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Mechanical Properties of Structural Concrete with Recycled Concrete Aggregates at High Replacement Ratios

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ABSTRACT
This paper presents the results of a large and systematic experimental investigation of structural concrete cast with recycled concrete aggregates (RCA) at high replacement ratios. The experimental campaign included determination of modulus of elasticity, compressive strength, and tensile strength, and was divided into two series comprising a total of 312 test specimens. The first series investigated the influence of the replacement ratio (RR) at a fixed target compressive strength, whereas the second series examined varying target strengths at a fixed RR. Proportioning of all concrete mixtures was based on achieving maximum packing density, and the RCA was well-characterised regarding water absorption capacity, density, compressive strength, and aggregate types, the latter two often unspecified in previous studies. The experimental campaign shows that even at considerably higher RRs than current recommendations in standards and the literature, RCA is a viable alternative to natural aggregate (NA) with no increase in cement content nor pre-treatment of the RCA, provided systematic handling of mixture design and production.

Key words: Recycled concrete aggregates, mechanical properties, high replacement ratios, structural concrete, construction and demolition waste

1. INTRODUCTION

The construction industry accounts for a substantial part of the global environmental footprint, which has emphasised the focus on increasing sustainability in the concrete industry. Currently, more than 25 billion tonnes of concrete are produced each year [1, 2], and the future global demand of aggregates for construction is expected to increase substantially [3]. Hence, a considerable amount of initiatives have commenced during the past decades, especially considering aspects of concrete production related to decreasing greenhouse gas emissions and resource scarcity. In the latter context, replacement of natural aggregate (NA) with recycled concrete aggregate (RCA) arising from construction demolition waste (CDW) shows potential by reducing the need for NA and increasing circular material economy. According to de Larrard and Colina [4], the European average use of recycled aggregate in concrete production is estimated around 1 % - 2 %. Recycling of CDW has been practised for decades as the material is often utilised as road fill or to stabilise soil, thus diverting large amounts of CDW from being deposited in landfills [1]. Similarly, the concept of replacing NA with RCA in concrete production is not new either. However, for structural concrete its application is still limited [2], which is partly due to production of RCA for road filling being less demanding with regard to technical requirements than production of RCA for structural concrete [5]. Considering the hierarchy of waste, it is more desirable to increase replacement of NA with RCA in structural concrete, where the material is recycled, compared to utilisation of RCA as base layers for infrastructure purposes, where the material ends its life cycle. To promote an increased use of RCA as replacement of NA, design standards specifying provisions for the use of RCA in structural concrete have been continuously updated during recent years [6], and further recommendations for adjustments of the provisions are provided in [7]. Currently, the Danish provisions are divided into two strength categories. Full replacement of both the fine and coarse aggregate fractions is permitted for strength classes below C35/45, whereas for strength classes above C35/45, the use of 20 % fine RCA and 50 % coarse RCA by mass is allowed [6], while for both strength categories, documentation of several specific RCA material properties is required. Consequently, one of the objectives of this paper is to challenge the limitations imposed on concrete of strength classes above C35/45.

RCA particles occur in different configurations with a size greater than the original NA particles as the aggregates are partly or fully covered in a layer of attached mortar (AM), smaller NA particles embedded in AM, or simply smaller particles consisting of pure mortar, see Figure 1. The amount of AM is determined by the composition of the donor concrete as well as the crushing method of the RCA, and it causes RCA to have lower density and substantially higher water absorption capacity [8] along with an increased specific surface area compared to NA [9]. Hence, replacement of NA with RCA usually results in a loss of workability due to high water absorption capacity and the angular geometry of RCA compared to NA, which increases the need of plasticiser or water and thereby cement for the most common RCA concrete proportioning methods which are based on either weight replacement, volume replacement, or obtaining an equivalent mortar volume. Proportioning methods for RCA concrete mixtures based on particle packing are sparse [10], and most of them have focused on the Compressible Packing Model (CPM) by de Larrard [11]. The CPM takes both shape, surface texture, and size of the aggregates into account in order to predict the compressive strength of the concrete, whereas mixture proportioning based on an ideal particle size distribution presents a more simplified approach to particle packing and is therefore made use of in the current experimental campaign.

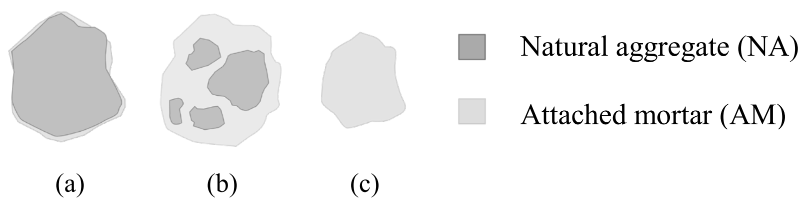


Figure 1 - Possible configurations of RCA. (a) Outer shallow layer of AM, (b) NA embedded in AM, (c) Mortar-only, figure adapted from [12]

Regarding experimental determination of basic material properties, such as compressive strength

[13–15], tensile strength [13, 16, 17], and modulus of elasticity [14, 18–20], numerous studies have been carried out and summarized in [11], most of which indicate that RCA concrete is inferior to conventional concrete. The reduction in these material parameters is mainly attributed to the AM [8, 21], and the compressive strength as well as the modulus of elasticity decrease with increasing replacement ratio (RR). As a result, several studies [9, 22, 23] recommend restricting the RR to 30 % for structural concrete, whereas other studies suggest different kinds of pre-treatments of the RCA such as mechanical treatment often carried out by several crushing procedures [24], washing, thermal treatment, or acid treatment in order to improve the quality of the RCA [25]. These additional procedures increase processing requirements of the RCA, hence raising costs and potentially imposing negative environmental impacts. However, for a substantial majority of the studies already carried out, neither the compressive strength, the type of aggregate used in the donor concrete, nor the method of crushing is provided, thus making it challenging to interpret whether these variables affect the behaviour of the investigated RCA concretes. Furthermore, additional variables occur in mixing procedures and mixture designs, several of which have the potential to mitigate some of the detrimental effects of RCA in concrete production. Nevertheless, a pioneering study by Hansen and Narud [26] found that the compressive strength of RCA concrete is largely affected by the strength of the donor concrete from which the RCA was produced. Furthermore, research on replacement of the fine aggregate fraction (d = 0-4 mm) is sparse, likely as this is considered less feasible than replacement of the coarse aggregate fraction (d > 4 mm) due to the fine RCA fraction consisting mainly of AM and containing more impurities than coarse RCA [25]. Hence, as replacement of NA with RCA based on particle packing methods has predominantly focused on the CPM, and as replacement of the fine aggregate fraction has been given limited attention in previous research, the current paper presents the results of an experimental study of the influence of high RRs of both fine and coarse aggregate fractions for RCA mixture designs based on particle packing in accordance with Fuller's ideal grading curve [27].

The experimental study focused on basic material properties, while knowing the composition and tested strength of the donor concrete. The study was carried out in a systematic manner with replacement of the fine (F-) aggregate fraction, the coarse (C-) aggregate fraction, and the fine and coarse aggregate fractions in combination (M-). Considerably higher RRs than recommended in previous research were applied to the RCA concrete mixtures to increase the effect of the RCA, hence RRs of F-RCA varied between 10 and 50 %, RRs of C-RCA varied between 50 and 100 %, and finally for M-RCA mixtures, replacement of C-RCA was fixed at 50 % along with varying RRs of F-RCA between 10 and 50 %. To post-test examine the influence of RCA on the fractured surfaces, the concrete mixtures were coloured red with iron oxide powder, which accentuated the aggregate in the fractured surfaces of the test specimens. Subsequently, the fractured surfaces of the specimens were all photographed post testing for examination of the surfaces appearing from the uniaxial compression failure (sliding) as well as the splitting failure (separation). The results of the experimental campaign demonstrated that even at high RRs exceeding current replacement recommendations for both fine and coarse aggregate fractions, RCA is a fully viable alternative to NA with regard to compressive and tensile strength, whereas an expected decrease in modulus of elasticity was observed. Moreover, the results of the current experimental campaign were obtained without increasing amounts of cement and without employing further processing technologies of the RCA, thus underlining that adoption of non-treated RCA as replacement of NA in structural concrete is feasible also at high RRs when applying appropriate mixture design methods. Finally, the material behaviour of RCA concrete was observed to be comparable to that of conventional concrete, given that the donor concrete had higher compressive strength than the RCA concrete and that both the mixture design and production were consistently conducted while adjusting water use to compensate for higher absorption capacities of RCA compared to NA and to maintain a constant effective water to cement ratio.

2. EXPERIMENTAL CAMPAIGN

The experimental campaign comprised two series, the first, A, with varying RRs for identical target mean compressive strengths and the second, B, with varying target compressive strengths at a fixed RR = 50 % of the fine aggregate fraction and a fixed RR = 100 % of the coarse aggregate fraction. For Series A, a total of 216 concrete cylinders were cast using 18 different mixture designs, of which two were reference mixtures using only natural aggregates, see Table 1. The RRs in the RCA mixture designs varied from 10 % to 50 % for the fine aggregate fraction, 50 % to 100 % for the coarse aggregate fraction, and from 10 % to 50 % for the fine aggregate fraction in combination with 50 % of the coarse aggregate fraction. Within Series B, five RCA mixtures were prepared for mean target compressive strengths in the interval of 28 MPa to 68 MPa and three reference mixtures in the interval from 28 MPa to 48 MPa, resulting in 96 cylinders in total.

