USE OF THE RESIDUAL BINDING OF YOUNG RECYCLED CONCRETE IN NEW CONCRETE MIXTURES

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Summary

During the production of precast concrete rubble arises from production residues, form errors and damages. Usually this concrete rubble is being collected throughout the year and stockpiled on the manufacturer's site. Only when there is a sufficiently large amount of concrete debris is present, a mobile crusher hired to crush the hardened concrete rubble into recycled concrete aggregates. Such crushing campaign is organized once or twice a year. At that moment the concrete rubble has already fully cured and the cement has largely hydrated.

This paper shows that it can be beneficial to use the residual binding present in recycled concrete aggregates, derived from concrete residues crushed at early age, and recycle the RCA in fresh concrete. The compressive strength of the recycled concrete increased with 10 % at a replacement rate of 30 %. Since crushing young concrete, which is weaker, requires less energy and aiming at the same required compressive strength as the original concrete could lead to a small reduction of the cement needed in the recycled concrete mixture, these finding contribute to finding solutions for a more sustainable concrete production industry.

Keywords: recycled concrete, recycled concrete aggregates, residual binding, hydration

1 Introduction

The development of sustainable and environmentally friendly building products is necessary. Sustainable materials management is therefore one of the key concepts in which recycling offers an opportunity to close the loop. Raw materials are ending materials, but their consumption still continues to increase. This has adverse effects on the environment and biodiversity. Through better and more efficient use of raw materials, an alternative for natural resources can be found. At the end of their lifetime, materials can be reused or recycled in a similar or another product without loss of quality or functional use. This allows depletion of natural resources to be slowed down.

During production of prefabricated concrete elements, concrete rubble originates from production residues, accidental production errors and damages. Only when there is a sufficient amount of concrete debris is present, a mobile crusher hired to crush the hardened concrete residue. This crushing activity mostly happens only once or twice a year. The longer the waiting period before crushing the concrete rubble, the longer concrete can cure and the more cement will be hydrated. Due to the controlled way of industrial production of pre-casted concrete elements, this debris is very pure and unlike concrete rubble coming from demolition activities on site, it is not mixed with other materials such as wood, plaster, brick, etc. The producer knows the exact composition of the concrete, making this debris a high quality material which can be recycled. Recycled concrete aggregate arising from residues during manufacturing concrete products, have a better and more uniform quality than recycled construction debris from recycling plants where debris from different destinations is brought together.

It is widely known that not all cement in concrete is hydrated during curing. In recycled concrete aggregates non-hydrated cement particles present in the attached mortar, come free after crushing during the recycling process. These particles can still hydrate. This is the reason why stockpiled recycled concrete aggregates start to cling together again. On the other hand, when completely cured concrete is being crushed, the fracture often runs through the original aggregates (trans-particle) while in incompletely cured concrete the fracture will occur between the aggregates (inter-particle). [1]

This study investigates whether it is advantageous to recycling of concrete residues at early age to make use of the remaining hydration of the cement and inter-particle fracture. The concrete residues are coming from the production of precast concrete products e.g. floor-slabs.

2 Theoretical background

Young concrete rubble contains residual binding capacity because reached hydration rate is lower than the ultimate level of hydration. In practice, complete hydration of the cement never takes place. There are two reasons for this: first, the available space for the new hydration products to be formed is limited and secondly, the free available water needed for the hydration reaction. [2]

The W/C-ratio determines the reached degree of hydration. The reached hydration rate is always lower than the ultimate hydration. There will always be a residual binding due to un-hydrated cement particles. Furthermore, young concrete never reaches the ultimate hydration degree because of its young age. [1] [3] [4] [5] Therefor there will be more residual binding present in recycled concrete aggregates coming from concrete residues crushed at young age. This residual binding could possibly contribute to the strength of recycling concrete. If a substantial strength increase would occur, then it would be more economical and sustainable to maintain the same required strength and redesign the recycling concrete mixture accordingly and reduce the cement dosage a little.

