World Academy of Science, Engineering and Technology
International Journal of Civil and Environmental Engineering
Vol:17, No:1, 2023

Enhancement of Recycled Concrete Aggregate Properties by Mechanical Treatment and Verification in Concrete Mixes with Replacement up to 100%

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Open Science Index, Civil and Environmental Engineering Vol:17, No:1, 2023 publications.waset.org/10012878.pdf

Abstract—The building industry has one of the most significant contributions to global warming due to the production of building materials, transportation, building activities, and demolition of structures when they reach the end of their life. Implementation of circular material flow and circular economy can significantly reduce greenhouse gasses and simultaneously reduce the need for natural resources. The use of recycled concrete aggregates (RCA) is one of the possibilities for reducing the depletion of raw materials for concrete production. Concrete is the most used building material worldwide, and aggregates constitute large part of its volume. RCA can replace a certain amount of natural aggregates (NA), and concrete will still perform as required. The aim of this scientific paper is to evaluate RCA properties with and without mechanical treatment. Analysis of RCA itself will be followed by compressive strength of concrete containing various amounts of treated and non-treated RCA. Results showed improvement in compressive strength of the mix with mechanically treated RCA compared to standard RCA, and even the strength of concrete with mechanically treated RCA in dose 50% of coarse aggregates was higher than the reference mix by 4%. Based on obtained results, it can be concluded that integration of RCA in industrial concrete production is feasible, at a replacement ratio of 50% for mechanically treated RCA and 30% if untreated RCA is used, without affecting the compressive strength negatively.

Keywords**—**Recycled concrete aggregates, RCA, mechanical treatment, aggregate properties, compression strength.

I. INTRODUCTION

As concrete is the most common building materials in the world, it is connected to high volumes of construction and demolition (C&D) waste. When constructions reach the end of their service life, landfilling and dumping of the concrete without any further utilisation is often the case. It is approximated that C&D waste accounts for 46% of total waste in the EU [1]. Of the 46%, concrete waste constitutes 60-70% of total C&D [2]. However, the recycling goals of most European countries are ambitious, with a goal to recycle 50-90% of their C&D waste production. And in countries like The Netherlands, Germany and Denmark, landfilling has become more costly than recycling. Among the total C&D recovery, recycled aggregates account for 6% to 8% of aggregates use in Europe [3]. Concrete demands significant amounts of natural materials to produce both cement and aggregates, and as these materials are non-renewable, incorporating greener alternatives to reduce the pressure on virgin sources is important. RCA come in as a solution to partially replace NA and contribute to circular material flow. It can partially or wholly be used as a raw material in new concrete and therefore help ease the pressure off our NA sources.

To create RCA, a concrete structure is demolished and impurities like steel, plastic, glass, brick and wood have to be removed. Then, the concrete is crushed and sieved into a fine (F-RCA) and coarse (C-RCA) fraction. The crushing process does not remove old mortar (OM), as it is still attached to the NA that were used in the parent concrete. The OM is shown to be leading to a higher water absorption and lower density of RCA, and numerous sources document a water absorption of C-RCA which ranges from 3.5% to 9.2%, and 5.5% to 13% for F-RCA. These values are significantly higher than those of the NA whose water absorption ranges from 0.5% to 1.0% [4]-[7]. Variations may also be found in these numbers based on factors like the condition of the demolished concrete, and method used for production of RCA.

Another issue that the remaining mortar on the RCA creates, is the introduction of a second interfacial transition zone (ITZ). ITZ develops between the cement paste and larger aggregates because of vibrations during the casting process. In normal strength concrete, pockets develop under the larger aggregates as they oscillate during vibration and creates a zone where there is a higher water content than other places in the concrete. This leads to the formation of more porous hydration formations which grows at a larger and faster scale, and as a consequence, is known to be less dense, and weaker in strength [8].

Because one ITZ is already present on the RCA, a second one is also introduced between RCA and new cement paste in new concrete. One ITZ is between the RCA and new mortar matrix (new ITZ), and the other is between aggregates and mortar present in parent concrete from which the RCA origins (old ITZ) [9]. This, in turn, leads to a volume increase of weaker zones within the concrete microstructure, and may lead to a negative effect on the strength of the new concrete containing RCA.

