Nordic Concrete Research – Publ. No. NCR 72 – ISSUE 1/ 2025 – Article 6, pp. 77-95

sciendo	Nordic Concrete Federation
	ISSN online 2545-2819 ISSN print 0800-6377
DOI: 10.2478/ncr-2025-0010	Received: March 27, 2025 Revision received: May 26, 2025 Accepted: June 2, 2025

Assessing the Mechanical Properties and Frost Resistance of Recycled Coarse Aggregate Concrete in Finland

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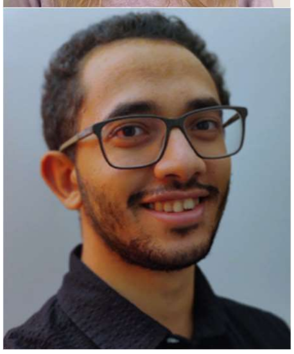

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ABSTRACT
Recycled concrete coarse aggregates (RCCA) offer a sustainable alternative to virgin aggregates in concrete production, addressing both environmental and economic concerns. This study evaluates the mechanical properties and freeze-thaw resistance of concrete with 50% and 100% RCCA replacement percentages, using aggregates sourced from demolished structures in Finland. A total of eleven concrete mixes were tested, categorized into four groups based on testing objectives: mechanical strength, elastic properties, creep and shrinkage, as well as freeze-thaw resistance. The results show that compressive strength decreased with higher RCCA replacement, but the extent of the reduction varied across mixes and testing ages. At 100% RCCA, the strength reduction was more noticeable, but it still varied depending on the mix. Young's modulus declined with increasing RCCA content, while creep strain increased, particularly at 100% RCCA replacement. In contrast, freeze-thaw resistance remained comparable to the control, with minimal internal damage and low surface scaling. These findings underscore the feasibility of RCCA in concrete applications, highlighting both its potential and performance limitations.

Key words: recycled coarse aggregates, compressive strength, flexural strength, Young's modulus, tensile strength, creep, freeze-thaw resistance.

1. INTRODUCTION

Concrete is the most widely used building material, with an average global production of about 25 billion tons per year [1], and its large-scale production accounts for 8% of global carbon dioxide emissions [2]. Given the serious threats posed by climate change, various authorities, companies, and social entities have been committed to mitigate its impact. Initiatives such as The Climate Promise 2025 aim to decrease greenhouse gas emissions on a multinational scale.

A significant global challenge in concrete production is the growing volume of construction waste. For instance, around 7.5 billion m³ of construction waste was dumped in landfills in China in 2013 [3]. This trend has led to decreasing landfill availability and rising disposal costs [4]. Recycling concrete waste into aggregates offers a dual benefit; it reduces waste by implementing the circular economy principle of transforming end-of-life concrete back into usable construction materials, while decreasing the environmental impact of quarrying virgin aggregates [5].

Furthermore, recycled concrete coarse aggregates (RCCA) can have a significantly lower carbon footprint compared to their virgin counterparts, as shown in Figure 1. This was reported by LCA Consulting Oy in Finland [6], as they analysed the carbon footprint of RCCA, crushed rock aggregates, and crushed gravel. RCCA demonstrated a negative carbon footprint of -26.9 $kgCO_2$-

eq/m³, primarily through carbon sequestration in its use and storage phases. In contrast, both crushed rock aggregates and gravel showed a positive carbon footprint of 5.7 and 6.8 $kgCO_2$-eq/m³, respectively. It should be noted that a significant portion of the negative carbon footprint arises from carbonation during the use phase, which can vary depending on the structural element. However, even if carbonation during the use phase were excluded from the calculation, the net carbon footprint would still be -1.4 $kgCO_2$-eq/m³, which is lower than that of the natural aggregates studied.

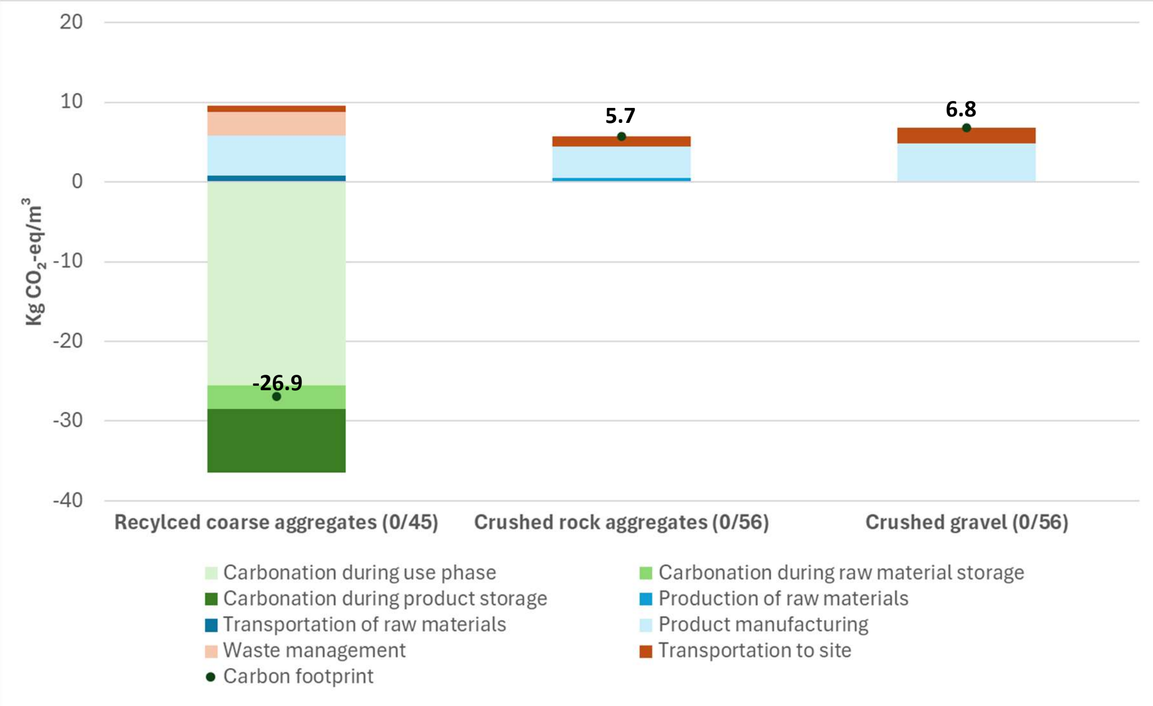


Figure 1 – Carbon footprint analysis of the recycled coarse aggregates used in this study, as well as their counterparts of crushed rock aggregates and crushed gravel in their use location in Vantaa, Finland

Despite the potential of RCCA, only a small fraction of concrete is currently recycled as aggregates [5, 7]. A large portion of RCCA in Finland has been used in road construction and similar applications, while some is directed toward lower-value uses such as landfills and noise barriers. To maximize its potential, it is essential to identify and promote higher-value applications for RCCA.

One way to integrate construction waste into concrete production is by replacing virgin aggregates (VA) with recycled coarse aggregates (RCCA). This approach is crucial because coarse aggregate production can account even up to 13% of the emissions in concrete production [8]. In Finland emissions for natural coarse aggregate is mostly much lower. However, the adoption of RCCA has been limited due to concerns about an inferior compressive strength [9, 10], a reduction in the elastic modulus [12, 13], poorer frost resistance [11], as well as an increase in creep and shrinkage [14–16] in RCCA concretes.