Concrete breaks according the way of the least energy. Young concrete would theoretically break mainly according an inter-particle fracture pattern because there are fewer contact points in between the hydration products. The fracture runs along the aggregate surface – “Figure 1 (A)” – which would lead to less broken original aggregates. At the age of 7 or 14 days, the concrete is much weaker than concrete of one year old. Therefore, the breaking of young concrete consumes less energy and less power will be needed to crush the concrete. As a result, a smaller crusher can be used and energy could be saved.

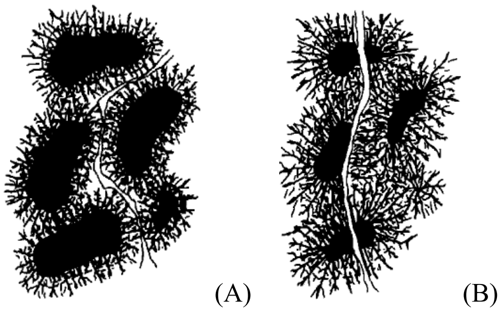

Fig. 1 *Inter-particle (A) and Trans-particle fracture (B) [1]*

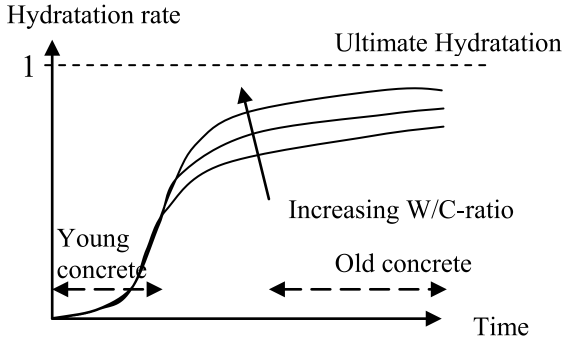

Fig. 2 *Scheme representing the degree of hydration [2]*

3 Research

To be able to compare the particle size distribution of the original limestone aggregates and recycled concrete aggregates, both are crushed in the same laboratory jaw crusher. The reference concrete was made with crushed limestone aggregate. After the determination of the properties of the reference concrete, the remains of the tested samples were crushed using the laboratory jaw crusher to produce recycled concrete aggregates. This operation was repeated with reference concrete at 7, 14, 28 and 112 days, after which recycling concrete with the recycled concrete aggregate was made. Geometrical and physical properties of the virgin and the recycled concrete aggregates were determined and also the properties of fresh and hardened concrete.

3.1 Mix design

All concrete mixtures in this study were designed to meet the requirements of concrete in strength class C25/30. In all concrete mixes the cement dosage was 350 kg/m³ and the W/C-ratio 0,55. “Table 1” shows the composition of the mix for the reference concrete and for the mix of the recycling concrete with 30% replacement of limestone aggregates by recycled concrete aggregates (RCA). The used sand was the same in both types of concrete.

The notation for each mixture is as follows: X/Y/[Z] representing

X = recycled concrete aggregates [%]
Y = age of the recycled concrete [d]
Z = age of the tested concrete [d]

Sometimes the notation is preceded with A or B, indicating different series. Example: 30%/7d/[28d] indicates concrete mixtures with 30% RCA, the RCA being made of concrete that is just 7 days old, and the age of testing the concrete samples is 28 days. The notation A/30%/7d/[28d] describes the same concrete but specifies that the concrete comes from series A.

The W-C-ratio was calculated taking into account the water-absorption of all aggregates.