There are some methods of treatment that have reported positive results in reducing the amount of mortar from the stones. Mechanical grinding in ball mills, chemical treatment with hydro chloric acid, carbonation and wrapping are

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examples of treatment methods for RCA [10].

This article presents an experimental study on mechanical treatment for C-RCA to improve compression strength of concrete containing RCA. Different replacement ratios of both untreated and treated RCA were used in new concrete to make comparisons possible.

II. EXPERIMENTAL PROGRAM

A. Aggregates

NA and RCA were used in varying proportions in the concrete mixes. Both the NA and RCA are separated into a fine (0-8 mm) and coarse (8-22 mm) fraction. The coarse abbreviated as C and fine as F. All aggregates were tested for particle size distribution according to EN 933-1, density and water absorption according to EN 1097-6. The C-RCA, mechanically treated C-RCA (MT C-RCA) and C-NA were also tested for flakiness index according to EN 933-3.

1) Natural Aggregates

The NA originate from the northern parts of Norway. These are delivered from manufacturer in sizes 0-8 mm (F-NA) and 8-22 mm (C-NA). The F-NA is moraine sand, and the C-NA are stones rich in quartz.

2) Recycled Concrete Aggregates

The RCA were produced in laboratory using a small jaw crusher. A concrete block (B30 concrete) was delivered from a concrete plant, which in turn was separated into smaller pieces by an impact hammer to fit in the jaw crushed. The crushed pieces were estimated to be between 0-100 mm. Since the RCA originated from a non-contaminated known source, the RCA used in this study is 100% concrete.

The pieces were then fed into the jaw crusher, and here the crushing process was repeated three times. The materials from this process were then sieved into fine fraction 0-8 mm (F-RCA) and coarse fraction 8-22 mm (C-RCA).

3) Mechanically Treated C-RCA (MT C-RCA)

Mechanical treatment of laboratory produced C-RCA was done in a ball mill resembling the Los Angeles test. This was done to reduce the amount of attached mortar to the C-RCA. 11 steel balls with a total weight of 4850 grams was added to a ball mill with a diameter 710 mm. For each batch, the drum was turned for 500 revolutions for 15 minutes (33 rpm), before being sieved through an 8 mm sieve to remove any fines produced by the milling process.

4) Water Treated C-RCA (WT C-RCA)

C-RCA was soaked in water and then surface dried with a towel before use in concrete mixing. This was done to see the effect on the concrete if the C-RCA was pre-soaked and the pores full of water.

5) Properties of Aggregates

a) Particle Size Distribution

Fig. 1 shows the particle size distribution of the fine aggregates used in concrete mixes in this study. The results show a higher content of fine fraction (0-8 mm) in the F-NA, with approximately 50% of the total amount being under 0.5 mm. F-RCA had only about 20% content in the same fraction.