Table 1 - Overview of mixture designs

Series ID	Reference mixtures	RCA mixtures	Specimens
Varying replacement ratio Series A	REF, REF RED	F-RCA10-50 C-RCA50-100 M-RCA10-50	216
Varying target strength Series B	REF28, REF38, REF48	RCA28, RCA38, RCA48, RCA58, RCA68	96

In the experimental campaign, compressive strength, tensile strength, and modulus of elasticity were determined with four replicates of each test adding up to 12 specimens for each mixture. All materials used for casting of the different RCA concrete mixtures and reference mixtures were identical, and in the following sections the experimental campaign is thoroughly described.

2.1 Materials

All concrete batches were produced using Aalborg Portland Rapid Cement, CEM I 52.5 N. Furthermore, iron oxide pigment with a density of approximately 4.6 g/cm^3 was added at a proportion of 2.0 % of the cement weight to visually accentuate the fractured surfaces of the tested cylindrical specimens. To enhance workability and reduce water requirements, a superplasticiser (MAPEI Dynamon Xtend 391) was added to all mixtures at a dosage of 0.7 % of the cement weight. Three gradations of NA were used in the reference and RCA mixtures, namely quartz sand (0/4 mm) and siliceous aggregates, i.e. crushed granite, (2/8 mm and 6/16 mm). These gradations correspond to the fractions of NA used in the production of the donor concrete. In the experimental campaign, the donor concrete originated from surplus production of hollow core slabs (HCS), which were sourced from Spæncom A/S. The mean compressive strength of the HCS at 28 days was tested to 65 MPa. In addition to the compressive strength, the known parameters of the donor concrete were the original mixture design, the particle size distribution as well as the densities and water absorption capacities of the NA. During production of RCA, the HCS were initially fragmented into smaller segments using a jaw crusher to remove prestressing wires. Subsequently, the smaller segments were further crushed using a rotary breaker and then distributed into three size fractions of 0/2 mm, 2/6 mm, and 6/16 mm, respectively. As the donor concrete had not previously been incorporated into any building structure, it was free of debris or contaminants. This is not necessarily representative of RCA typically obtained from CDW. Therefore, the RCA used in the experimental campaign is considered high quality in comparison to RCA obtained from less controlled sources, which may exhibit greater variability and lower quality due to impurities. Table 2 shows the experimentally determined densities and water absorption capacities of both NA and RCA.

Table 2 - Measured densities and water absorption capacities for NA and RCA

	Natural aggregate, NA			Recycled concrete aggregate, RCA		
Grading [mm]	0/4	2/8	6/16	0/2	2/6	6/16
Density [kg/m^3]	2647	2633	2645	2397	2367	2503
Water absorption capacity [%]	0.2	0.8	0.7	6.4	7.4	3.7

Densities and water absorption capacities were estimated in accordance with [28], and water absorption capacities were notably higher for the RCA fractions than for the corresponding NA fractions, validating the conclusions of [11, 29]. A method to mitigate the effect of a potential overestimate of absorption capacity is pre-soaking of the aggregates, which is conducted in experimental campaigns carried out by e.g. Butler et al. [30] and Pepe et al. [8]. However, other studies have concluded that pre-soaking of the aggregates affects RCA concrete negatively, particularly in relation to the interfacial transition zones, ITZs, of the aggregates, due to the presence of excess water [14, 31]. Therefore, in the current two test series, the aggregates were not pre-soaked in order to resemble standard factory casting conditions in Denmark, where aggregates are often stored outside in silos and used in their current moisture state throughout the year. Consequently, NA as well as RCA were stored outdoors in polypropylene bags. In order to maintain a constant effective w/c-ratio of all concrete mixtures, water compensation was carried out by adjusting the amount of water based on water absorption capacities and the actual moisture content of each type of aggregate, NA as well as RCA, for each mixture. Additionally, the water incorporated in the superplasticiser was considered in the determination of the total water content.

2.2 Aggregate composition and mixture design

Traditionally, mixture designs aiming for maximum packing density result in a smaller paste content than other methods. To maximise material utilisation without increasing cement consumption, the aggregate composition of the current test series was therefore designed with the aim of achieving a particle size distribution similar to an optimized curve. In this case given by Fuller's ideal grading curve [27, 32].

$$p(d) = 100 \sqrt{(d/d_{\max})} \quad (1)$$

Where $p(d)$ is the percentage of aggregates finer than a given aggregate diameter, d, and d_{max} is the maximum aggregate diameter. Fuller's ideal grading curve seeks to combine amounts of differently sized particles to obtain the highest possible packing density. Therefore, the particle size distribution of each type of aggregate, NA as well as RCA, was determined. This was done in accordance with [33], and the shape of the aggregate particles was not taken into account. The particle size distributions for all fractions of both NA and RCA are shown in Figure 2, where the prefix F corresponds to the fine fraction of NA and RCA. Similarly, the coarse fractions are denominated C-NA and C-RCA, and each coarse fraction is further divided into two sub fractions dependent on aggregate diameter. In Figure 2, a considerable difference between F-NA and F-RCA can be observed, as the majority of F-NA particles are in the 0.25 mm - 0.50 mm interval, whereas F-RCA is more evenly distributed between particle sizes up to 4 mm. Furthermore, there is a larger amount of coarse grains in the C-RCA fractions in comparison to C-NA, which is likely due to the settings of the crushing machinery. To obtain a theoretically comparable workability of the reference and RCA mixtures with regard to particle size distribution, the two sub fractions of both C-NA and C-RCA were combined into one coarse fraction of NA and RCA, respectively. Therefore, a fixed distribution of 12 % of C-NA 2/8 mm and 88 % of C-NA 6/16 mm along with a distribution of 38 % of C-RCA 2/6 mm and 62 % of C-RCA 6/16 mm were chosen for the combined coarse fraction of RCA being as similar as possible to the combined coarse fraction of NA. The resulting coarse fractions of both NA and RCA can be seen in Figure 3.

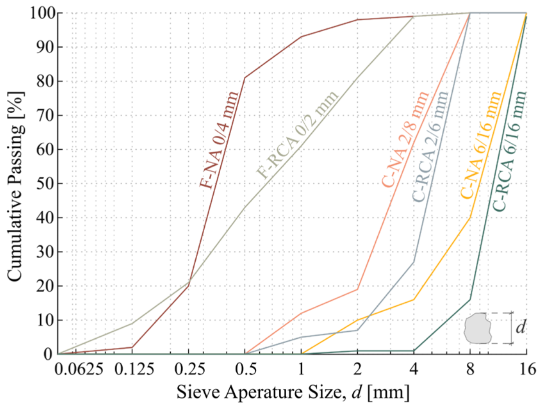


Figure 2 - Particle size distributions for NA and RCA

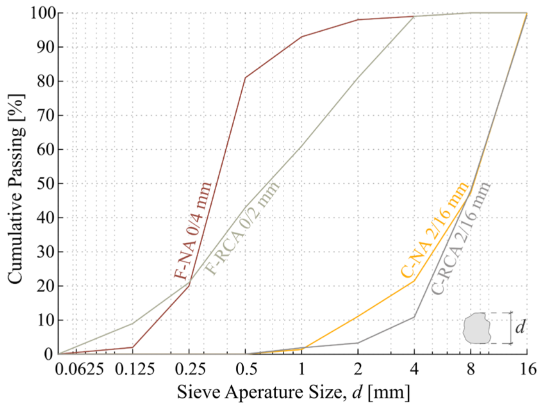


Figure 3 - Particle size distributions for NA and RCA with combined coarse fractions

In order for the full particle size distribution to resemble Fuller's ideal grading curve, the distribution between the coarse and fine aggregate fractions for each mixture design was determined through quadratic regression using least squares. Hence, the deviation between the points on the combined mixture gradation curves and Fuller's ideal gradation curve was minimized. This approach was applied to all mixtures, thus, the aggregate replacement was neither carried out by weight nor by volume, however, by determining the ratio between fine and coarse aggregate to obtain the closest fit to Fuller's ideal gradation curve.