Researchers [5,16,17] have investigated methods to improve the quality of concrete made with RCCA. Kou et al. [16] showed improvement in the 28-day compressive strengths of RCCA concrete made with 25% fly ash additions, with reductions in drying shrinkage. However, the early age compressive strength remained low. More mineral admixtures in RCCA were studied by Kou et al. [17], who found an increase in both compressive and tensile strengths for 10% silica fume or 15% metakaolin replacement levels. Whereas, both fly ash and slag lowered the early age strengths. Furthermore, Sadagopan et al. [5] tested the impact of slag replacement and mechanical preprocessing on the compressive strength of RCCA concrete. They [5] found an improvement in the 28-day strength, while the 7-day strength remained lower than the reference unless mechanical pre-processing was employed.

Efforts to improve concrete sustainability also include updates to building standards. The new Eurocode 2 for concrete structures will come into effect in Finland within a few years, once the national annexes are created and approved. This is expected to occur by 2027. Eurocode 2 (EN 1992) introduces Environment Resistance Classes (ERC) for designing concrete structures. To fully utilize ERC classes, further research is needed to link these design values with the exposure classes outlined in EN 206 [20].

In response to these concerns and the need for more sustainable concrete production, this study extensively tested several mechanical properties and the freeze-thaw resistance of concrete with varying RCCA replacement percentages. The RCCA used was sourced from crushed concrete from demolished buildings and structures in Finland. The mechanical properties tested include compressive strength, tensile strength, flexural strength, elastic modulus, Poisson's ratio, and creep. Such research is vital for understanding the potential of RCCA in concrete and ensuring that it meets the necessary standards for performance and durability.

2. EXPERIMENTAL PROCEDURE AND METHODS

2.1 Materials and concrete mix designs

In this research, almost all concretes were prepared using the most used cement in Finland CEM II/B-M (S-LL) 42.5N. Based on previous testing, the same batches of CEM II/B-M showed unexpected poor performance in frost resistance in concrete mixes containing VA. However, using the sulphate-resistant CEM I 42.5N – SR3 with the same VA and at similar air entrainment levels, provided acceptable frost resistance, hence CEM I 42.5 – SR3 was used instead in the group tested for freeze-thaw resistance. This replacement should help reflect the impact of the used RCCA and eliminate the possibility of poor performance due to the cement itself. The typical composition of each cement is presented in Table 1. It should be noted that CEM II/B-M contains 8% added limestone, and 17% blast-furnace slag.

Table 1 – The chemical composition of CEM II/B-M (S-LL) 42.5N, and CEM I 42.5N – SR3

Cement	CEM II/B-M (S-LL) 42.5N						CEM II/B-M (S-LL) 42.5N					
Component	Ca	Si	Al	Fe	Mg	S	Ca	Si	Al	Fe	Mg	S
Mass%	58	21	6	3	3	3	67	22	5	3	3	0

The virgin aggregates (VA) used in this study were granitic, and consisted of 0–8 mm natural sand, 0–5 mm crushed rock fines, and 8–16 mm crushed aggregate, and their densities varied from 2.65 to 2.73 t/m³, while their water absorption ranged from 0.3–0.4%. The recycled coarse aggregates (RCCA) were of the size 8–16 mm, and their densities were around 2.68 t/m³, with a measured water absorption of 6.5%. All RCCA used were extracted from recycled crushed concrete scrapped from old, demolished structures, which contained some impurities such as tiles and bricks. In turn, around 1% of the used RCCA's mass consisted of the same impurities. The age and origin of the crushed concrete is unknown.

The RCCA can be visually classified into four groups based on the percentage of their surface covered with cement paste, as RCCA presented in Table 2. More than 60% of the mass of RCCA used contained at least 90% cement paste, whereas about a third of the mass of RCCA had only 10% of its surface covered with cement paste. The different classified RCCAs are shown in Figure 2. The higher the percentage of RCCA's surface covered with cement paste, the lower its density and the more water it absorbs [18]. Mechanically removing this adhered cement paste improves the quality of RCCA [19], which in turn increases the compressive strength of concretes made with those preprocessed RCCA [5, 19].

Table 2 –Classification of the recycled coarse aggregates (RCCA) based on the percentage of surface covered with cement paste

RCCA group	Percentage of surface covered with cement paste	Mass percentage from total RCCA
A	5%	12
B	10%	31.5
C	50%	3.1
D	90%	64.2

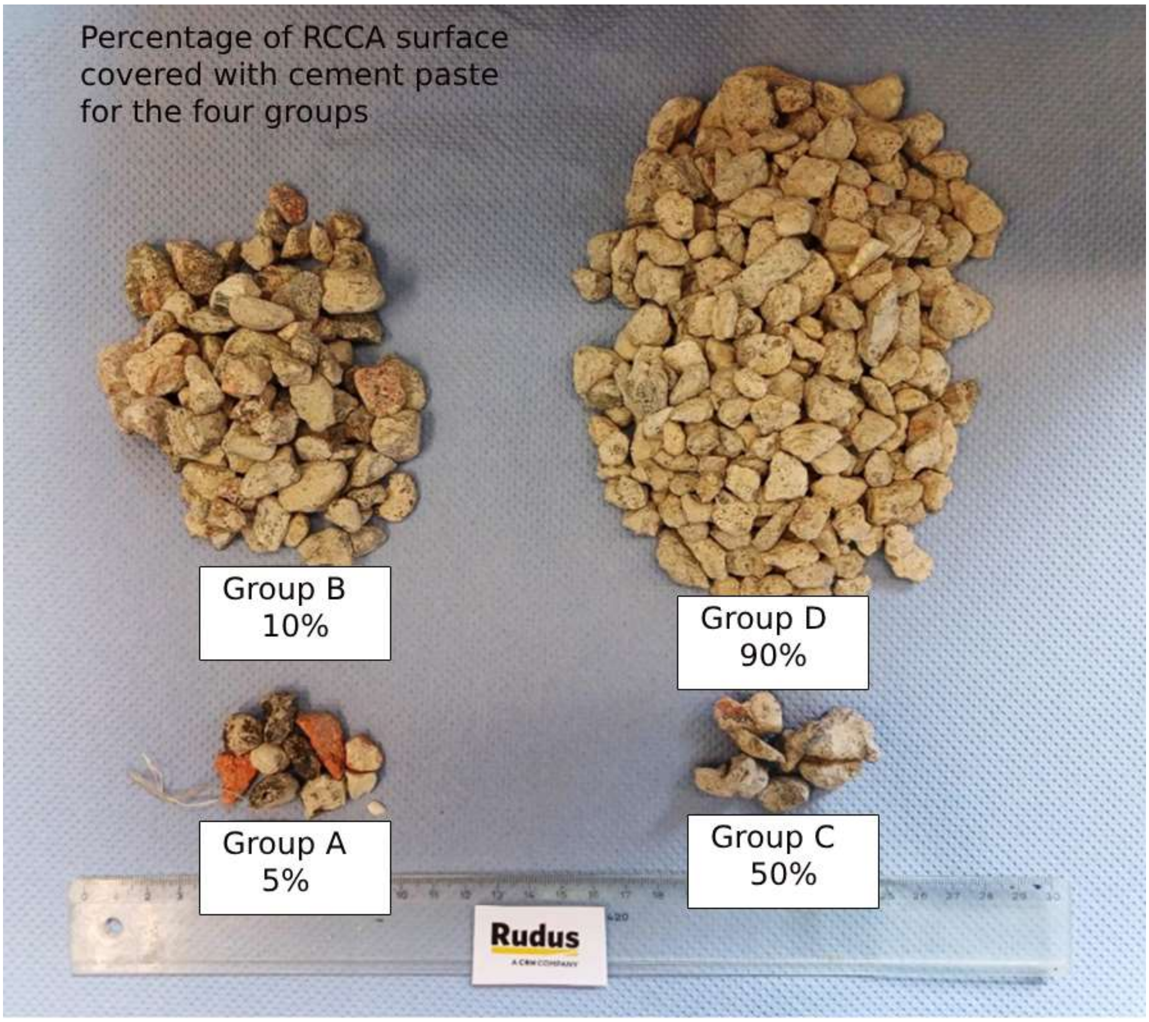


Figure 2 – Classification of the recycled concrete coarse aggregates based on the percentage of their surface covered with cement paste as shown in Table 2

A total of eleven concrete mixes were prepared for this study, divided into four groups based on testing objectives: Mechanical Strength (MS), Elastic Properties (EP), Creep (C), and Freeze-Thaw resistance (FT). The mix designs for each group are presented in Table 3. The MS group consists of two mixes, MS-0 and MS-50, where the number after the dash indicates the percentage of the replaced VA by RCCA, where all mixes with 0% RCCA are used as the control concrete of their group. This group was tested for compressive, flexural, and tensile strengths. The EP group was used to determine Elastic Properties, including Poisson's ratio and Young's modulus, while the C and FT groups were tested for their respective properties.