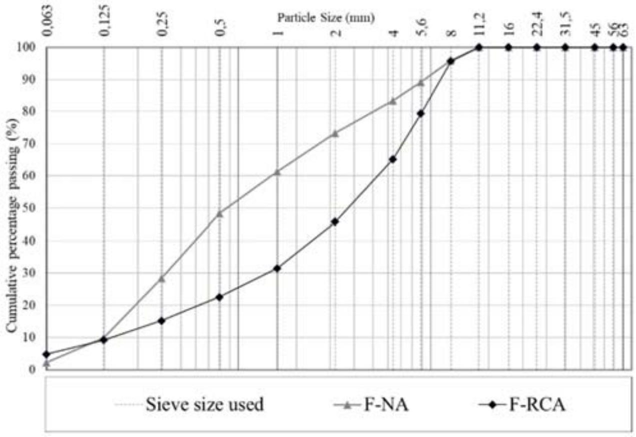

Fig. 1 Particle size distribution, fine aggregates

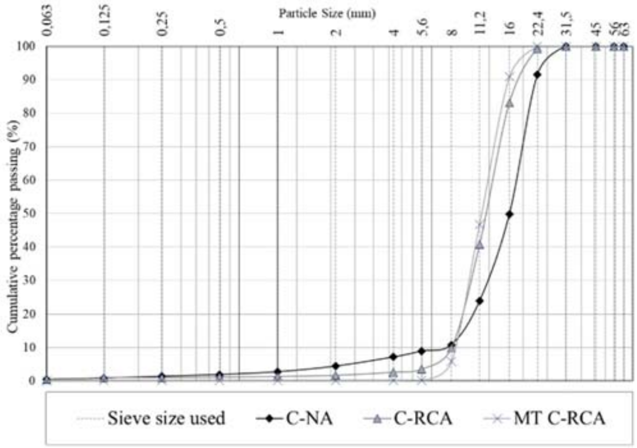

Fig. 2 Particle size distribution, coarse aggregates

Fig. 2 shows results for the particle size distribution of the coarse fraction of aggregates. While the C-RCA and MT C-RCA have a similar content of coarser stones (8-22 mm), the C-NA in comparison has almost a 10% content of 22-31 mm fraction, which is above the specified max size of 22.4 mm from the manufacturer. The C-NA also has a higher amount of fine fraction (0-8 mm) than both the C-RCA and MT C-RCA. The C-RCA contains a higher amount of coarse material than the MT C-RCA, this is most likely due to the mechanical treatment removing mortar from the coarser stones, reducing their size.

b) Density and Water Absorption

Table I shows the density and water absorption of all the analysed aggregate types. Two key differences can be seen between the NA and treated or non-treated RCA. The first difference is a higher water absorption of C-RCA and MT C-RCA, particularly by 4,09% and 1,89% in comparison to C-NA. The second difference is the lower density of all RCA in comparison to natural aggregates between 90 and 270 kg/m^3. Both differences are caused by adhered mortar with a lower

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density as it is more porous and less dense than the NA [11].

Further, it is observed about a 50% reduction of water absorption of MT C-RCA, and a higher density when compared to regular untreated C-RCA. This is caused by the removal of porous mortar from the underlying stone during the mechanical treatment.

TABLE I
DENSITY AND WATER ABSORPTION OF AGGREGATES

Type of aggregate	Density [kg/m^3]	Water absorption [%]
F-NA	2670	0,81
C-NA	2780	0,51
F-RCA	2400	7,30
C-RCA	2555	4,60
MT C-RCA	2690	2,40

c) Flakiness Index

Table II shows the results from the flakiness index for the coarse aggregates. Results show a lower flakiness index for the C-RCA compared to the C-NA, and then a further reduction in flakiness index for the MT C-RCA. The first difference between C-NA and C-RCA can be explained by previous research showing that jaw crushers reduce the flakiness index of the aggregate [12]. Secondly, the difference between C-RCA and MT C-RCA is contributed to the crushing of the weaker parts of the C-RCA in the mechanical treatment process. A lower flakiness index indicates a more cubic aggregate shape, and cubic shaped aggregates are known to be better when used in concrete than elongated ones.

TABLE II
FLAKINESS INDEX OF COARSE AGGREGATES

Type of aggregate	Particle size [mm]	Flakiness index [%]
C-NA	8-22	5.59
C-RCA	8-22	3.71
MT C-RCA	8-22	2.11

B. Concrete Mixtures

This experimental study used the mixes shown in Table III. The C-RCA mixes had the C-NA replaced between 5% and 100% by amounts of C-RCA. Further, F-RCA mixes had its F-NA replaced with F-RCA in ratio 50% and 100%. The MT C-RCA mixes had its C-NA replaced with 50% and 100% replacement ratio of MT C-RCA. The WT C-RCA mixes had its C-NA replaced again with 50% and 100% replacement ratio of WT C-RCA. The F-RCA and C-RCA section in the table shows the replacement ratio in percentage. Same cement type was used in all mixes, CEM II/B-S 52,5 N and the dose was kept constant in order to keep variable only in aggregates proportion. The intention was to maintain constant w/c ratio and adjust the mix only by superplasticizer. Nevertheless, the actual water content in RCA was slightly varying and therefore w/c ratio vary from 0.44 to 54. Higher w/c ratio can be noticed with F-RCA 0-8 mm which has higher water absorption (7.3%) and higher replacement ratio of C-RCA 8-22 mm.