Mixture design for varying replacement ratios

For Series A, two reference and 16 RCA mixture proportions were designed based on chosen ratios between NA and RCA. The content of RCA was varied for the fine and coarse aggregate fractions, respectively, as well as for the fine and coarse fractions combined, allowing for an investigation of the influence of the crushed aggregate from a well-known donor concrete on the new concrete. The objective of the various mixture designs in Series A was to develop RCA concrete mixtures with a compressive strength comparable to the target characteristic compressive strength of the two reference mixtures, chosen as f_{ck} = 35 MPa, whilst targeting a slump of approximately 120 mm to ensure workability of the concrete mixtures. Consequently, the initial reference mixture was designed to comply with the desired compressive strength, using an initial water quantity determined based on the target slump, the aggregate type, and aggregate size. Next, the cement content was calculated from the specified water-to-cement ratio to achieve f_{cm} = 43 MPa, based on the mean compressive strength in CEN-DS/EN 1992-1-1 [34] being expressed for conventional concrete as:

$$f_{cm} = f_{ck} + 8 \text{ MPa} \quad (2)$$

Where f_{cm} is the mean compressive strength and f_{ck} is the characteristic compressive strength. In [7] it was established that the same relation can be considered applicable to RCA concrete. For the second reference mixture, the procedure was repeated with addition of iron oxide pigment to enhance visibility of the fractured surfaces after testing and to verify that the presence of iron oxide did not influence the obtained properties. In both reference mixtures only the fine and coarse NA fractions were used to depict the complete granulometric curve, and the aggregate composition was determined as described in Section 2.2. Following the initial design of the reference mixtures, the water quantity was adjusted to achieve the chosen slump target and superplasticiser was added to reduce the required amount of water and cement, resulting in a water-to-cement ratio of 0.52 for all mixtures in Series A. To ensure reproducibility of the reference mixtures, several test batches were produced, and the quantities of water, cement, superplasticiser, and iron oxide powder were kept constant across all mixture designs. The reference mixtures according to the saturated surface dry condition in both the natural and coloured versions are presented in Table 3, and the final reference mixtures where water compensation was carried out with regard to the determined moisture content of the aggregates on the day of casting are available at DTU Data [35]. In Table 4, the distribution between aggregates determined for each RCA mixture is provided along with the ratio between fine and coarse aggregates and the total replacement ratio.

Table 3 - Overview of reference concrete mixture designs for Series A

REF Mixture	Rapid CEM I 52.5 N	Water	Iron oxide powder	Dynamon Xtend 391	F-NA 0/4 mm	C-NA 2/8 mm	C-NA 6/16 mm	F/C
	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[%]
REF	323.2	167.4	-	2.3	561.6	158.5	1167.8	30/70
REF RED			6.5		560.5	158.2	1165.6	

The designation of each RCA mixture design was based on the chosen RR and the replaced aggregate fraction, namely fine, coarse, and mixed fine and coarse, where the numbers indicate the percentage replacement, see details in Table 4. For replacement of both fine and coarse aggregates, the coarse RR was always set at 50 %, whereas the fine RR was varied between 10 % and 50 %, due to which the naming of the mixtures with combined replacement of fine and coarse aggregates is based on the RR of the fine aggregate fraction. For instance, the RCA mixture M-RCA20 has a RR of 20 % of the fine aggregate fraction along with 50 % of the coarse aggregate fraction, resulting in a total RR of 38.1 % by mass. As the RR was a fixed parameter for each mixture, the aggregate compositions were determined as previously described. Figures 4, 5, and 6 show the gradation curves for each of the concrete mixtures in Series A including the gradation curve of the reference mixtures.

Table 4 - Overview of RCA concrete aggregate composition for Series A

RCA Mixture	F-NA 0/4 mm [kg/m³]	C-NA 2/8 mm [kg/m³]	C-NA 6/16 mm [kg/m³]	F-RCA 0/2 mm [kg/m³]	C-RCA 2/6 mm [kg/m³]	C-RCA 6/16 mm [kg/m³]	F/C [%]	RR [%]
F-RCA10	519.0	156.3	1151.4	52.2	-	-	31/69	2.7
F-RCA20	474.5	154.3	1136.9	107.4	-	-	31/69	5.7
F-RCA30	427.1	152.3	1121.9	165.8	-	-	32/68	8.9
F-RCA40	376.5	150.2	1106.6	227.4	-	-	33/67	12.2
F-RCA50	322.7	148.1	1091.0	292.2	-	-	34/66	15.8
C-RCA50	591.9	77.2	569.0	-	219.8	379.3	31/69	32.6
C-RCA60	598.3	61.5	453.0	-	262.5	452.9	32/68	39.1
C-RCA70	604.6	45.9	338.0	-	304.8	525.8	32/68	45.7
C-RCA80	611.0	30.4	224.2	-	346.6	597.9	32/68	52.2
C-RCA90	617.4	15.1	111.6	-	387.9	669.3	33/67	58.7
C-RCA100	623.8	-	-	-	428.8	739.9	33/67	65.2
M-RCA10	547.7	76.3	561.7	55.1	217.0	374.4	32/68	35.2
M-RCA20	500.5	75.2	554.1	113.3	214.1	369.4	33/67	38.1
M-RCA30	450.2	74.2	546.2	174.8	211.1	364.3	34/66	41.1
M-RCA40	396.7	73.1	538.5	239.5	208.1	359.0	35/65	44.4
M-RCA50	339.7	72.0	530.5	339.7	205.0	353.7	36/64	47.9

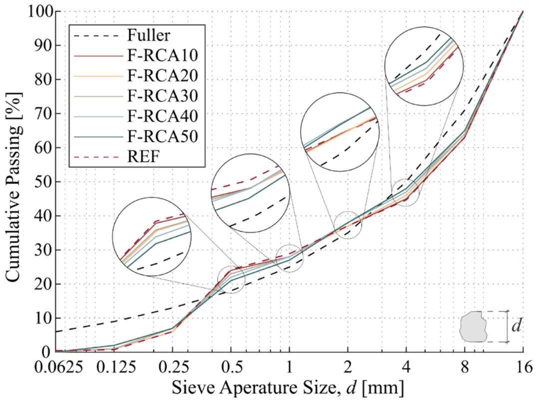


Figure 4 - Particle size distributions for F-RCA and reference mixtures in Series A

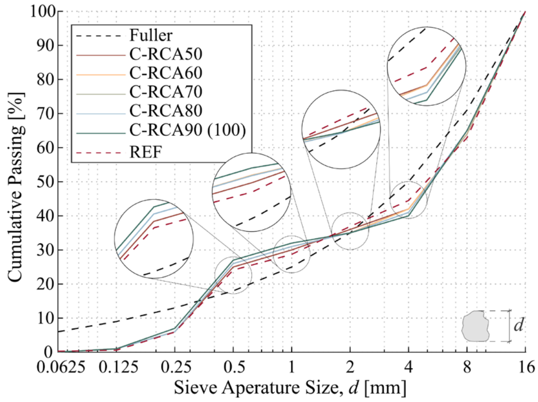


Figure 5 - Particle size distributions for C-RCA and reference mixtures in Series A

Differing from the gradation curves with partial replacement of the fine aggregate fraction, the reference mixtures are closer to Fuller's ideal grading curve regarding replacement of the coarse aggregate fraction, see Figure 5.

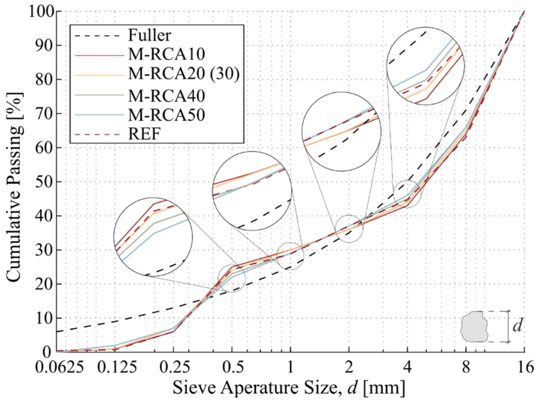


Figure 6 - Particle size distributions for M-RCA and reference mixtures in Series A

Furthermore, it can be seen in Figure 6, that particle size distributions for the reference curves are in between the M-RCA mixtures.

Mixture design for varying target strengths

In Series B, five different RCA mixtures were designed with mean compressive strengths ranging from 28 MPa to 68 MPa, in order to investigate the effect of the strength of the donor concrete on RCA concretes with varying target compressive strengths. Hence, the mean strength of the donor concrete was higher than or approximately equal to the targeted strength of the RCA mixtures. Common for these RCA mixtures was a fixed replacement ratio of 50 % of the fine aggregate fraction and 100 % of the coarse aggregate fraction. In addition, three different reference mixtures using only NA were designed to comply with mean target compressive strengths varying from 28 MPa to 48 MPa.

For each target compressive strength, the mixture design was based on determination of an initial amount of water with respect to aggregate shape and size as well as a target slump of 120 mm, after which the cement content was chosen based on the required water-to-cement ratio for the targeted strength. Next, superplasticiser was used to reduce the initial amount of water by 20 %, due to which the cement content was also decreased to maintain the specified water-to-cement ratio for each mixture. The amount of superplasticiser corresponded to 0.7 % of the cement weight for all concrete mixtures. Aggregate compositions were identical for the reference mixtures and the RCA mixtures, respectively, and determined as described in Section 2.2 and shown in Figure 7.

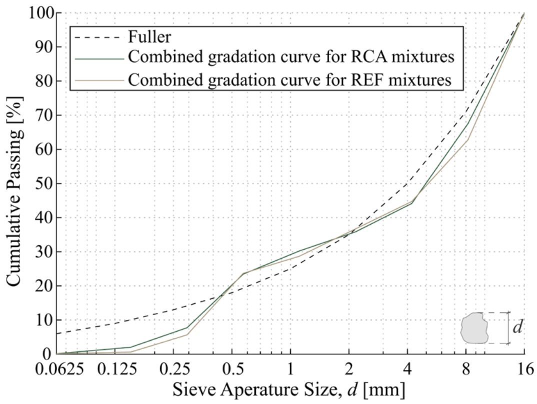


Figure 7 - Particle size distributions for RCA and reference mixtures in Series B

Thus, the only variation between the mixtures was an increase in cement content corresponding to the prescribed water to cement ratio for each mixture, which in turn entailed a larger amount of superplasticiser for increasing target compressive strengths. The prescribed water to cement ratios for the concrete mixtures in Series B can be seen in Table 5.