Tab. 1 *Mix design*

Concrete Mix [kg/m³]	0%	30%
Cement CEM III/A N LA 42,5	350	350
Water (W/C_{eff}-ratio = 0,55)	193	193
Air [%]	1,5	1,5
Sand 0/4	618	618
Limestone aggregate 0/32	1169	819
Recycled concrete aggregate 0/32	0	319

4 Results

4.1 Particle size distribution

To exclude the effect of large aggregates on properties of fresh and hardened concrete, like effects on the workability of on mechanical properties, all aggregates – original and recycled – were processed through the same laboratory jaw crusher. The particle size distribution of all processed aggregates was determined according the standard NBN EN 933-1 (1997). The average particle size distributions from series A and B are shown in “Figure 3”.

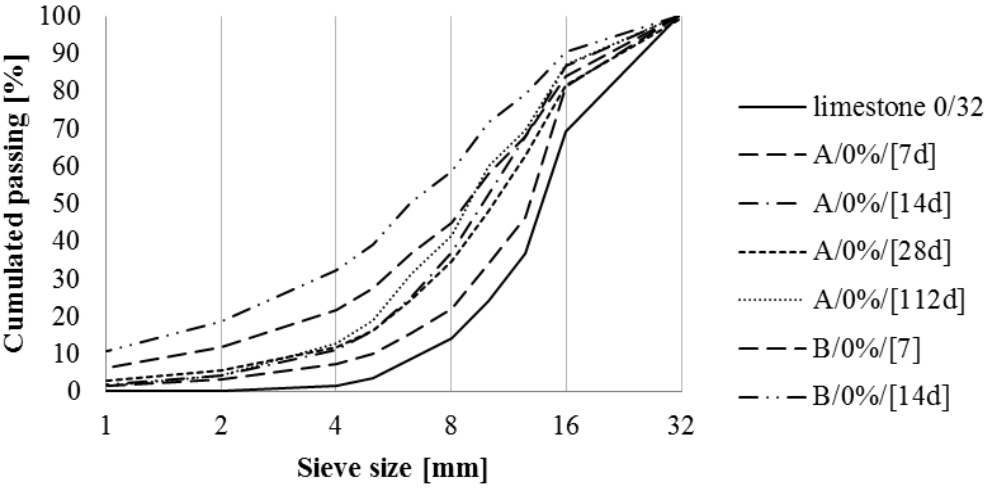

Fig. 3 *Mean gradation for series A and B*

Typically, after the breaking of reference concrete at various ages, a finer particle size distribution was found. In series A, after crushing 7 days old original concrete, the obtained recycled concrete aggregates A / 0% / [7d] contained more finer particles than the other recycled concrete aggregates obtained after a longer age. This phenomenon was not observed in series B. The other particle size distributions of the recycled concrete aggregates in series A are situated close together.

4.2 Determination of the particle shape

The shape of the aggregates affects the workability of ready-mixed concrete. The rounder the shape, the easier the concrete will flow. In addition, the particle shape affects the content of voids, the compaction and the compressive strength of the concrete. The shape of coarse aggregates is determined by the flakiness index according to the standard NBN EN 933-3 (2012). Results are shown in "Table 2".

The limestone in series A fits in class FI15 which means that the aggregates contain little flat particles. The flakiness index of the limestone in series B is slightly higher. These aggregates contain a little more flat particle. Compared to round aggregates, broken aggregates lead to somewhat less workability for fresh concrete, but also to a good cohesion of the hardened concrete under compression load. The flakiness index of recycled concrete aggregates made of crushed seven days old concrete is lower than from those of recycled concrete aggregates of crushed older concrete. Due to the inter-particle fracture, crushing concrete at early age results in lesser flat shaped aggregates because the concrete is still weaker and breaks up easier during crushing.