TABLE III
CONCRETE MIXTURES

Mix name	Cement dose [kg/m^3]	W/C ratio [-]	F-RCA 0-8 mm [%]	C-RCA 8-22 mm [%]
REF	370	0.44	0	0
C-RCA 5%	370	0.45	0	5
C-RCA 10%	370	0.45	0	10
C-RCA 20%	370	0.46	0	20
C-RCA 30%	370	0.47	0	30
C-RCA 40%	370	0.48	0	40
C-RCA 50%	370	0.49	0	50
C-RCA 100%	370	0.53	0	100
F-RCA 50%	370	0.49	50	0
F-RCA 100%	370	0.54	100	0
MT C-RCA 50%	370	0.46	0	50
MT C-RCA 100%	370	0.49	0	100
WT C-RCA 50%	370	0.48	0	50
WT C-RCA 100%	370	0.53	0	100

C. Fresh Concrete

The fresh concrete was tested for slump and density according to NS-EN 1235, and results are given in Table IV. Various amounts of superplasticizer (SP) were added depending on the slump measurement. The target slump in this trial was 200 mm. A decreasing trend in the amount of SP used can be observed as the RCA ratios increase. Table III shows an increase in W/B ratio as the RCA content increases, this may be the reason for the better flowability without as much SP.

TABLE IV
SUPERPLASTICIZER AMOUNT AND SLUMP MEASUREMENTS OF FRESH CONCRETE

Mix name	Wet density [kg/m^3]	Super plasticizer [kg/m^3]	Slump [mm]
REF	2426	3	200
C-RCA 5%	2432	3	225
C-RCA 10%	2334	3	220
C-RCA 20%	2440	3	230
C-RCA 30%	2439	3	230
C-RCA 40%	2441	1.5	200
C-RCA 50%	2445	1	160
C-RCA 100%	2460	0.8	170
F-RCA 50%	2448	1.5	155
F-RCA 100%	2470	1	175
MT C-RCA 50%	2436	2	195
MT C-RCA 100%	2489	2	170
WT C-RCA 50%	2441	1	175
WT C-RCA 100%	2460	1	185

D.Hardened Concrete

Compressive strength test was performed on cubes with 100 mm edge, according to NS-EN 12390. Specimens were subjected to water curing in 20 °C for 28 days and 56 days depending on when they were tested. The target compressive strength class chosen in this trial was C35/45 according to EN-206. To meet this class, a cubic compressive strength of 45 MPa is required. The reference mixture in this study ended up being almost 61 MPa at 28 days, which is 35% stronger than necessary to meet the C35/45 strength class. This points to a reduction in cement content as a possibility and still make the target strength.

Fig. 3 shows the density of the hardened concrete. The graph shows little variance in density among the REF, C-RCA 5% and C-RCA 10%. However, for the mixes with a replacement ratio of C-RCA over 10% and mixes containing F-RCA, MT C-RCA and WT C-RCA, a decreasing trend in density is observed with an increase in RCA content. The largest decrease is observed in the C-RCA 100% and F-RCA 100% with a decrease in 6.3% and 6.8% respectively when compared to the REF mix. Interestingly, the MT C-RCA shows an increase in density of hardened concrete by 2.3% and 3.2% for the MT C-RCA 50% and MT C-RCA 100% respectively when compared to their untreated counterpart with the same replacement ratio. This is believed to be due to the removal of porous mortar from the C-RCA, increasing the natural stone content in the new concrete.