Table 5 - Overview of prescribed water to cement ratios for mixture designs in series B

	REF 28	REF38	REF48	RCA28	RCA38	RCA48	RCA58	RCA68
w/c	0.70	0.56	0.47	0.70	0.56	0.47	0.40	0.35

The increase in volume of the cement pastes with increasing target compressive strengths subsequently caused a decrease in the nominal amounts of aggregates used for each reference and RCA mixture, details can be found in Tables 6 and 7.

Table 6 - Overview of reference concrete mixture designs for Series B

REF Mixture	Rapid CEM I 52.5 N	Water	Iron oxide powder	Dynamon Xtend 391	F-NA 0/4 mm	C-NA 2/8 mm	C-NA 6/16 mm	Sum
	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]	[kg/m^3]
REF28	240.0	166.9	4.8	1.7	582.4	164.4	1210.9	2371
REF38	300.0	167.2	6.0	2.1	566.6	160.0	1178.2	2380
REF48	357.6	167.6	7.2	2.5	551.5	155.7	1146.8	2389

Table 7 - Overview of RCA concrete mixture designs for Series B

RCA Mixture	Rapid CEM I 52.5 N	Water	Iron oxide powder	Dynamon Xtend 391	F-NA 0/4 mm	F-RCA 0/2 mm	C-RCA 2/6 mm	C-RCA 6/16 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]
RCA28	240.0	166.9	4.8	1.7	370.8	335.8	413.8	713.9
RCA38	300.0	167.2	6.0	2.1	360.7	326.7	402.6	694.6
RCA48	357.6	167.6	7.2	2.5	351.1	318.0	391.9	676.1
RCA58	417.6	167.9	8.4	2.9	341.1	308.9	380.7	656.8
RCA68	477.6	168.2	9.6	3.3	331.1	299.9	369.5	637.6

Casting of cylinders

Cylinders with a height of 200 mm and a diameter of 100 mm were cast at the DTU Concrete Laboratory under conditions conforming to the provisions given in [36]. On each designated day of casting, the actual moisture contents of all types of aggregate were determined in coherence with [37], however, using a microwave oven instead of a drying cabinet as allowed for in [6]. The amount of water in the mixture designs was then adjusted accounting for the measured moisture content of the aggregates. A standardised procedure was employed for casting of each batch. Initially, coarse and fine fractions of aggregate were mixed in a 50 L Zyklos rotating pan mixer, after which iron oxide colouring powder was introduced and dry mixed for 30 seconds. Subsequently, cement was added to the mixture and dry mixed for an additional 30 seconds. Following this, water and superplasticiser were added, and mixing was carried out for a duration from 60 seconds to 150 seconds depending on the workability of the individual mixtures. The workability of the fresh concrete mixture was assessed by measuring the slump and air content of each mixture, conducted in accordance with [38] and [39], respectively. Preparation of the specimens was carried out in accordance with [40], hence, the cylinders were filled halfway and compacted, then completely filled and compacted again. Compaction was performed using a vibration table with a frequency of 50 Hz. One day after casting, the cylinders were demoulded and placed in water at room temperature of approximately 20 °C.

2.3 Test methods

The compressive strength, tensile splitting strength, and modulus of elasticity were determined for the various mixture designs, with four cylinders allocated for each test. The assessments of fundamental material properties were conducted in accordance with DS/EN 12390-3 [41], DS/EN 12390-6 [42], and DS/EN 12390-13 [43], respectively. Splitting tensile tests were conducted using an MTS electromechanical test machine [44] with a capacity of 600 kN. The tests were conducted in force control using a designated splitting fixture at a loading rate of 1.6 kN/s corresponding to an average rate of 0.05 MPa/s. Compressive testing and determination of the modulus of elasticity were carried out using a Toni Technik servohydraulic test machine [45] with a capacity of 2.8 MN. The load was applied in force control at a rate of 4.7 kN/s, corresponding to 0.6 MPa/s. During the load cycles specified for determining the modulus of elasticity, an extensometer was mounted on each test specimen. On the day of testing, the relevant test specimens were extracted from the curing tub, weighed, and measured in terms of height and diameter. All specimens were tested 28 days after casting apart from the splitting tensile tests for mixtures MRCA10, M-RCA20, and M-RCA30, which were tested 30 days after casting.

3. RESULTS, OBSERVATIONS, AND DISCUSSIONS

The following section presents the test results for all reference and RCA mixtures in both experimental series. This includes results of the slump tests, compressive and tensile strength, as well as elastic modulus, which are apparent from Tables 8 and 9 for Series A and Series B, respectively. Furthermore, a number of representative fractured surfaces are examined visually with a focus on a qualitative determination of the presence of the RCA particles in the fractured surfaces, including identification of failure going through or around the aggregate particles. All data related to the experimental study can be accessed at DTU Data [35].

Table 8 - Overview of test results for series A

Mixture design	f_{cm}	f_{ctm}	E_{cm}	ρ_m	Slump	Air content
	[MPa]	[MPa]	[GPa]	[kg/m^3]	[mm]	[%]
F-RCA10	53.6	4.0	39.1	2401	135	1.3
F-RCA20	52.2	4.1	38.6	2382	145	1.5
F-RCA30	60.4	3.9	41.7	2380	35	2.0
F-RCA40	54.3	4.1	38.7	2376	30	2.2
F-RCA50	55.6	3.8	37.5	2373	40	2.1
C-RCA50	52.3	3.7	38.0	2338	135	0.8
C-RCA60	52.4	3.6	36.2	2354	130	*
C-RCA70	51.1	3.5	33.7	2335	75	1.0
C-RCA80	53.9	3.6	33.4	2326	100	1.4
C-RCA90	50.6	3.4	34.7	2322	145	1.4
C-RCA100	48.6	3.8	35.0	2289	180	1.4
M-RCA10	49.0	3.7	35.1	2330	140	1.1
M-RCA20	55.0	3.9	37.1	2332	150	1.6
M-RCA30	47.0	3.7	35.5	2327	150	1.4
M-RCA40	47.1	3.6	34.7	2322	145	1.8
M-RCA50	46.0	3.5	34.2	2310	175	1.8
REF	54.0	3.9	41.5	2399	105	0.8
REF RED	58.7	4.2	41.0	2399	50	0.9

* Failed test

Table 9 - Overview of test results for series B

Mixture design	f_{cm}	f_{ctm}	E_{cm}	ρ_m	Slump	Air content
	[MPa]	[MPa]	[GPa]	[kg/m^3]	[mm]	[%]
RCA28	27.4	2.8	25.7	2215	160	2.5
RCA38	41.7	3.3	31.0	2247	155	1.6
RCA48	43.0	3.2	31.6	2231	205	1.9
RCA58	59.1	4.1	34.1	2265	200	2.5
RCA68	61.7	3.8	34.0	2263	210	2.3
REF28	38.8	3.2	37.2	2394	55	0.8
REF38	54.8	3.8	40.4	2412	65	0.9
REF48	64.3	4.1	41.5	2386	70	2.0

In Figure 8, a density decrease can be observed with increasing RR for Series A, confirming results found in [30]. The increase in RR results in a decrease in hardened concrete density, which is caused by the lower density of RCA in comparison to NA for both the fine and coarse aggregate fractions. The same tendency is seen in Figure 9, where the RCA mixtures in Series B exhibit significantly lower densities than the corresponding reference mixtures, with RCA mixtures having a fixed RR of 50 % of the fine aggregate fraction and 100 % of the coarse aggregate fraction, thus corresponding to a total RR of 80 %. No mixtures exhibited signs of bleeding or separation.

