

Table 2

Standard compressive strength of cements with ground recycled concrete fines as cement additive (separate grinding)

Mark	Composition	Compressive strength (28 days) [MPa]	Loss of strength [%]
K00	100% CEM I 42.5 N	61.10	–
K01	80% K00 + 20% F01	54.56	10.7
K02	80% K00 + 20% F02	55.40	9.3
K03	80% K00 + 20% F03	59.16	3.2

The negative effect of concrete fines additive on compressive strength of cement can be moderated by increasing the grinding fineness of the recycled concrete fines.

For emphasizing the importance of separate grinding of concrete fines Table 3 shows our earlier results of laboratory cements made with 20 m/m% of limestone by co-grinding to different fineness (Gável, 2024).

Table 3

Standard compressive strength of laboratory cements without limestone and with 20 m/m% of limestone (co-grinding)

Specific surface area (Blaine) [cm^2/g]	Compressive strength (28 days) [MPa]		Loss of strength [%]
	100% clinker	80% clinker + 20% limestone	
3000	50.6	37.3	26.28
3500	53.8	40.0	25.65
4000	57.6	44.8	22.22

It is clear that not only the grinding fineness of the cement but rather the fineness of cement components, i.e. the fraction composition and the particle size distribution of the cement are decisive for its compressive strength. Separate grinding is more suitable for adjusting the proper grinding fineness of cement components that has also a significant effect on the applicable properties of cement and on the durability of concrete. Further tests of recycled concrete fines as cement additives, that concern especially long-term durability tests, are also the focus of our research. Those results are the subject of a future article.

4. Discussion and Conclusions

Our test results indicate that, in addition to the physical characteristics of aggregates laid down in the technical specifications, it is advisable to carry out additional raw material tests before using recycled concrete as aggregate. These characteristics fundamentally influence the properties of fresh and hardened concrete, and by knowing them, it is possible to design a concrete mixture composition that can have more favorable properties than concrete that does not contain recycled concrete.

These results also draw attention to the importance of knowledge of the types of recycled concrete aggregate (crushed concrete) and of original concrete waste constituents and their limitations before use. In general, demolished concrete structures or manufacturing scrap can be used as recycled concrete aggregates, especially if they have been selectively demolished and stored.

Satisfying these technical requirements is the task of the producers of recycled concrete aggregates, who, when choosing the required crushing machine, must pay attention to the fact that different crushing technologies result in different grain shapes, which significantly affects the properties of both fresh and hardened concrete. In addition, efforts must currently be made to minimize the amount of the 0/4 fraction that cannot be used as a concrete filler. In this regard, it should be noted that the new EN 197-6 European cement product standard published in August 2023 offers the opportunity to use the fine part of recycled concrete waste (0/4 fraction) as a cement additive. Cement with recycled concrete fines can have a similar compressive strength as an ordinary Portland cement, but in this case grindability of crushed concrete has to be taken into consideration! Despite of these promising results, we cannot expect the mass appearance of these new types of cements in the near future, because as far as we know, suitable concrete fines are not yet widely available in industrial quantities, and the experiments establishing the bases for the production of these cements and the concrete technology tests that facilitate their practical use are still in their initial stages.

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