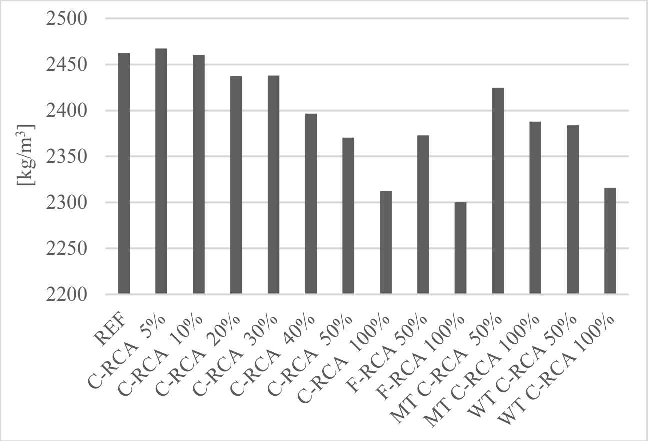

Fig. 3 Density of hardened concrete

III. Results and Discussion

Compression strength results are divided into three different chapters based on the RCA type and replacement ratios. Strength variations of the various concrete mixes in relation to the reference concrete at 28 days and 56 days are also presented (Designated by Δ).

A. *Compression Strength, C-RCA*

Results in Table V and Fig. 4 show the effect on compression strength when replacing C-NA with C-RCA in replacement ratio 5% to 100%. An increase in compression strength is found as the replacement ratio of C-RCA goes towards 30%. The large increase in compressive strength after 28 days was 9% in the case of 30% replacement ratio. The reason for this strength gain might be related to good bond between the rough surface of the RCA and cement paste. However, when the replacement ratio of C-RCA exceeded 30% up to 100%, a decrease in compression strength is observed, with the largest decrease being 15% at 28 days for the C-RCA 50% mix compared to the reference mix. This decrease in strength can be due to the C-RCA having a lower capacity for carrying loads since it contains parts of the old parent concrete, and not just natural minerals which are stronger. All mixes are still within the target compression strength of 45 MPa, and therefore strong enough to be classified as a C35/45. This not only points to 30% C-RCA replacement ratio being feasible for construction purposes, but also that a higher replacement ratio can be relevant for industrial purposes where moderate concrete classes are used.

TABLE V
Compression Strength, C-RCA Mixes

Mix name	28 days Strength [MPa]	Δ 28 REF [%]	56 days Strength [MPa]	Δ 56 REF [%]
REF	60.90	-	68.03	-
C-RCA 5%	63.12	3.63%	69.90	2.74
C-RCA 10%	64.09	5.24%	69.90	2.74
C-RCA 20%	65.21	7.07%	69.90	2.74
C-RCA 30%	66.53	9.24%	70.73	3.97
C-RCA 40%	55.65	-8.63%	61.77	-9.21
C-RCA 50%	51.90	-14.79%	59.60	-12.40
C-RCA 100%	53.12	-12.77%	57.10	-16.07

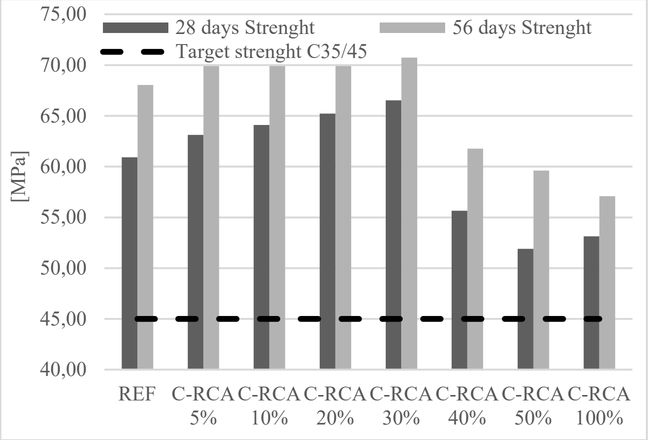

Fig. 4 Compression strength, C-RCA mixes

B. *Compression Strength, C/F-RCA 50%/100%*

Table VI and Fig. 5 show compressive strength results from mixes where C-NA is replaced with C-RCA, and mixes where F-NA is replaced with F-RCA in replacement ratio 50% or 100%. Results on compression strength show that F-RCA 50% outperforms C-RCA 50% at 28 days and 56 days, although the difference is minimal (1%) at 56 days. When comparing C-RCA 50% and F-RCA 50% to the reference mix, both are weaker by a margin of 15% and 11% respectively.