Table 3 – Mix designs for the four groups: MS (Mechanical Strength), EP (Elastic Properties), C (Creep), and FT (Freeze-Thaw resistance). The number after the dash in the Mix ID denotes the recycled coarse aggregate (RCCA) replacement percentage.

Test group	**MS**		**EP**			**C**			**FT**		
Mix ID	**MS-0**	**MS-50**	**EP-0**	**EP-50**	**EP-100**	**C-0**	**C-50**	**C-100**	**FT-0**	**FT-50**	**FT-100**
Cement (kg/m³)	320	320	320	320	320	310	310	310	334	334	335
Natural sand 0–8 (kg/m³)	1320	1320	940	940	940	1180	1200	1180	461	461	461
Crushed rock fines 0–5 (kg/m³)	0	0	180	180	180	0	0	0	176	176	176
Crushed aggregate 8–16 (kg/m³)	550	270	750	375	0	725	350	0	730	365	0
Recycled coarse aggregate 8–16 (kg/m³)	0	280	0	385	775	0	310	620	0	368	736
Superplasticizer (kg/m³)	1.9	1.9	1.9	2.6	2.9	1.55	2.2	2.2	1.55	2.2	2.2
Air entraining Agent (kg/m³)	0	0	0	0	0	0	0	0	6.4	6.3	5.8
Effective water (kg/m³)	192	192	192	192	192	186	186	186	180	180	180
Water-to-cement ratio	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.54	0.54	0.54

According to standard EN 206 [20], around 30% to 50% of VA in concrete can be replaced by RCCA, depending on exposure classes. However, in this study, the replacement percentages of RCCA were either 50% or 100%, to get a better understanding of the impact of the tested RCCA on the examined concrete properties. It should be noted that the RCCAs were not wetted against absorption before mixing.

A water-to-cement ratio of 0.6 was used for the first three groups, whereas the FT group had a water-to-cement ratio of 0.54. Both water-to-cement ratios correspond to commonly used strength classes in Finnish construction. Furthermore, a dose of the superplasticizer Master Builders Solutions, MasterGlenium SKY 600 from Finland, was added to the mixes to achieve a targeted slump class of S3. In addition, the FT group was air-entrained using the air entraining agent Master Builders Solutions, MasterAir 100, from Finland, with a target air content of 6±1%.

2.2 Methods

Testing overview

For all mixes, the slump, air content, and the fresh density were measured from the fresh concrete following the standards SFS-EN 12350-2 [21] and SFS-EN 12350-7 [22]. In addition to measuring the compressive strength of the MS mixes at ages 28 days and 91 days, the compressive strengths of the EP group, were measured at 91 days. The following subchapters will outline the casting, sampling, and testing procedures for each property.

Mechanical strength testing

To avoid the wall effect commonly observed in standard cast specimens, which can influence strength measurements, all specimens were drilled from slabs, which better replicate real construction conditions and material behaviour in situ. Hence, for both the tensile and compressive strength tests, two slabs were cast, each measuring 76x57x20 cm^3. The slabs were cured and stored under a plastic sheet at a temperature of 20°C until the testing dates. For compressive strength testing, three cylindrical cores were drilled from the slabs, with diameters ranging from 71 to 74 mm and lengths approximately equal to their diameters. Whereas for tensile strength testing, six cores were drilled, each had a diameter of 73 mm with heights ranging from 72 to 110 mm. The compressive and the tensile strengths were determined according to the standards EN 12390-3 [23], and SFS 5445 [24], respectively, and were tested at 28 and 91 days. On the other hand, the four-point bending test was carried out to measure the flexural strength at 91 days only according to EN 12390-5 [25] using three beams with dimensions of 500x100x100 mm^3.

The compressive and tensile strengths were calculated according to Equation 1:

$$f = \frac{F}{A} \quad (1)$$

where f is the compressive or tensile strength (MPa), F is the load at failure during compression or tension (N), and A is the cross-sectional area of the specimen (mm^2). Equation 2 was used to determine the flexural strength:

$$f_{ct,fl} = \frac{F \times l}{d_1 \times d_2^2} \quad (2)$$

where $f_{ct,fl}$ is the flexural strength (MPa), F is the maximum load (N), l is the distance between the lower rollers (mm), d_1 is the width of the specimen (mm), and d_2 is its height (mm).

Elastic properties testing

Young's modulus was determined according to "Method A" in the standard EN 12390-13:2021 [20] at the age of 91 days, by casting three 150x300 mm cylinders each EP mix. The elastic modulus was determined from Equation 3:

$$E_{c,s} = \frac{\Delta\sigma}{\Delta\varepsilon_0} = \frac{\sigma_a^m - \sigma_b^m}{\varepsilon_{a,1} - \varepsilon_{b,0}} \quad (3)$$

where $E_{c,s}$ is the elastic modulus (MPa), $\Delta\sigma$ is the difference between the measured upper stress (σ_a^m) and lower stress (σ_a^m) (MPa), and $\Delta\varepsilon_0$ is the difference between the average strains at the upper ($\varepsilon_{a,1}$) and lower stress levels ($\varepsilon_{b,0}$). The suitable upper and lower stresses were determined by testing three 150x300 mm cylinders from each mix under compression according to the standard EN 12390-3 [23].

Poisson's ratio was measured from the same cylinders by using two strain gauges, each with an initial length of 60 mm. The gauges were positioned perpendicular to each other, where one measured the longitudinal strain and the other measured the transverse strain. Poisson's ratio was calculated using Equation 4:

$$\nu_{c,s} = \frac{\varepsilon_t}{\varepsilon_l} \quad (4)$$

where $\nu_{c,s}$ is Poisson's ratio, ε_t is the transverse strain, and ε_l is the longitudinal strain.

Creep and shrinkage testing

Creep and shrinkage were determined according to the standards EN 12390-17 [27], and EN 12390-16 [28], respectively. A total of six cylinders with a diameter of 100 mm and a height of 200 mm were cast from each C mix, three were tested for creep and three for shrinkage. All six specimens were stored in a climate chamber at a temperature of 20°C, and at a relative humidity of 50%. Shrinkage can be calculated as the change in length according to Equation 5.

$$\varepsilon_{cs}(t, t_0) = (l(t_0) - l_{cs}(t))/L_0 \quad (5)$$

where $\varepsilon_{cs}(t, t_0)$ is the total shrinkage strain at time ***t***, L_0 is the gauge length (mm), $l(t_0)$ is the initial length at time t_0 (mm), and $l_{cs}(t)$ is the length at time *t (mm).*

For creep testing, the required load was added in 20 increments, and the compressive strength of the concrete at 91 days was used to confirm the 40% load limit, representing the maximum serviceability load.