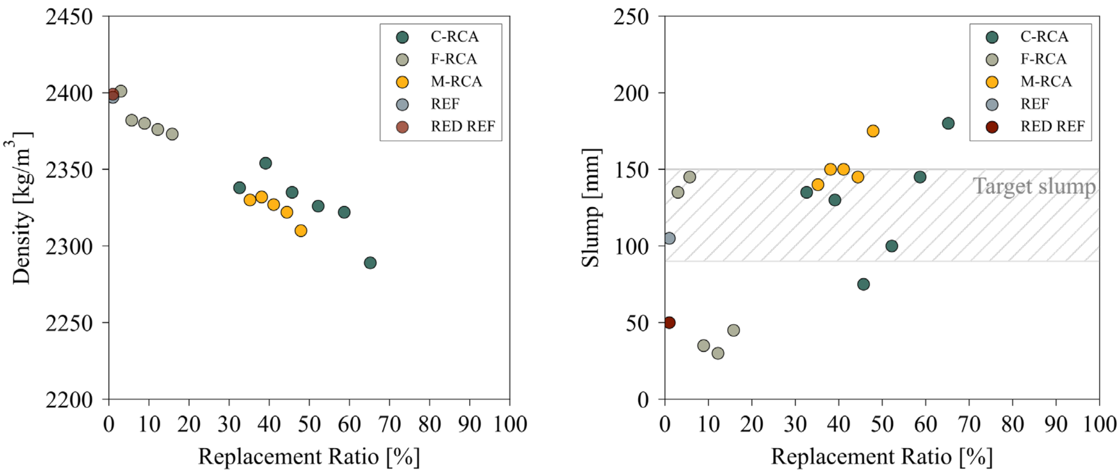


Figure 8 - Average density and slump for all mixture designs in Series A

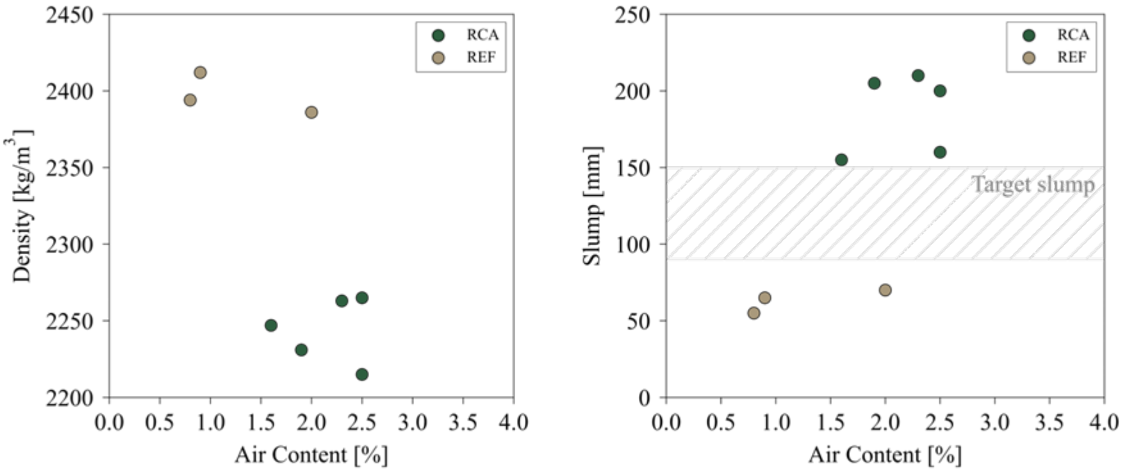


Figure 9 - Average density and slump for all mixture designs in Series B

Additionally, Figures 8 and 9 illustrate the slumps recorded for all mixture designs in both series, where significant deviations from the target slump range of 120 mm ± 30 mm were observed. For Series A, slightly more than half of the mixtures were within the target range, whereas none of the mixtures were within the target range for Series B. The varying workability of the mixtures was primarily governed by factors such as the determination of the actual water content of the aggregates, for both NA and RCA, on the designated days of casting, and likely also the high absorption capacities determined for the RCA. An incorrect determination of the actual moisture states of NA and RCA causes over- or under-adjustments of the required amount of water for the mixture designs, potentially causing RCA to absorb mixture water. Additionally, an overestimate of the absorption capacities of the different gradations of RCA will cause excess water that cannot be absorbed by the aggregate, hence increasing the effective water-to-cement ratio. For the two investigated test series, the absorption capacities of the RCA gradations were presumably overestimated due to the test methods currently available, which are applicable to NA. This poses a significant risk of error as the mortar attached to the NA of the donor concrete increases the porosity and surface area of RCA, thus making it challenging to assess the saturated surface dry state of the aggregate, which is necessary to determine the absorption capacity. In general, for both test series, the slumps were higher for RCA mixtures than for the reference mixtures, which was likely caused by the slump being measured immediately after mixing, due to which the absorption capacities of the RCA were not yet reached, consequently causing free water to be present in the mixtures at the time of slump measurement. This resulted in workability being notably affected by the replacement of NA with RCA, a tendency which confirms findings in [46], and may result in undesirable behaviour of the concrete, particularly in terms of structural performance. Furthermore, varying workability may also affect properties such as dimensional stability, surface quality, and compaction efficiency adversely, due to which controlled workability is critical for practical applications and large-scale production.

3.1 Compressive strength

In total, 104 cylindrical specimens were tested to determine the mean compressive strength, f_{cm}, of all RCA and reference mixtures in both test series with a distribution of 72 specimens for Series A and 32 for Series B. In Series A, a reduction in compressive strength was observed for both the C-RCA and the M-RCA concrete mixtures, while a slight increase was observed for the F-RCA mixtures with increasing RRs. The mean compressive strengths of all mixtures along with the standard deviations can be seen in Figure 10, where the proportioning strength of 43 MPa is exceeded for all mixtures. Overall, the observed reductions in compressive strength align well with the findings in the existing literature.

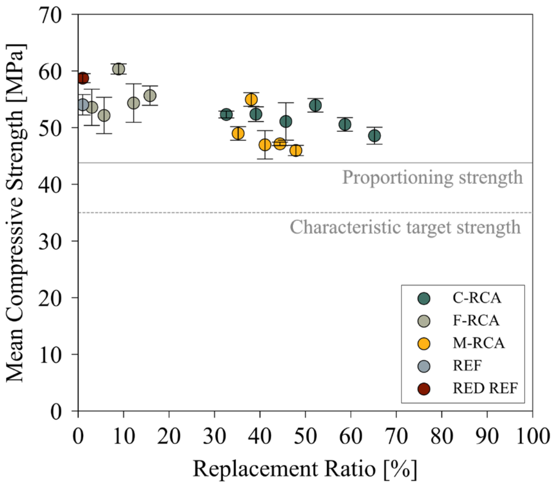


Figure 10 - Mean compressive strengths of RCA and reference mixtures for Series A

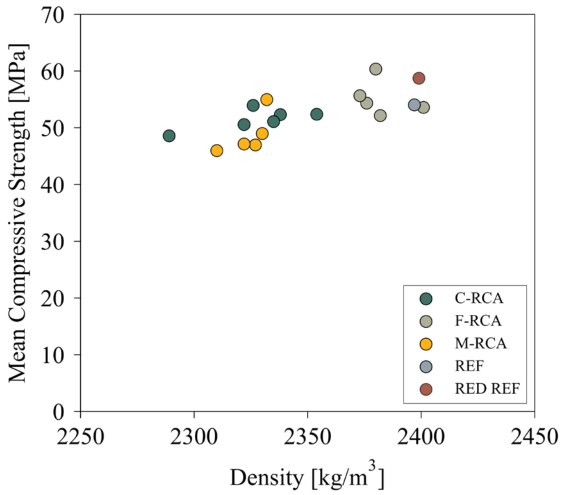


Figure 11 - Mean compressive strengths of RCA and reference mixtures versus density for Series A

In Figure 10, it can be observed that most M-RCA mixtures exhibit lower compressive strengths than C-RCA mixtures, indicating that simultaneous replacement of the fine and coarse aggregate fractions is not necessarily advantageous. However, an increase in replacement of F-RCA tended to enhance the packing of the concrete mixtures at low replacement ratios. The maximum reduction in strength was 22 % for M-RCA50 in comparison to the red reference concrete, which exhibited higher strength than the non-coloured reference concrete. For the majority of the remaining mixtures, the reduction in compressive strength was significantly smaller, while still illustrating an overall decrease in compressive strength with increasing RR. As anticipated throughout Series A, it was observed that compressive strength increased along with an increase in hardened material density of the concrete mixtures, which can be seen in Figure 11.

For all RCA and reference mixtures in Series B, a natural air content of $a_0 = 1.5$ % was aimed for as the basis-target of the mixture design. Figure 12 shows that the actual air content was exceeded in all RCA mixtures, while it was lower in the two reference mixtures, REF28 and REF38. This suggests that replacing NA with RCA leads to an increase in voids within the concrete mixtures due to RCA being more porous than NA, which is further supported by the lower densities of RCA compared to NA, as shown in Figure 9.

Overall, the compressive strengths of the RCA mixtures tested slightly lower than the corresponding mean strengths of the reference mixtures. Seeing that the actual air content of both RCA and reference mixtures is known, the compressive strength according to Bolomey's expression [32] can be determined.

$$f_c = K\,(1/(w/c)-\alpha)\,(1-0.04\,(a-a_0)) \tag{3}$$

Where f_c is the target compressive strength, a is the current air content, and K as well as α are constants dependent on cement type and age of the concrete at the day of testing, which is 28 days in the current experimental campaign. In Figure 13, the mean compressive strengths for the RCA and reference mixtures are shown for Series B in comparison to the calculated compressive strengths given by [34] and by [32], where the reference mixtures all tested significantly higher than their corresponding RCA mixtures.

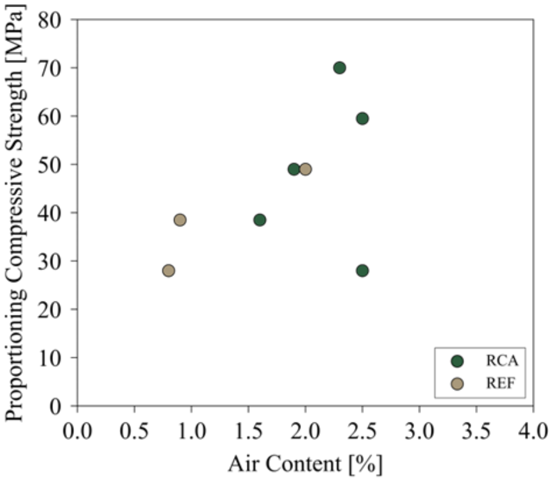


Figure 12 - Proportioning compressive strengths of RCA and reference mixtures versus measured air content for Series B

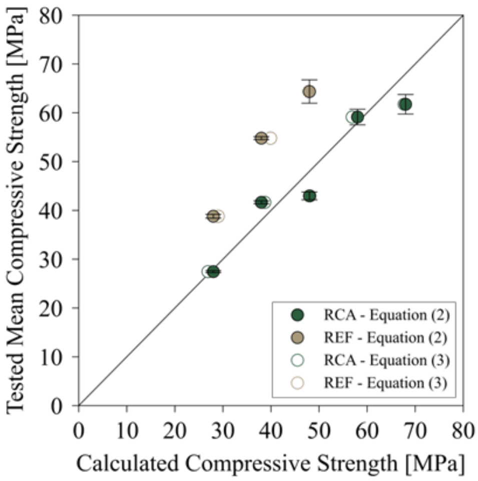


Figure 13 - Tested and calculated compressive strengths for Series B

The largest deviation between the predicted compressive strength using Equation 3 and the proportioning strength is less than 5 %, which is expected as the air content of all concrete mixtures in Series B varied by approximately 1.5 %. Both strength prediction methods align fairly well with the compressive strengths of the RCA mixtures, indicating that the methods are applicable to RCA concrete as well as traditional concrete. However, the methods are considerably less conservative for the RCA mixtures than for the reference mixtures.