TABLE VI
Compression Strength, F/C-RCA Mixes 50%/100%

Mix name	28 days Strength [MPa]	Δ 28 REF [%]	56 days Strength [MPa]	Δ 56 REF [%]
REF	60.90	-	68.03	-
C-RCA 50%	51.90	-14.79%	59.60	-12.40%
C-RCA 100%	53.12	-12.77%	57.10	-16.07%
F-RCA 50%	54.40	-10.68%	60.40	-11.22%
F-RCA 100%	48.57	-20.25%	53.73	-21.02%

Further, when increasing the replacement ratio of both mixes to 100%, the opposite is observed with C-RCA 100%

outperforming F-RCA 100% with a 13% decrease in strength compared to 20% decrease in strength respectively at 28 days when compared to reference mix. All mixes are within the target strength of C35/45 at above 45 MPa.

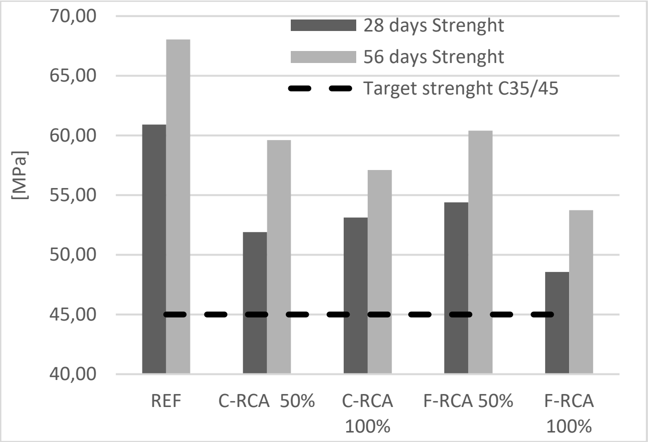

Fig. 5 Compression strength, F/C-RCA mixes 50%/100%

C. Compression Strength, MT/WT C-RCA

Table VIII and Fig. 6 show the compression results from mixes where different pre-treatment methods were used on the C-RCA. Two methods of treatment were used during this study: mechanical treatment and water treatment. Results show that mechanically treated C-RCA improves the compression strength significantly, and the 50% replacement of C-NA with MT C-RCA outperforms the compression strength of the reference mix with 4% at 28 days. This increase in strength constitutes a 22% higher compressive strength over the regular C-RCA that has no mechanical treatment. These results are believed to be due to an effective removal of the weak adhered mortar to the stone by mechanical treatment, and an improved aggregate shape as shown by the flakiness index results. Also, the MT C-RCA may have had better surfaces for the new mortar to adhere to, leading to superior compressive strength when compared to the reference mix. These results point towards mechanically treating the RCA as a good treatment for increasing the compression strength when it is used as a replacement of NA in new concrete. However, there is a question about the feasibility of mechanically treating large amounts of C-RCA, as it can be labour intensive, and require large machines. Furthermore, the 0-8 mm fraction that is produced out of mechanical treatment will have poor quality since it will consist of removed adhered mortar that has been removed from the bigger aggregates.

For the WT C-RCA mixes, varying results are found. The WT C-RCA 50% outperforms the regular C-RCA 50%, but at 100% replacement ratio, opposite results are true, where the regular C-RCA 100% outperforms the WT C-RCA 100%. This points towards pre-wetting C-RCA as an ineffective treatment method in this specific case. The difference in compressive strength for the WT C-RCA 50% and WT C-RCA 100% mixes when compared to the C-RCA mixes with the same replacement ratios are 7.0% and -1.3% respectively. The reason for the improved compressive strength for the WT C-RCA 50% may be due to the water from individual RCA grains being released with a delay, which feeds the cement paste and causes internal curing to take place. Further trials would be necessary to confirm this.