The creep test lasted for 343 days, and the total creep strain was calculated from Equation 6:

$$\varepsilon_{cc}(t, t_0) = \varepsilon_{cc}(t) - [\varepsilon_{cs}(t, t_0) + \varepsilon_{cc}(t_0)] \quad (6)$$

where $\varepsilon_{cc}(t, t_0)$ is the total creep strain, $\varepsilon_{cc}(t)$ is the measured strain at the time (*t*), $\varepsilon_{cs}(t, t_0)$ is the mean strain of shrinkage specimens at the given age from the date of loading, and $\varepsilon_{cc}(t_0)$ is the initial strain.

Freeze-thaw testing

Freeze-thaw resistance was estimated in two different laboratories based on CEN/TR 15177 [29], using deionized water as the saturation solution. Cubes measuring 150×150×50 mm^3 were cast and subjected to freeze-thaw cycles in an automated climate chamber at each testing facility. Both internal structural damage and surface scaling were measured. Internal damage was evaluated using ultra-sonic pulse transit time measurements via a PUNDIT LAB+ ultrasonic device, with a measurement frequency of 150 kHz. Whereas surface scaling was determined by weighing the dried scaled material. Measurements were performed every seven freeze-thaw cycles until 56 cycles were reached. Internal damage was quantified based on the relative dynamic modulus of elasticity given in Equation 7.

$$RDM_n = \left(\frac{X_n}{X_0}\right)^2 \times 100 \qquad (7)$$

where RDM_n is the relative dynamic elastic modulus (%), X_n is the reciprocal of the ultra-sonic pulse transit time (µs), measured after n freeze-thaw cycles, and X_0 is the reciprocal from the initial measurement.

3. RESULTS AND ANALYSIS

3.1 Fresh concrete properties

The slump, air content, and fresh densities of the mixes are presented in Table 4. Given that the superplasticizer amount was kept fixed for the MS group, the slump of MS-50 dropped to less than 50% of MS-0's slump. This huge drop can be due to the absorption of RCCA being more than 16 times higher than that of VA, potentially leading to the absorption of the superplasticizer. In addition, the inherently different surface characteristics of RCCA also contribute to higher water demand. Furthermore, variance in water absorption properties within the RCCA sample itself might result in such drops in slump. Similarly, for the EP mixes, the slump decreased as the replacement ratio of RCCA increased, even though the superplasticizer dose was increased by around 36% from EP-0 to EP-50, and by about 12% from EP-50 to EP-100 as shown in Table 3. A similar trend is found in the C and FT mixes as well.

This drop in slump highlights an inherent challenge in the workability of RCCA-concretes, as they require a large increase in the superplasticizer amount, and possibly increasing the water amount, where the latter can negatively impact the mechanical properties and durability of said concretes.

Table 4 – Slump, air content and fresh densities of the tested mixes. Note: the measurement for fresh density of MS-50 was missing.

Mix ID	Slump (mm)	Air content (%)	Fresh density (kg/m³)
MS-0	175	2.0	2410
MS-50	80	2.5	–
EP-0	160	1.8	2400
EP-50	135	1.8	2340
EP-100	100	2.2	2360
C-0	165	2.5	2416
C-50	160	1.6	2333
C-100	120	3.8	2272
FT-0	140	6.4	2320
FT-50	120	6.3	2240
FT-100	120	5.8	2230

As presented in Table 4, the air content for the first mechanical properties main groups without air entraining agent was within the expected limits ranging from 1.6% to 2.5%, except for C-100, which had an elevated air content of 3.8%. Such elevated air content can be caused by the porous nature of recycled concrete aggregate (RCCA), as pressure during the test forces water into its pores, reducing water volume in the chamber and leading to an overestimation of air content. As for the FT group, the air entrainment was within the target level of 6±1%. The differences in air content and aggregate amounts –specified in Table 3– were reflected in the measured fresh densities shown in Table 4.

3.2 Compressive, tensile, and flexural strengths

The compressive strengths for both the MS and EP groups are shown in Figure 3, with exact values and their differences compared to the control presented in Table 5. Between MS-0 and MS-50, huge drops of 33% and 37% are observed in the 28- and 91-day strengths, respectively. This suggests that replacing half of the coarse aggregates by RCCA could potentially reduce compressive strength by more than one-third. However, the EP group shows a milder decline. The compressive strength decrease is almost halved with a loss of about 15% of strength between EP-0 and EP-50, and around 18% between EP-0 and EP-100.

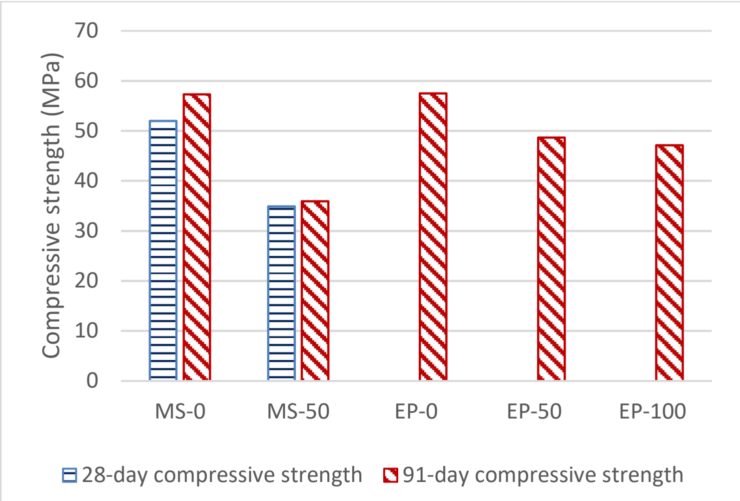


Figure 3 – Cylinder compressive strengths at ages 28 days and 91 days for the eleven mixes.

Table 5 – Cylinder compressive strengths at ages 28 days and 91 days as well as the strength change in percentage relative to the control mix for the eleven mixes

Mix ID	28-day compressive strength	91-day compressive strength	28-day strength change	91-day strength change
MS-0	52	57.3	–	–
MS-50	34.9	35.9	33 %	37 %
EP-0	–	57.5	–	–
EP-50	–	48.63	–	15 %
EP-100	–	47.13	–	18 %

Such differences in compressive strengths for the same replacement levels of RCCA between the groups highlight the variance in performance of RCCA even when batched from the same source. For instance, at a replacement ratio of 50% in one mix might results in a larger decrease in strength than a 100% replacement of coarse aggregates with RCCA. This is evident in the 91-day compressive strength of EP-100, which dropped by 18% only compared to MS-50 that dropped by 37% in reference to their control mixes. Such inconsistent impact highlights the need for comprehensive testing and characterization of RCCA before their implementation in concretes.

Figures 4a and 4b show the results of the direct tensile and flexural tensile testing for the MS group. A drop of almost 39% in the tensile strength is observed for both the 28-day and 91-day strengths. However, a smaller decrease of 20% is seen in the 91-day flexural strength. This, in combination with the compressive strength results, shows that for the MS group, replacing 50% of the coarse aggregates with RCCA can have severe consequences on the material strength properties. Both tensile and compressive strengths are more severely affected than flexural strength.