Tab. 2 *Flakiness index*

Aggregate	mean FI	σ	Class FI
Limestone – (A)	13,3	4,9	FI_{15}
A/0%/[7d]	10,7	1,3	FI_{15}
A/0%/[14d]	14,0	2,5	FI_{15}
A/0%/[28d]	13,2	2,6	FI_{15}
A/0%/[112d]	13,8	0,8	FI_{15}
Limestone – (B)	16,8	1,7	FI_{20}
B/0%/[7d]	10,6	0,4	FI_{15}
B/0%/[14d]	16,2	0,8	FI_{20}

4.3 Water-absorption

Recycled concrete aggregate contains a portion attached mortar. During the hydration process of concrete, pores are being formed in the mortar and due to shrinkage during hardening micro-cracks start to appear. [4] [6] These pores cause a high water-absorption in the attached mortar of the recycled concrete aggregates. The water uptake by absorption is taken into account in the concrete composition in order to avoid that mixing water, required for the hydraulic bonding and workability, gets absorbed by the recycled concrete aggregates.

The water-absorption of fraction 4/31,5 mm is lower than that of fraction of 0.063/4 mm. This is because in the fine fraction 0.063/4mm the presence of crushed mortar is higher than in fraction 4/31,5 mm. The water-absorption of crushed limestone is in the range of 0.9 %. The water- absorption of the fraction 0.063/4 mm decreases as the age of the recycled concrete aggregates increases. At first, the mixing water is present in a continuous network of large pores. When cement gets in contact with water, an exothermic chemical reaction occurs for some minutes, which is called the "initial period" of cement hydration. It is mainly a part of the clinker phase C3A, which is reacting with water and sulphate ions to form elongated ettringite needles. During free available water gets "consumed" and the growth of elongated ettringite needles start to clog the pores. As the hydration continues, smaller pores are created between hydration products. The more time has elapsed, the more the hydration products are formed and the lower the porosity gets, and so the water consumption for hydration drops. [2] [3] [5] [6]

"Table 3" shows the results of the density of limestone aggregates compared to recycled concrete aggregates coming from crushed reference concrete with different ages: 7, respectively 14 and 28 days of age. The absolute density ρ_a of recycled concrete aggregate is almost constant. The values for the apparent dry density ρ_{rd} and the density of saturated surface dry aggregates ρ_{ssd} of recycled concrete aggregates are lower than those of limestone aggregates. The lower density of the recycled concrete aggregate will result in a lower density for recycling concrete.

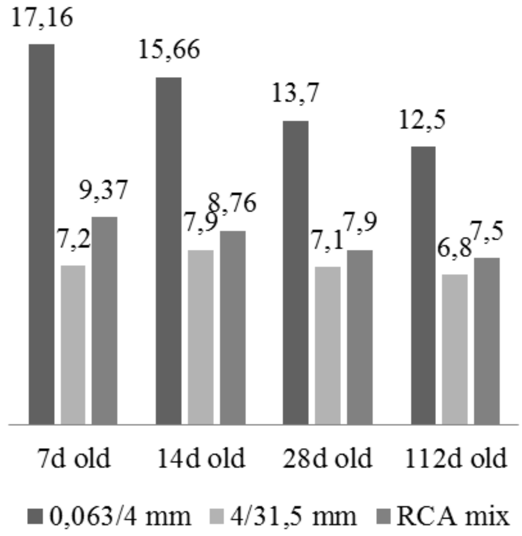

Fig. 4 *Water-absorption [%] of recycled concrete aggregates with different ages*

Tab. 3 *Density of limestone aggregates and recycled concrete aggregates*

Aggregate	ρ_a [kg/m³]	ρ_{rd} [kg/m³]	ρ_{ssd} [kg/m³]
Limestone	2680	2620	2640
RCA 0%/[7d]	2760	2200	2400
RCA 0%/[14d]	2710	2200	2390
RCA 0%/[28d]	2690	2220	2400
RCA 0%/[112d]	2700	2250	2420

(RCA 0%/[xd] = recycled concrete aggregate made of reference concrete x days of age)

4.4 Mechanical properties

The whole idea of exploring the possibility of using residual binding present in RCA is to see if the mechanical properties of recycling concrete can benefit from this. That is why recycling of concrete at a young age is investigated while the residual binding is at its highest. To evaluate the influence of residual binding in RCA on the mechanical properties of recycling concrete, the compressive, the flexural and splitting strength were determined on several recycling concrete compositions made with 30 % RCA from young concrete crushed at age of 7days, respectively 14–28–112 days, and tested for mechanical properties at 28 days.