3.2 Tensile strength

To determine the mean tensile strength, f_{ctm}, of the concrete mixtures, 72 specimens from Series A and 32 specimens from Series B were tested. The tensile strengths of all concrete mixtures were determined in accordance with CEN-DS/EN 1992-1-1 [34], where the relation between splitting tensile strength, $f_{ct,sp}$, and axial tensile strength, f_{ct}, is as follows:

$$f_{ct} = 0.9\, f_{ct,sp} \tag{4}$$

As shown in Figure 14 for Series A, a general decrease in tensile strength was observed with increasing RRs. However, this decrease was less pronounced than the one observed regarding compressive strength in terms of percentage reduction. Compared to the red reference concrete, the maximum reduction in tensile strength was 17 % for C-RCA90. According to [17], tensile strength is primarily governed by the binder matrix and is, therefore, less affected by the aggregates and thereby an increasing value of RR. Unlike the compressive strength, the M-RCA mixtures exhibited higher tensile strengths than the C-RCA mixtures, suggesting that the geometric properties of F-RCA may potentially enhance the binder matrix. Overall, the tensile strength of RCA mixtures was comparable to that of the reference mixtures considering the usual scatter in experimental results for concrete materials.

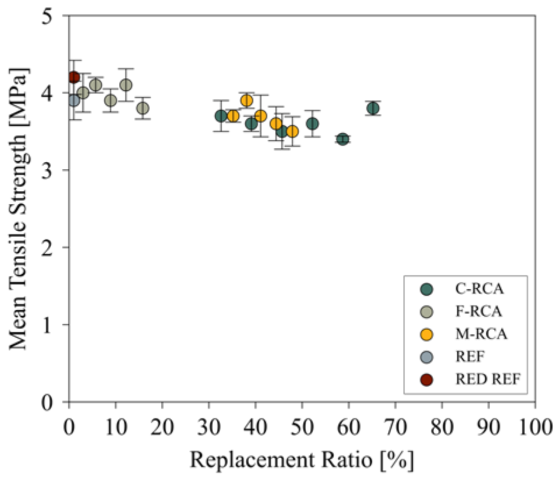


Figure 14 - Mean tensile strengths of RCA and reference mixtures for Series A given by Equation (4)

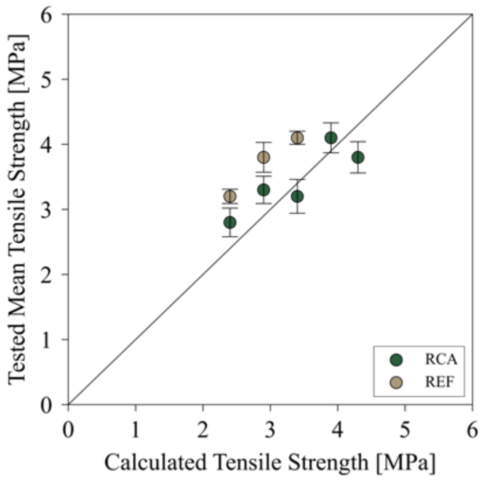


Figure 15 - Tested tensile strengths for Series B (converted by use of Equation (4)) versus calculated uniaxial tensile strengths according to Equation (5)

In Figure 15, the mean tensile strengths of the RCA and reference mixtures are plotted against the mean tensile strength determined according to the well-established relation given in [47] as stated in Equation (5):

$$f_t = 0.26\, f_c^{2/3} \tag{5}$$

Where f_c is in MPa. At target mean compressive strengths of 28 MPa, 38 MPa, and 58 MPa, the RCA mixtures exhibited tensile strengths higher than those predicted by Equation 5, as did all reference mixtures. Conversely, for RCA mixtures with target mean compressive strengths of 48 MPa and 68 MPa, reduced tensile strengths were observed. This indicates that replacement of NA with RCA at a total RR of 80 % has a greater impact on tensile strength for higher compressive target strengths compared to lower ones. Also, it underlines the relevance of dividing restrictions for replacement of NA with RCA into two strength categories (above and below f_{ck} = 35 MPa), which is currently the case in Denmark, see [6]. However, since methods for determining the tensile strength vary, no definitive conclusion can be drawn regarding the potential inferiority of RCA concrete compared to conventional concrete.

The tested mean compressive strengths are plotted against the corresponding mean tensile strengths in Figure 16(a) for Series A and in Figure 16(b) for Series B, respectively. Overall, the relation between compressive and tensile strengths found in both experimental series appears to follow the relation given in [47]. Hence, the data presented in Figure 16 for both test series indicate that the tensile strength of RCA concrete mixtures may be estimated based on their compressive strength as for conventional concrete. Despite the scatter observed in the figure, neither RR nor varying compressive strength for normal strength concretes appear to have a significant influence on the relation between compressive and tensile strength, confirming findings in [7].

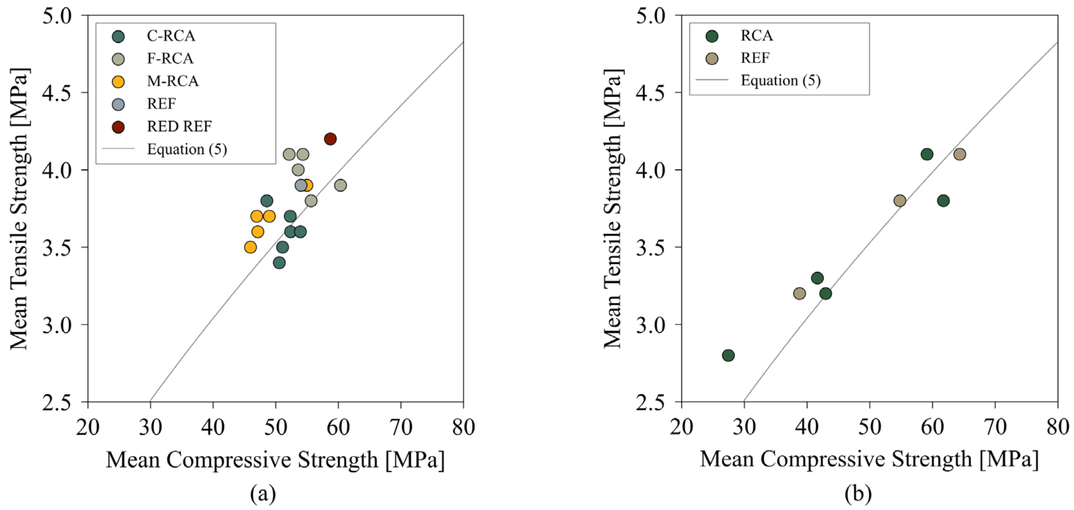


Figure 16 - Mean compressive strengths versus mean tensile strengths for Series A and B

3.3 Modulus of elasticity

To study the influence of RCA on the mean modulus of elasticity, E_{cm}, 72 specimens from Series A and 32 specimens from Series B were evaluated. A decrease in the modulus of elasticity was observed for all RCA mixtures in Series A, with the maximum reduction being 19 % in comparison to the modulus of elasticity of the reference concrete. However, as the RRs increased, the modulus of elasticity was roughly constant for the C-RCA mixtures, while both F-RCA and M-RCA mixtures exhibited an expected decrease in the modulus of elasticity with increasing RRs, considering a decreasing tendency for f_{cm}.

The observed reduction of stiffness for the RCA mixtures is primarily attributed to the stiffness of the cement paste within the RCA as the aggregate materials of the donor concrete were sourced from identical batches as the NA used in the RCA mixtures. As anticipated, the reduction in density seen in all RCA concrete mixtures with increasing RRs suggests an increased porosity, which is likely to lead to lower stiffness in the RCA mixtures. Additionally, it is plausible that the crushing process during RCA production induced microcracks in the aggregate, further contributing to the reduced stiffness of RCA compared to NA. In Figure 18, the mean modulus of elasticity for each RCA and reference mixture in test Series B is compared to the mean modulus of elasticity, E_{cm} (in GPa), as defined in CEN-DS/EN 1992-1-1 [34], which is given by:

$$E_{cm} = 22\ (f_{cm}/10)^{0.3} \qquad (6)$$

Where f_{cm} is inserted in MPa. An overestimate in stiffness is observed across all RCA mixtures, while an underestimate is found for all reference mixtures relative to the calculated modulus of elasticity, which is determined entirely based on the compressive strength of the concrete mixture. This indicates that Equation 6 should be used with care in relation to structural design of RCA concrete, where deflections in the serviceability limit state as well as buckling capacity in the ultimate limit state could be underestimated.