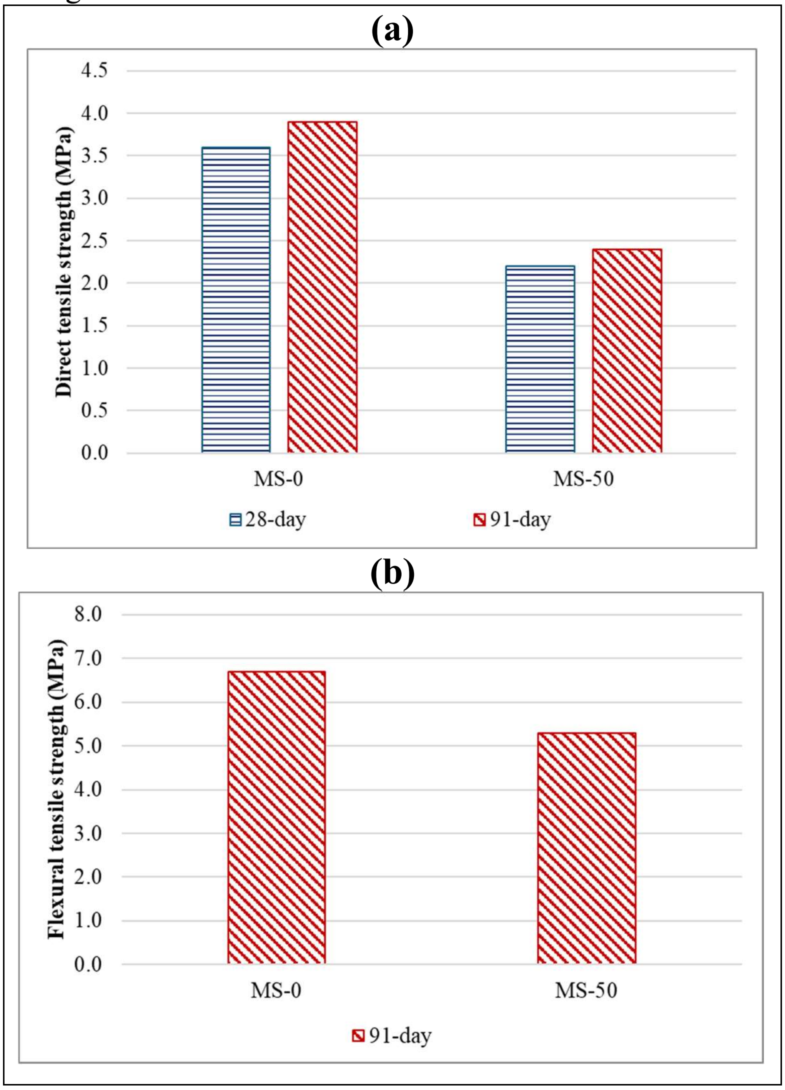


Figure 4 – Measured (a) flexural and (b) tensile strengths at ages of 28 and 91 days for the Mechanical Strength (MS) group.

3.3 Young's modulus and Poisson's ratio

The averaged values of the measured Young's moduli and Poisson's ratios for the EP group are presented in Figure 5a, and 5b, respectively. The higher the replacement rate of RCCA, the lower Young's modulus. Replacing 50% of coarse aggregates with RCCA drops Young's modulus by 12%, and increasing the replacement ratio to 100% increases the drop to 21%. Those drops are quite close to those observed in the compressive strength values of the EP group of 15% from EP-0 to EP-50, and 18% from EP-0 to EP-100.

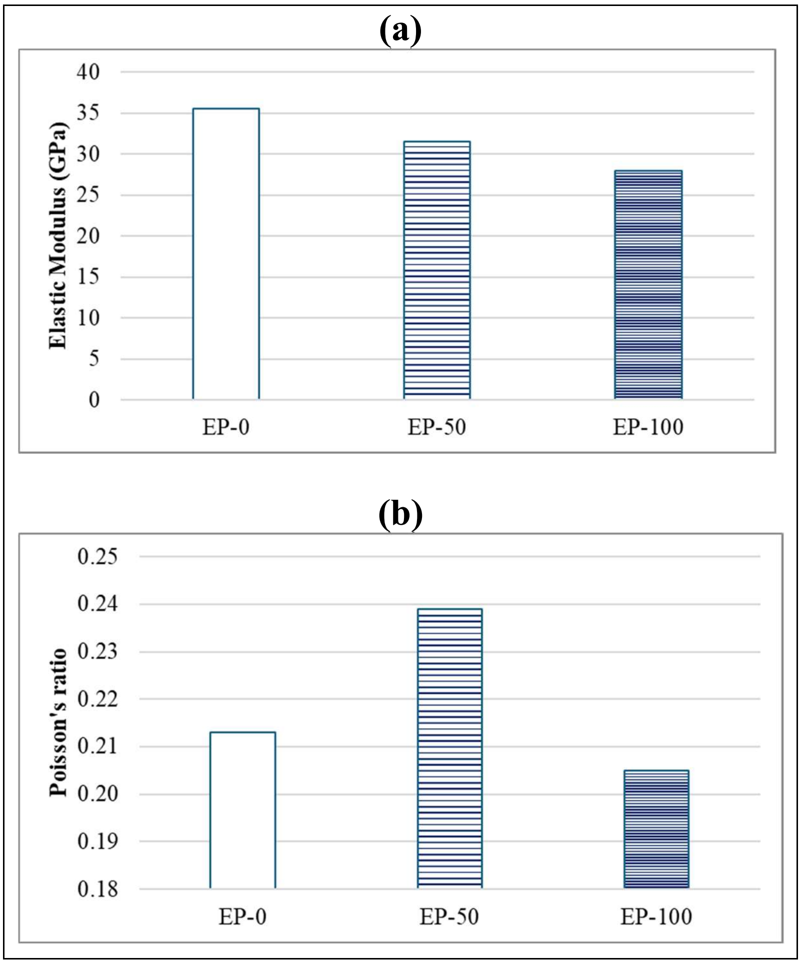


Figure 5 – (a) Measured Young's modulus, and (b) Poisson's ratio for the Elastic Properties (EP) group

As for Poisson's ratio, it did increase by 12% from EP-0 to EP-50, suggesting that at that replacement level RCCA concrete was more prone to lateral deformation. However, it decreased by about 4% from EP-0 to EP-100, which suggests a slightly stiffer concrete at a much higher replacement rate. Those inconsistencies highlight the complexity of the behaviour of RCCA concrete, and the need for case-by-case testing for different replacement levels.

3.4 Creep and shrinkage

Shrinkage values are presented in Figure 6. At 50% replacement of coarse aggregates with RCCA, shrinkage deformation follows closely to that of the control. For the first 231 days, the average shrinkage deformation of C-50 varies within 40 µm/m compared to that of C-0, and from ages 231 to 343 days, shrinkage of C-50 is on average higher by 95 µm/m than that of C-0. On the other hand, for a 100% replacement rate, the shrinkage is on average 200 µm/m higher than that of the control, reaching maximum differences up to 313 µm/m.

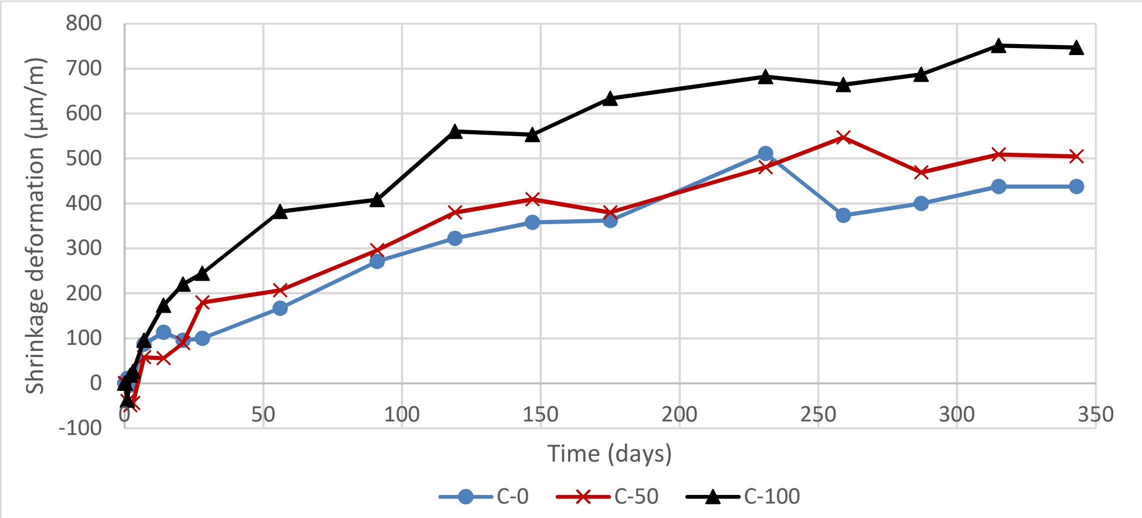


Figure 6 – Shrinkage deformation over 343 days of loading for the C (creep) group, with recycled coarse aggregate replacement rates of 0% (C-0), 50% (C-50), and 100% (C-100).