The compressive strength was determined on cubes of size 150 mm according to the standard NBN EN 12390-3 (2002). Except for the mixtures A/28d/[28d] and B/30%/112d/[28d], all recycling concrete compositions reached the set limit of Cfk,cube 30 MPa and meet the compressive strength demanded in strength-class C25/30. In both series A and B, compositions with RCA of 7 and 14 days age obtain a higher compressive strength than the reference concrete A/0%/[28d] & B/0%/[28d]. The compressive strength of recycling concrete with use of 30 % RCA from early crushed concrete does not decrease up to an age of the young concrete of 14 days. In mixtures with 30 % RCA from young concrete crushed at age of 28 days and more, the compressive strength is lower than that of the reference concrete. See "Figure 5".

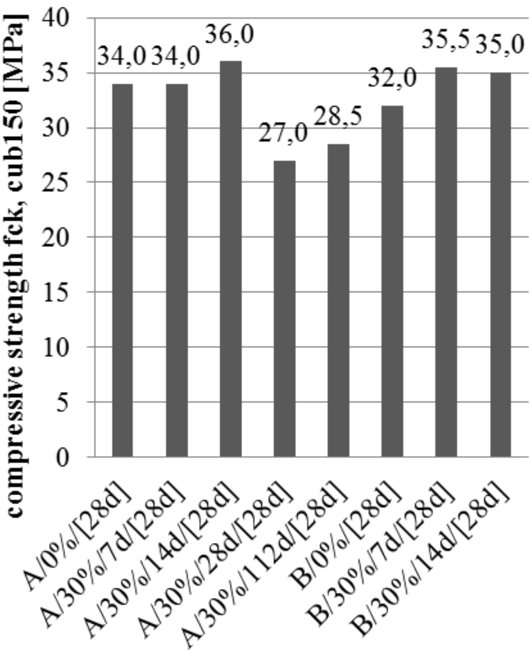

Fig. 5 *Compressive strength*

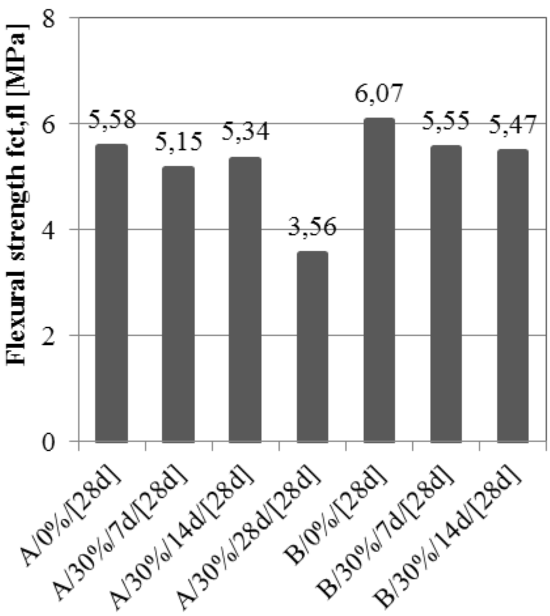

Fig. 6 *Flexural strength*

The flexural strength was determined according to the standard NBN EN 12390-5 (2001) using a four point bending test on prisms with dimensions 50 cm x 10 cm x 10 cm. The flexural strength of recycling concrete compositions 30%/7d/[28d] and 30%/14d/[28d] vary slightly from that of the reference concrete. The use of RCA from young concrete crushed up to an age of 14 days has no adverse effect on the flexural strength. When using RCA from young concrete crushed at age of 28 days (or more), as in the mixture A/30%/28d/[28d] the flexural tensile strength decreases. See "Figure 6".