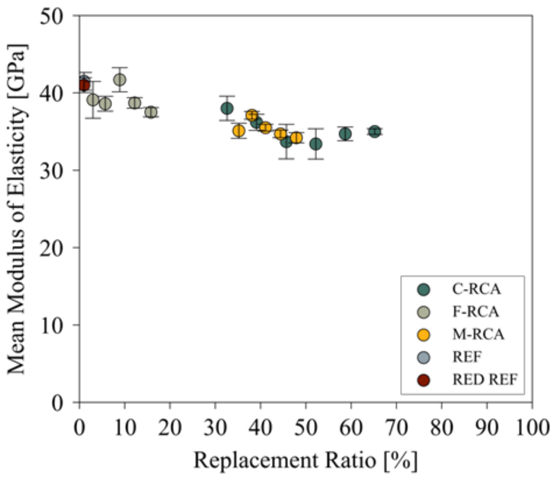


Figure 17 - Modulus of elasticity of each RCA and reference mixture for Series A

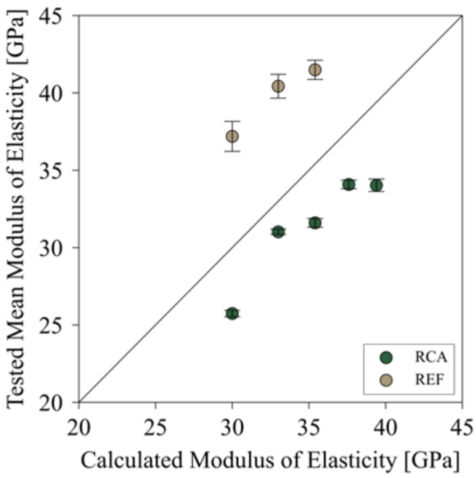
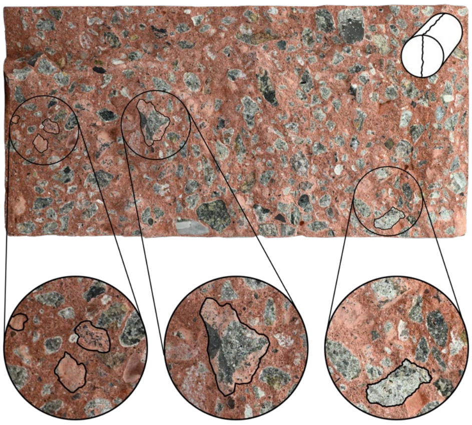


Figure 18 - Tested and calculated modulus of elasticity according to Equation 6 for Series B

This reduction in stiffness for the RCA mixtures is likely due to both the lower density of RCA compared to NA and potential microcracks introduced in the aggregates during the crushing process, which are effects that become increasingly pronounced at high RRs. Additionally, the stiffness of the mixtures decreases slightly with an increase in the volume of cement paste as the target strength increases, highlighting that the stiffness of hardened concrete is strongly influenced by the aggregates, particularly the coarse fraction, where NA is entirely replaced by RCA in all RCA mixtures in Series B, hence, the underestimate by the expression in Equation 6 for conventional concrete.

3.4 Fractured surfaces

The intention of colouring the concrete mixtures in both test series was to accentuate the aggregates, NA as well as RCA, in the fractured surfaces of all test specimens. This enabled the distinction between paste and the aggregates, especially with regard to the RCA, where the difference between the new paste and the old paste of the donor concrete was emphasized. Generally, intergranular failure is expected to occur when the paste is weaker than the aggregate, whereas transgranular failure will occur when the cement paste is stronger than the aggregate [48]. Thus, for intergranular failure, the fracture path goes around the aggregate, whereas the aggregate is fractured for transgranular failure. Finally, inter- and transgranular failure can also be combined. All three failure modes of the aggregates were observed for both NA and RCA in all mixtures. Hence, the addition of iron oxide to the concrete mixtures made it possible to identify whether the failure was intergranular or transgranular, which can be seen in Figure 19. In general, fractured surfaces with intergranular aggregate failure have a higher amount of protruding aggregates than surfaces with transgranular aggregate failure, where the fractured aggregate particles decrease surface roughness as the failure typically develops over the shortest possible distances.



(a) (b) (c)

Figure 19 - Failure modes of aggregate for mixture C-RCA100 with 100 % replacement of the coarse aggregate fraction. (a) Intergranular, (b) Combined inter- and transgranular, (c) Transgranular

However, in spite of both the NA and the RCA exceeding the strength of the cement paste in Series A, mostly transgranular failures were observed throughout all RRs for both uniaxial compression failure and splitting failure of the tested cylinders. As expected, in Series B, transganular failure of the aggregate increased with increasing compressive strength of the mixtures, which can be seen in Figure 20. Thus, for uniaxial compression failure, the surface roughness decreased with increasing material strength. Regarding intergranular failure of the aggregate, there is no significant difference between NA and RCA, as the failure occurs in the ITZ between cement paste and large aggregate particles. Here, smaller aggregate particles and hydration products cannot pack as closely, effectively increasing the water to cement ratio around the aggregates [48]. Thus, the intergranular failure mechanism is the same for NA and RCA as shear bond failure occurs at the surface of the aggregates [48]. However, due to the increased surface area of RCA compared to NA, it is to be expected that the ITZs of RCA concretes are likely weaker than corresponding ITZs of conventional concretes, as more water will be able to accumulate when water films form around the aggregate particles. In contrast, for transgranular failure of the aggregate, the difference between NA and RCA is more pronounced.

(a) (b) (c)

Figure 20 - Fractured surfaces of cylinders tested in uniaxial compression in Series B. (a) RCA20, (b) RCA40, (c) RCA60

Due to transgranular failure resulting in fractured aggregate particles, the fracture path for RCA can either pass through the paste and around the embedded NA of the donor concrete, or it can split the entire RCA particle, which is also the case for NA. Hence, transgranular failure for RCA concrete potentially gives rise to increased surface roughness compared to conventional concrete, due to protruding aggregates of the donor concrete in the fractured surface. Examples of this were observed for both Series A and B for the uniaxial compression failure as well as splitting failure. The observations made regarding the fractured surfaces are general for both test series, and indicate that detrimental effects of RCA concrete are primarily caused by the AM. As the observations in the current study were derived from macro images, a more detailed investigation of the fractured surfaces and ITZs of the RCA would necessitate a microstructural analysis. Additionally, regarding fracture of the aggregates, less energy is required to extend an already existing crack than to propagate a new crack. Hence, lower loads can be sustained by the RCA concretes when micro cracking is present. In the current experimental series, it was not possible to evaluate the extent of potential micro cracking of the RCA, and thus more research is needed to explore this in relation to the roughness of fractured surfaces of RCA concrete.

4. CONCLUSIONS

The current study presented a systematic experimental investigation of the influence of varying RRs and varying target compressive strengths on basic mechanical properties of RCA concretes, including compressive strength, tensile strength, and modulus of elasticity. The results were compared to the properties of reference specimens, and the main conclusions of the study are:

- The experimental campaign suggests that it is feasible to significantly exceed current recommendations of allowable replacement ratios, provided that the target compressive strength is lower than the compressive strength of the donor concrete. Hence, untreated RCA is a viable alternative to NA, even at a total replacement ratio of up to 80 %.
- Both compressive and tensile strength of RCA concrete depend on the replacement ratio and the size of the aggregate fraction that is replaced. Addition of the fine aggregate fraction of RCA seems to contribute positively to the packing properties.
- A decrease in modulus of elasticity is observed compared to conventional concrete, and it appears to be more influenced by increasing replacement ratio than the particle fraction that is replaced.
- Consistent workability at high replacement ratios remains difficult to maintain, potentially being a challenge when using RCA in large-scale production in practice.
- Large amounts of RCA do not cause considerable changes in the investigated material properties. However, the increased porosity, absorption capacity, and surface area of the RCA contribute to a slight reduction in the basic material properties of RCA concrete. Most issues related to RCA may therefore be attributed to the attached mortar, nevertheless, replacement of the fine NA fraction with the fine RCA fraction, consisting primarily of crushed mortar, appeared not to affect the investigated mechanical properties adversely.

Overall, the results of the current systematic study corroborate indicative findings of previous research by proportioning RCA mixture designs based on a simplified particle packing approach. Consequently, target compressive and tensile strengths of RCA concretes can be achieved at high replacement ratios, whereas a reduction in the modulus of elasticity is anticipated. The results were obtained without any increase in cement content or pre-treatment of the RCA before mixing it in new concrete, and the observed material behaviour remains comparable to that of conventional concrete.