The total creep strain values over time are shown in Figure 7. During the first 147 days, the total creep strain for C-0 and C-50 varied within a margin of 15%. On the other hand, the creep strain for C-100 on the 28th day was on average more than 40% larger than that of C-0 and C-50. The creep strain of C-100 continued to be larger than that of C-50, and C-100, with a creep strain at 343 days 27%, and 16% higher than that of C-0, and C-50, respectively. These results show that for our tested RCCA, replacing 50% of the VA with said RCCA, can increase the terminal creep by strain by 9%, while a replacement rate of 100% can triple that rise to 27%.

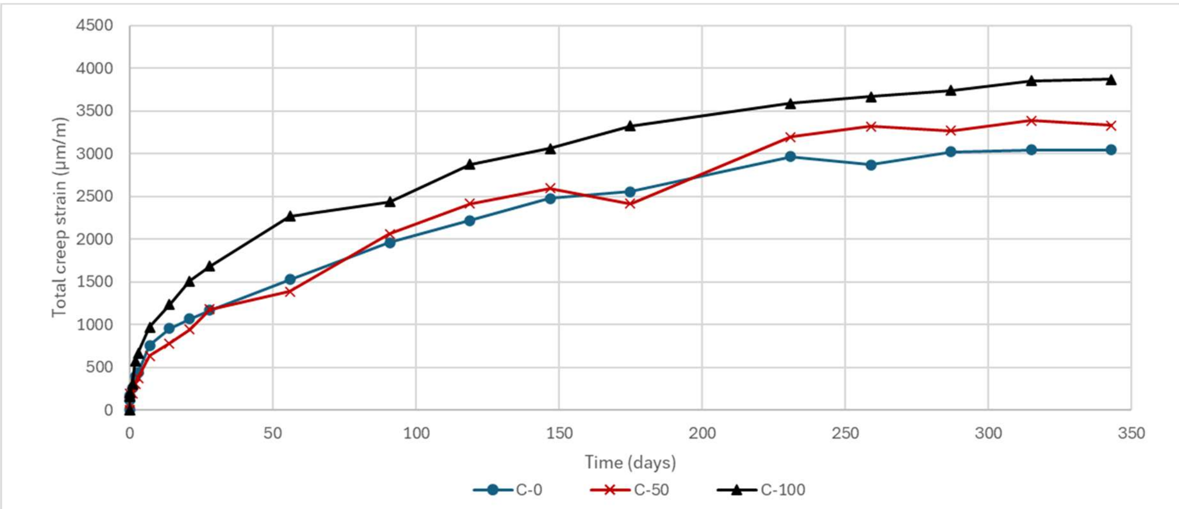
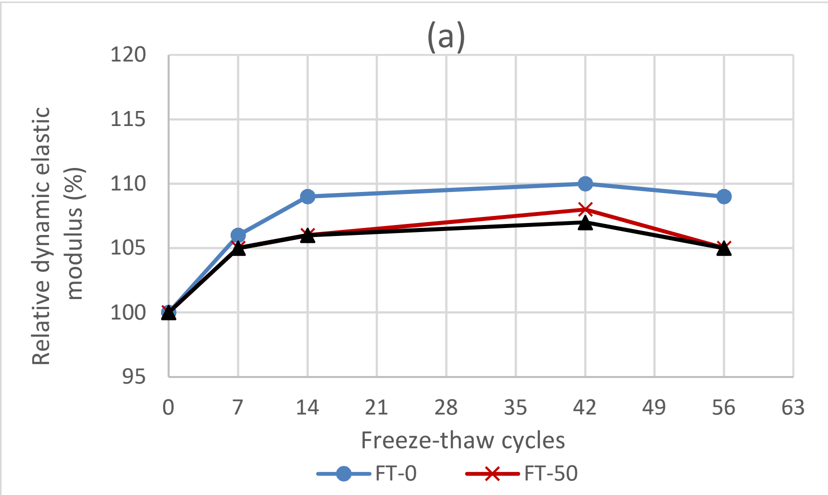


Figure 7 – Total creep strain over 343 days of loading for the C (creep) group, with recycled coarse aggregate replacement rates of 0% (C-0), 50% (C-50), and 100% (C-100).

It should be noted that the drops in creep strain observed in C-0 at 259 days, in C-50 at 175 days, and in C-100 at 91 days are likely due to measurement errors. Since creep strain should not decrease under constant load, and subsequent readings show the expected creep behaviour.

3.5 Freeze-thaw resistance

The relative dynamic elastic modulus, RDM_n, for the FT group, is shown as a function of the freeze-thaw cycles in Figures 8a and 8b, for specimens tested according to CEN/TR 15177 [29] at laboratory A, and laboratory B, respectively. As shown in Figure 8a based on results from laboratory A, no signs of internal damage were found in any of the groups, as the RDM_n value remained above 100% for all testing ages, even for a 100% replacement of coarse aggregates with RCCA. Similarly, as shown in Figure 6b, samples sent to laboratory B did not show internal damage in the FT-0 group, where RDM_n kept on rising through the duration of 56 freeze-thaw cycles. As for 50% replacement rate of RCCA, FT-50 showed a minor decrease in RDM_7, which was then followed by a steady rise until cycle 42, then dropped to 104% remaining above the 100% starting value. A similar trend is found for a 100% replacement rate of RCCA, as FT-100 showed a slight decrease of RDM_n until the 14th cycle, followed by an increase, then ending with an RDM_{56} of 105%. These results indicate that concretes incorporating the tested RCCA experience minimal internal damage due to freeze-thaw cycles, even at replacement rates of 100%.



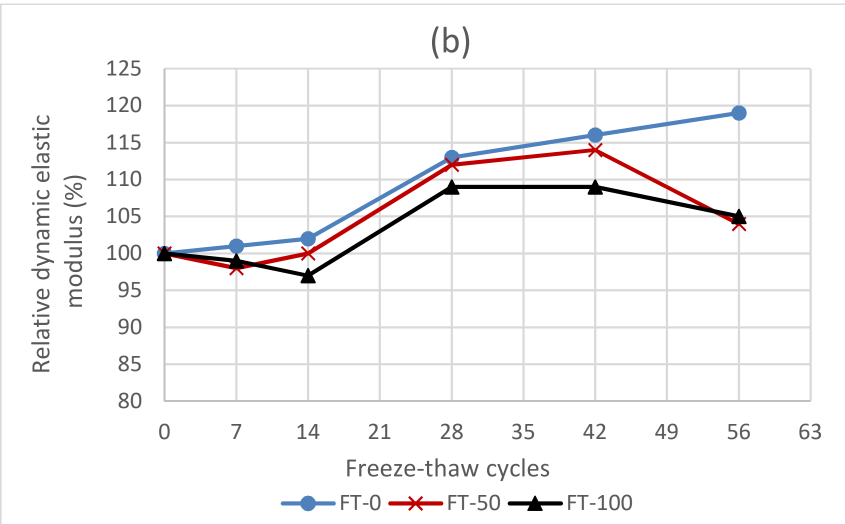


Figure 8 – Internal structural damage measured as the relative dynamic elastic modulus as defined in Equation 6 for the FT group with recycled coarse aggregate replacement rates of 0% (FT-0), 50% (FT-50), and 100% (FT-100). (a) Results from laboratory A; (b) Results from laboratory B.