The splitting tensile strength was determined on the test halves of retrieved after flexural testing. The test was performed according to the standard NBN EN 12390-6 (2001). Results of this test are shown in "Figure 7". The splitting tensile strength of A/30%/7d/[28d] and A/30%/14d/[28d] vary little with the reference A/0%/[33d]. In series B, the difference is a slightly larger. The splitting tensile strength of mixtures B/30%/7d/[28d] and B/30%/14d/[28d] is lower than the reference, contrarily to conclusions of the values of the compressive strength. The splitting tensile strength decreases at A/30%/28d/[28d] and A/30%/112d/[28d]. The splitting tensile strength decreases as the concrete is recycled at a later age.

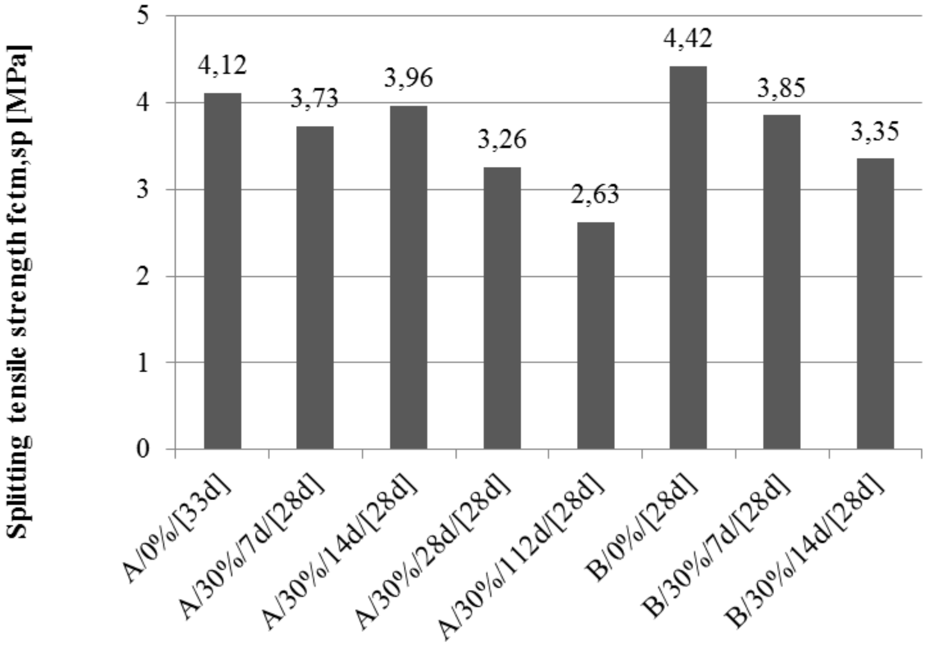

***Fig.** 7 Splitting tensile strength*

5 Sustainability aspects

Natural resources and sources of energy on this world are finite. Currently, natural resources are being used at a rate that cannot be sustained indefinitely. The energy that is expended in exploiting these resources and in the ways these resources are used and consumed, produces pollution and degrades the environment. Greenhouse gasses resulting from use of resources contribute significantly to the global climate change. Much more attention must be paid to the way we deal with our natural environment. This can be done by trying to make use of all small advantages which are present or can be linked with recycling of residues. In the case of the production concrete elements, the residues consist mostly of surpluses of fresh concrete at the end of the day or minor errors in production. The quality of the concrete is in fact very good and well controlled. Usually, these residues end up on a stockpile and once a year an external crusher is hired to crush the residues that have hardened out. Meanwhile the concrete residues have hardened and the process of hydration has reached its highest level. It is knows that not all of the cement particles will have taken part in the hydration process. This can easily be ascertained by the fact that recycled concrete aggregates start to cling together when stockpiled. This effect can be recorder even stronger when stockpiling fine recycled concrete aggregates. The reason for this is obvious: fine recycled concrete aggregates contain more cement stone.