D. Comment on Results

Since the required strength for the concrete mixtures in this trial was 45 MPa for a C35/45 concrete, the reference mix is well beyond that at almost 61 MPa. This means that the reference mix can instead be validated as a C45/55 mix which requires a minimum compressive strength of 55 MPa. If the compressive strength target value would be 55 MPa, mixes with C-RCA up to replacement ratio 40% will match it, see Table V. Furthermore, none of the mixes containing F-RCA would be classified as C45/55. And looking at Table VIII for the pre-treated mixes with C-RCA, both MT C-RCA mixes are beyond 55 MPa and therefore classified as C45/55. However, for the WT mixes, only the WT C-RCA 50% is above 55 MPa.

It is important to take note of the limitations set in EN-206 when deciding on RCA content for concrete. Even though the concrete mixtures in this study met the compressive strength requirement for C35/45 concrete, there are limitations in the European standard for how much RCA content can be used. The maximum replacement ratios based on exposure classes and RCA type are defined in EN-206, see Table VII.

TABLE VII
Replacement Percentage of RCA Based on Exposure Class According to NS-EN 206

Exposure class	Type A	Type B
X0	50%	50%
XC1,XC2	30%	20%
XC3,XC4, XF1,XA1,XD1	30%	0%
Other	0%	0%

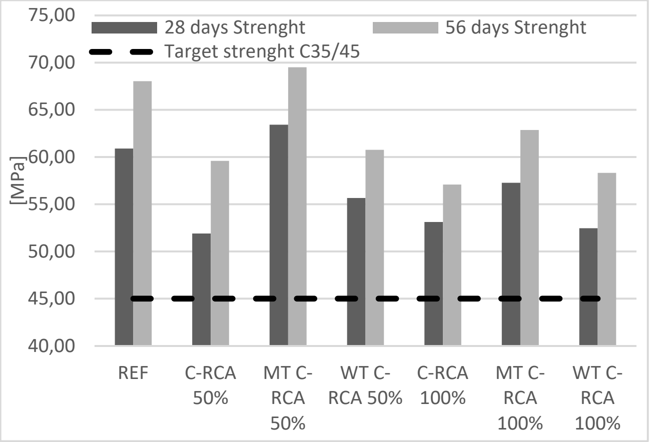

Fig. 6 Compression strength, pre-treated C-RCA mixes

Assorting RCA into class A or B is based on different properties stated in the standard. EN-206 only handles recommendations RCA > 4 mm. All the F-RCA mixes in this trial are therefore not usable according to EN-206.

TABLE VIII
COMPRESSION STRENGTH, PRE-TREATED C-RCA MIXES

Mix name	28 days Strength [MPa]	Δ 28 REF [%]	56 days Strength [MPa]	Δ 56 REF [%]
REF	60.90	-	68.03	-
C-RCA 50%	51.90	-14.79%	59.60	-12.40%
MT C-RCA 50%	63.42	4.14%	69.50	2.16%
WT C-RCA 50%	55.66	-8.60%	60.77	-10.68%
C-RCA 100%	53.12	-12.77%	57.10	-16.07%
MT C-RCA 100%	57.27	-5.96%	62.87	-7.59%
WT C-RCA 100%	52.46	-13.87%	58.33	-14.26%

IV. CONCLUSION

The aim of study was to verify if the mechanical treatment of RCA improves properties of concrete with RCA mechanically treated RCA in comparison to non-treated RCA. Mechanically treated RCA had reduced water absorption in comparison to non-treated RCA by 2.2% and also density increase by 135 kg/m^3 with mechanical treatment. Concrete with 50% of MT RCA achieved strength lower only by 2.16% lower in comparison to REF mix and by 7.59% in case of 100% replacement after 56 days. On the other hand, water treatment/ prewetting of RCA did not have significant effect on concrete strength. Therefore, it can be concluded that mechanical treatment improves coarse recycled aggregates for utilisation in concrete production.

All mixes met requirement for C35/45 concrete regarding compressive strength. If the target strength in this trial was 55 MPa for a C45/55 concrete, the REF, C-RCA up to 40%, MT C-RCA 50%/100% and WT C-RCA 50% would still comply. Up to 30% C-RCA replacement outperforms the reference mix when tested for compressive strength.

ACKNOWLEDGMENT

The outcome has been achieved with the financial support of the Circulus project, No. 299322 funded by the Norwegian Research Council.

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