The cumulative scaled mass is plotted against the freeze-thaw cycles as shown in Figures 9a and 9b, for specimens tested according to CEN/TR 15177 [29] at laboratories A and B, respectively. As shown in Figure 7a, for FT-0, there was no surface scaling throughout the 56 cycles. Very minor scaling was found in both the FT-50 and FT-100 concretes, with the cumulative scaling being 30 g/m² at the end of testing. As previously mentioned, deionized water was used as the stress solution, and based on these results FT-0, FT-50, and FT-100 concretes all fulfil the frost resistance requirements of exposure classes XF1 and XF3. This shows that the freeze-thaw resistance remained strong for both RCCA replacement rates of 50% and 100% in the tested concrete.

In contrast, as shown in Figure 9b, specimens with a 100% replacement rate that were sent to laboratory B had a cumulative scaling of 64 g/m² at age 56 days, which is 50 g/m² higher than that of the control, and around six times more the value. However, at a replacement rate of 50%, the cumulative scaled mass was on average only 4–6 g/m² higher than that of the control. The significant difference in scaling for FT-100 specimens between laboratories A and B suggests two possible issues: variability in the properties of the RCCA used, or inconsistencies in the testing procedure, potentially due to human error or limitations of the method itself.

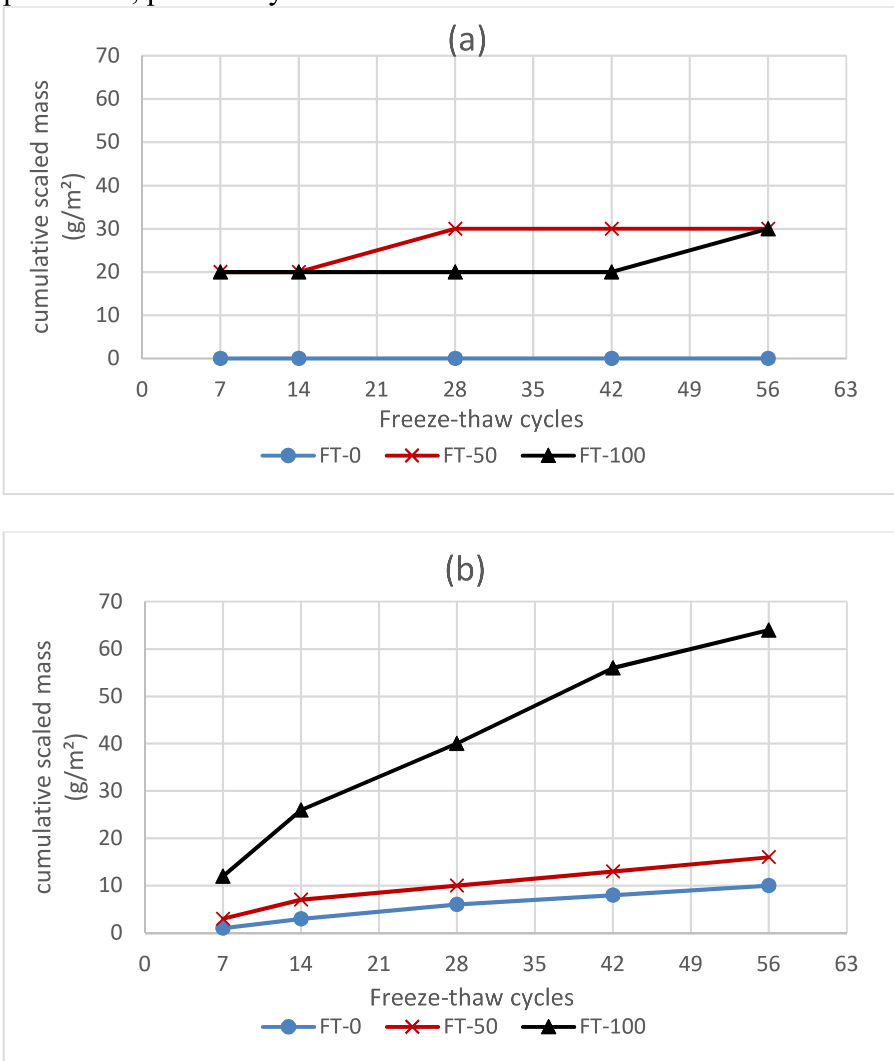


Figure 9 – Cumulative scaled mass from the surface of the FT group specimens proportioned with recycled coarse aggregate replacement rates of 0% (FT-0), 50% (FT-50), and 100% (FT-100). (a) Results from laboratory A, and (b) Results from laboratory B.

4. DISCUSSION AND FUTURE RESEARCH

The results of this study provide valuable insights into the mechanical properties and freeze-thaw resistance of concrete with varying replacement percentages of RCCA. However, the variability in the results raises important questions about the practical use of RCCA and the methods used to evaluate its performance. Below, we discuss these aspects in the context of the study's findings followed by the possibilities for future research.

The compressive strength results showed significant variability, with some mixes exhibiting strength reductions of up to 33%, while others showed smaller drops of 15% or even slight increases. This variability highlights the challenges associated with using RCCA, as its performance depends heavily on factors such as the quality of the source concrete, the amount of adhered cement paste, and the mix design. One approach to determine the amount of cement paste adhered to the surface of RCCA would be to perform the Los Angeles abrasion test, which measures the resistance of aggregates to degradation and can indirectly indicate the quantity of the attached mortar.

Beyond compressive strength, the properties of fresh concrete present another significant challenge when using RCCA. As water demand increases with RCCA content, concrete quality tends to deteriorate, potentially requiring higher cement content to maintain performance standards. This creates a paradox where the environmental benefits of using recycled materials might be offset by increased cement usage and its associated carbon footprint.

The variability in mechanical performance observed in this study suggests that a more nuanced approach to RCCA implementation is necessary. Rather than viewing RCCA as a universal replacement for natural aggregates, determining the optimal applications for RCCA concrete is crucial for its practical implementation. Based on the performance variability observed, RCCA concrete may be more suitable for certain structural elements than others. For instance, it is not recommended for pre-tensioned elements where consistent high strength is critical but could perform adequately in simple beams and less structurally demanding applications.

While this study provides valuable insights into the mechanical properties and freeze-thaw resistance of concrete with varying RCCA replacement percentages, several areas warrant further investigation:

- Exploration of treatment methods for improving RCCA quality to address the variability in performance observed across different replacement rates and testing parameters.
- The correlation between RCCA quality, source characteristics, adhered cement paste amount and resulting concrete performance to develop predictive models for optimizing RCCA usage.
- Investigation of combined supplementary cementitious materials with RCCA to potentially mitigate strength reductions while enhancing sustainability benefits.
- Investigating intermediate replacement percentages of coarse aggregates with RCCA between 0%, 50%, and 100% to determine optimal RCCA content that balances mechanical properties with sustainability benefits.

These research directions would contribute to more effective utilization of RCCA in construction, supporting both sustainability goals and performance requirements in concrete applications.