Instead of waiting such a long time to crush the hardened concrete residues, one can ask himself the question, from a sustainable point of view, if it would be beneficial to try to recycle these residues much earlier. What are the benefits one could get out of this approach?

First of all, one can think of the residual hydration. Many researchers [4][5][6][7] have investigated the way cement hydrates. The hydration of cement is not something that happens just at once, it takes some time and this is illustrated here in “Figure 2”. Concrete never reaches the ultimate hydration rate, but depending also on the W/C-ratio reaches a maximum hydration at certain time much later that at 28 days. At young age, and certainly before 28 days of age, the hydration of cement is at its early beginning. This means that there is still a lot of potential binding left in the residues that are thrown away at the end of the day. Cement, certainly Portland cement accounts for a lot of embodied energy and carbon dioxide. This negative impression is largely compensated by the fact that concrete has a long lifetime. So it seems quite important to make good use of the potential of cement and therefor it is a pity not to make use of the residual binding present in concrete residues. Question that remains is if making use of the residual binding could help to reduce the amount of cement needed in production. If this could be the fact, than it would not only be contributing to the sustainability of the concrete product, it would also be economical to do so.

Another possible reason for recycling concrete residues out of production of concrete elements is the fact that when crushing hardened concrete some of the original aggregates get crushed as well. This is caused by trans-particle fracture. [1] If concrete residues were to be crushed at a very young age, let's say at the end of the week, then the behaviour of the fracture would be inter-particle leaving the natural particle in its original form. This is beneficial because that way the recycled concrete aggregates could be used in the same way as the virgin aggregates, while in the case of trans-particle fracture much more fine aggregates will be produces and so the grading of the concrete mixture will have to be recalculated.

Finally some consideration can be made regarding the energy consumption. It is obvious that crushing concrete residues at a young age will be easier than crushing completely hardened concrete. Doing so will require less energy, moreover it will be possible to use a smaller crusher which will not only consume less energy, also the energy for transportation will be less.

Al this moment these suggestions are quite hypothetical and a lot of research is needed to prove the validity of this idea. However, the first conclusions of the research done here, looks promising and point in the same direction as the hypotheses.

6 Conclusions

Concrete rubble contains residual binding capacity because the reached hydration rate is always lower than the ultimate level of hydration. There remains a small latently present hydraulic binding because of the non-hydrated cement particles. In addition, the remaining binding capacity in RCA made from crushed concrete at very young age is at its largest.

In this investigation, concrete was crushed at different ages using the same laboratory jaw crusher. The results of this study show that recycling of concrete residues up to 14 days of age and using it as recycled aggregate in new concrete is advantageous. The tests on the RCA include 30 gradation analysis, 76 determinations of the bulk density and water-absorption, 37 tests of the flakiness index. Due to inter-particle breakage during crushing of young concrete residues less flat shaped stones are produced. A comparison of the gradations could not detect with certainty that the breaking at later time leads to an increased production finer fractions. It is desirable to test this aspect on an industrial scale.

Conclusions on the mechanical properties of recycling concrete with 30% replacement of natural aggregates by RCA are based on 306 compressive tests, 44 flexural tests, 88 splitting tensile tests and 184 density determinations. Recycling concrete with 30 % recycled, 14 days old RCA shows no decrease in flexural and compressive strength. Once the RCA are older, there is a noticeable decrease in the mechanical properties. These results illustrate that the presence of residual binding in young RCA is utilizable in the manufacture of concrete products.

Cement dosage is usually one of the most determining factors for the durability grade of concrete. In this regard further investigation could indicate whether the residual binding in young RCA can lead to a reduction of the amount of cement. Further research could indicate what the optimal age for recycling of concrete residues is and what the ideal ratio of replacement in recycling concrete is. Next to this, the influence of cement-type and the appropriate dosage should be considered.

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