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REFERENCES

1. Marinkovic S. Josa I., Braymand S., and Tošić N.: “Sustainability Assessment of Recycled Aggregate Concrete Structures: A Critical View on the Current State-of-Knowledge and Practice”. *Structural Concrete,* 24(2), 2023, 1956-1979.
2. McGinnis M. J., Gangone M. V., Nogales A., Gomez-Santana L. M., Weldon B., Reihl A., Tošić N., and Kurama Y.: “Experimental and numerical investigation of the bending, shear, and punching shear behavior of recycled aggregate concrete precast/prestressed hollow core slabs”. *Structural Concrete,* 25(6), 2024, 4340–4364 .
3. Dhir R., de Brito J., Silva R., and Lye C.: “Sustainable Construction Materials: Recycled Aggregates, 3 Availability of Recycled Aggregates”. Elsevier, 2019, 35-56.
4. de Larrard F. and Colina H.: “Concrete Recycling Research and Practice”. Taylor and Francis Group, 2019.
5. Pacheco J., de Brito J., and Tornaghi M. L.: “Use of Recycled aggregates in concrete: opportunities for upscaling in Europe”. Tech. Rep. Publications Office of the European Union, 2023.
6. Danish Standards Association. “DS 206:2024 Beton - Specifikation, egenskaber, produktion og overensstemmelse - Regler for anvendelse af EN 206 i Danmark”. Tech. Rep. 2024, (in Danish).
7. Tošić N., Torrenti M., Sedran T, and Ignjatović I.: “Toward a Codified Design of Recycled Aggregate Concrete Structures: Background for the new fib Model Code 2020 and Eurocode 2“. *Structural Concrete,* 22(5), 2021, 2916-2938.
8. Pepe M., Filho R. D. T., Koenders E. A. B., and Martinelli E.: “A Novel Mix Design Methodology for Recycled Aggregate Concrete”. *Construction and Building Materials,* 122, 2016, 362-372.
9. Gómez-Soberón J. M. V.: “Porosity of Recycled Concrete with substitution of Recycled Concrete Aggregate”. *Cement and Concrete Research,* 32(8), 2002, 1301-1311.
10. de Andrade G. P., de Castro Polisseni G., Pepe M., and Filho R. D. T.: “Design of Structural Concrete Mixtures containing Fine Recycled Aggregate using Packing Model”. *Construction and Building Materials,* 252, 2020.
11. Xiao J. and Zhang Y.: “Technical Committee for Structural Behaviour and Innovation of Recycled Concrete Aggregate: Report on Recycled Aggregate Concrete, Part I – Material Properties”. RILEM, 2022.

12. Kim J.: "Influence of Quality of Recycled Aggregates on the mechanical properties of Recycled Aggregate Concretes: An overview". *Construction and Building Materials*, 328, 2022.
13. Singh G: "Influence of Partial Replacement of RCA on Properties of Concrete". *Materials Today: Proceedings*, 37(2), 2021, 2432-2438.
14. Etxeberria M., Vázquez E. Marí A., and Barra M.: "Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete". *Cement and Concrete Research,* 37(5), 2007, 735-742.
15. Kazemian F., Rooholamini H., and Hassani A.: "Mechanical and Fracture Properties of Concrete Containing Treated and Untreated Recycled Concrete Aggregates". *Construction and Building Materials,* 209, 2019, 690-700.
16. Peng G., Huang Y., Wang H., Zhang J., and Liu Q.: "Mechanical Properties of Recycled Aggregate Concrete at Low and High Water/Binder Ratios". *Advances in Materials Science and Engineering,* 2013, 1-6.
17. Robalo K., Costa H., do Carmo R., and Júlio E.: "Experimental Development of Low Cement Content and Recycled Construction and Demolition Waste Aggregates Concrete". *Construction and Building Materials,* 273, 2021.
18. Sato R., Maruyama I., Sogabe T, and Sogo M.: "Flexural Behaviour of Reinforced Recycled Beams". *Journal of Advanced Concrete Technology,* 5, 2007, 43-61.
19. Soares D, de Brito J., Ferreira J., and Pacheco J.: "Use of Coarse Recycled Aggregates from Precast Concrete Rejects: Mechanical and Durability Performance". *Construction and Building Materials,* 71, 2014, 263-272.
20. López-Gayarre F., Serna P, Domingo-Cabo A., Serrano-López M. A., and López-Colina C.: "Influence of Recycled Aggregate Quality and Proportioning Criteria on Recycled Concrete Properties". *Waste Management*, 29(12), 2009, 3022-3028.
21. de Juan M. A. and Gutiérrez P. A.: "Study on the Influence of Attached Mortar Content on the Properties of Recycled Concrete Aggregate". *Construction and Building Materials,* 23(2), 2009, 872-877.
22. Ahmed H., Tiznobaik M., Huda S. B., Islam M. S., and Alam M. S.: "Recycled Aggregate Concrete from Large-Scale Production to Sustainable Field Application". *Construction and Building Materials,* 262, 2022.
23. Evangelista L. and de Brito J.: "Durability Performance of Concrete made with Fine Recycled Concrete Aggregates". *Cement and Concrete Composites,* 32(1), 2010, 9-14.
24. Nagataki S., Gokce A., Saeki T., and Hisada M.: "Assessment of Recycling Process Induced Damage Sensitivity of Recycled Concrete Aggregates". *Cement and Concrete Research,* 34(6), 2004, 965-971.
25. Nuno Pacheco J., de Brito J., and Lamperti Tornaghi M.: "Use of Recycled Aggregates in Concrete – Opportunities for upscaling in Europe". Publications Office of the European Union, Luxembourg, 2023.
26. Hansen T. C. and Narud H.: "Strength of Recycled Concrete Made from Crushed Concrete Coarse Aggregate". *Concrete International,* 5(1), 1983, 79-83.
27. Fennis S. A. A. M and Walraven J. C.: "Using particle packing technology for sustainable concrete mixture design". Heron, 57, 2012, 73-101.
28. European Committee for Standardization (CEN), "DS/EN 1097-6:2022 Tests for mechanical and physical properties of aggregates - Part 6: Determination of particle density and water absorption". Tech. Rep. 2022.
29. Thrysøe J.: "Absorption i tilslag til beton". Tech. Rep. 2019, Aalborg Portland A/S, (in Danish).

30. Butler L., West J., and Tighe S.: "Effect of Recycled Concrete Aggregate Properties on Mixture Proportions of Structural Concrete". *Transportation Research Record Journal*, 2290, 2012, 105-114.
31. Belén G., Fernando M., Diego C., and Sindy S.: "Stress-Strain Relationship in Axial Compression for Concrete using Recycled Saturated Coarse Aggregate". *Construction and Building Materials,* 25(5), 2011, 2335-2342.
32. Munch-Petersen G. N.: "Betonhåndbogen, Kapitel 6: Proportionering". Dansk Betonforening, 2013, (in Danish).
33. European Committee for Standardization (CEN), "DS/EN 993-1:2013 Tests for geometrical properties of aggregates - Part 1: Determination of particle size distribution - Sieving method". Tech. Rep. 2013.
34. European Committee for Standardization (CEN), "Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings". Tech. Rep. 2008.
35. Kristensen C., Hoang L. C., Sørensen J. H., Fischer G., and Hansen L. Z. P.: "Supplementary Material for "Mechanical Properties of Structural Concrete with Recycled Concrete Aggregates at High Replacement Ratios". Technical University of Denmark, https://doi.org/10.11583/DTU.28296110
36. European Committee for Standardization (CEN), "DS/EN 12390-1:2021 Testing hardened concrete - Part 1: Shape, dimensions and other requirements for specimens and moulds". Tech. Rep. 2021.
37. European Committee for Standardization (CEN), "DS/EN 1097-5:2013 Tests for mechanical and physical properties of aggregates - Part 5: Determination of the water content by drying in a ventilated oven". Tech. Rep. 2008.
38. European Committee for Standardization (CEN), "DS/EN 12350-2:2019 Testing fresh concrete - Part 2: Slump test". Tech. Rep. 2019.
39. European Committee for Standardization (CEN), "DS/EN 12390-2:2022 Testing hardened concrete - Part 2: Making and curing specimens for strength tests". Tech. Rep. 2019.
40. European Committee for Standardization (CEN), "DS/EN 12390-2:2022 Testing hardened concrete - Part 2: Making and curing specimens for strength tests". Tech. Rep. 2019.
41. European Committee for Standardization (CEN), "DS/EN 12390-3:2019 Testing hardened concrete - Part 3: Compressive strength of test specimens". Tech. Rep. 2019.
42. European Committee for Standardization (CEN), "DS/EN 12390-6:2023 Testing hardened concrete - Part 6: Tensile splitting strength of test specimens". Tech. Rep. 2023.
43. European Committee for Standardization (CEN), "DS/EN 12390-13:2021 Testing hardened concrete - Part 13: Determination of secant modulus of elasticity in compression". Tech. Rep. 2021.
44. MTS, EME-083-MTS-600KN Criterion C45.606, Technical University of Denmark, 2024, https://doi.org/10.57735/12257
45. Toni Technik, SHY-035-Toni Technik-280Ton, Technical University of Denmark, 2024 https://doi.org/10.57735/426
46. Kou S., Poon C., and Agrela F.: "Comparisons of Natural and Recycled Aggregate Concretes prepared with the Addition of Different Mineral Admixtures". *Cement and Concrete Composites*, 33(8), 2011.
47. Nielsen M. P. and Hoang L. C.: "Limit Analysis and Concrete Plasticity, Taylor and Francis Group, 2011.
48. Metha P. K. and Monteiro P. J. M: "Concrete: Microstructure, Properties, and Materials, 4th edition". McGraw-Hill Education, 2014.