4. CONCLUSIONS

This study examined the mechanical properties and freeze-thaw resistance of concretes with varying RCCA replacement percentages, sourced from crushed concrete from demolished buildings and structures in Finland. A total of eleven concrete mixes were prepared, divided into four groups based on testing objectives: Mechanical Strength (MS), Elastic Properties (EP), Creep (C), and Freeze-Thaw resistance (FT). The results provide insight into the feasibility of using RCCA in concrete while meeting performance and durability standards. This is particularly relevant given the upcoming Eurocode 2 updates and the introduction of Environmental Resistance Classes (ERC). The key conclusions from the analysis are as follows.

- Large variations were observed in the drop of compressive strengths for different RCCA replacements. At 100% RCCA a drop of only 15% in the 91-day compressive strength was observed compared to a 37% drop in concretes made with a 50% of RCCA. This highlights the variability in RCCA performance, which can lead to significantly or slightly lower compressive strengths than that of the control concrete.
- Flexural and tensile strengths were both lower when replacing 50% of the coarse aggregate with RCCA, with flexural strength dropping by 20% and tensile strength by 39% compared to the control concrete.
- Young’s modulus decreased by 12% for concretes with 50% RCCA, and by increasing the replacement rate to 100% RCCA, it decreased by an additional 9%. However, Poisson’s ratio increased when replacing 50% of coarse aggregate with RCCA and was less than that of the control at 100% RCCA replacement.
- Creep strain increased with RCCA content. At 50% replacement of coarse aggregate with RCCA, it remained similar to the control for the first 147 days before rising, ending 9% higher at 343 days. When replacing 100% of the coarse aggregates with RCCA, it deviated earlier, exceeding the control after one week and reaching a strain 27% higher.
- Freeze-thaw resistance, for exposure classes XF1 and XF3, was nearly equivalent to that of the control, when replacing 50% of the coarse aggregate with RCCA. As tested in two laboratories, The dynamic relative elastic modulus showed minimal internal damage during the first quarter of cycles, with values exceeding 100% at 56 cycles. This was further supported by the low surface scaling of 30 g/m². However, when replacing 100% of the coarse aggregate with RCCA, the results from the two laboratories were not in agreement. Laboratory A provided scaling results of 60 g/m², while laboratory B showed half of that scaling for specimens made from the same mix. This highlights possible challenges in frost resistance at a 100% RCCA replacement level.

REFERENCES

1. Wimala M, Fujiki A & Kawai K: “Environmental Impact of Waste Concrete Treatment in Precast Concrete Production”. *Proceedings,* Annual Conference Japan Concrete Institute, Japan, 2011.
2. Walberg D: “Solid and Timber Construction in Residential Buildings”. *Mauerwerk*, 2016, pp. 16-31.
3. Zheng L, Wu H, Zhang H, Duan H, Wang J, Jiang W, Dong B, Liu G, Zuo J & Song Q: “Characterizing the Generation and Flows of Construction and Demolition Waste in China”. *Construction and Building Materials*, 2017, pp. 405-413.
4. Ma M, Tam V W, Le K N & Li W: “Challenges in Current Construction and Demolition Waste Recycling: A China Study”. *Waste Management*, 2020, pp. 610-625.

5. Sadagopan M, Malaga K, Lundin M & Nagy A: "Effects of Slag Addition and Mechanical Pre-Processing on the Properties of Recycled Concrete in Terms of Compressive Strength and Workability". *Nordic Concrete Research*, 2021, pp. 11-29.
6. LCA Consulting Oy: "Carbon footprint of Betoroc crushed concrete in infrastructure construction". Report version 1.1, July, 2021.
7. Helsing E, Brander L & Martinsson P: "Durability of Concrete with Recycled Aggregate". *Nordic Concrete Research*, 2024, pp. 69-89.
8. Flower D J M & Sanjayan J G: "Green House Gas Emissions Due to Concrete Manufacture". *The International Journal of Life Cycle Assessment*, 2007, pp. 282-288.
9. Wang B, Yan L, Fu Q & Kasal B: "A Comprehensive Review on Recycled Aggregate and Recycled Aggregate Concrete". *Resources, Conservation & Recycling*, 2021.
10. Kumutha R & Vijai K: "Strength of Concrete Incorporating Aggregates Recycled from Demolition Waste". *ARPN Journal of Engineering and Applied Sciences*, 2010.
11. Liu K, Fu K, Sang Y, Yang Y, Zou C, Xie T & Zhao X: "Frost Resistance of Recycled Aggregate Concrete: A Critical Review". *Journal of Building Engineering*, Vol. 90, 2024.
12. Maruyama I, Sogo M, Sogabe T & Sato R: "Flexural Properties of Reinforced Recycled Concrete Beams". *Proceedings,* Conference on the Use of Recycled Materials in Buildings and Structures, Barcelona, Spain, 2004.
13. Kheder G & Al-Windawi S: "Variation in Mechanical Properties of Natural and Recycled Aggregate Concrete as Related to the Strength of Their Binding Mortar". *Materials and Structures*, 2005, pp. 701-709.
14. Gómez-Soberón J M: "Relationship Between Gas Adsorption and the Shrinkage and Creep of Recycled Aggregate Concrete". *Cement Concrete and Aggregates*, 2003.
15. Doming-Cabo A, Lázaro C, López-Gayarre F, Serrano-López M, Serna P & Castaño-Tabares J: "Creep and Shrinkage of Recycled Aggregate Concrete". *Construction and Building Materials,* 2009, pp. 2545-2553.
16. Kou S. C., Poon C. S. and Chan D.: "Influence of fly ash as a cement addition on the hardened properties of recycled aggregate concrete". *Materials and Structures*, 2008, Vol. 41, pp. 1191-1201.
17. Kou S. C., Poon C. S., Agrela F.: "Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures". *Cement & Concrete Composites*, 2011, Vol. 33, pp. 788-795.
18. Padmini, A.K., Ramamurthy, K., Mathews, M.S.: "Influence of parent concrete on the properties of recycled aggregate concrete". *Construction and Building Materials*, 2009, Vol. 2, pp. 829-836.
19. Sadagopan M, Malaga K, and Nagy A: "Improving recycled aggregate quality by mechanical pre-processing". *Materials*, 2020.
20. Finnish Standards Association: "SFS-EN 206. Concrete. Specification, Performance, Production and Conformity", Helsinki, Finland, 2014. 93 pp.
21. Finnish Standards Association: "SFS-EN 12350-2. Testing Fresh Concrete. Part 2: Slump Test", Helsinki, Finland, 2019. 12 pp.
22. Finnish Standards Association: "SFS-EN 12350-7. Testing Fresh Concrete. Part 7: Air Content. Pressure Methods", Helsinki, Finland, 2019. 5 pp.
23. Finnish Standards Association: "SFS-EN 12390-3. Testing hardened concrete. Part 3: Compressive strength of test specimens", Helsinki, Finland, 2019. 20 pp.
24. Finnish Standards Association: "SFS 5445. Betoni. Vetolujuus (Concrete. Tensile Strength)", 1988. 2 pp. (In Finnish)
25. Finnish Standards Association: "SFS-EN 12390-5. Flexural Strength of Test Specimens", 2019. 20 pp.

26. Finnish Standards Association: "SFS-EN 12390-13. Testing Hardened Concrete. Part 13: Determination of Secant Modulus of Elasticity in Compression", 2021. 14 pp.
27. Finnish Standards Association: "SFS-EN 12390-17. Testing Hardened Concrete. Part 17: Determination of Creep of Concrete in Compression", 2019. 16 pp.
28. Finnish Standards Association: "SFS-EN 12390-16. Testing Hardened Concrete. Part 16: Determination of the shrinkage of concrete", 2019. 13 pp.
29. European Committee for Standardization: "CEN/TR 15177. Testing the Freeze-Thaw Resistance of Concrete. Internal Structural Damage", 2006. 34 pp.