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Investigating the Mechanical Properties and Performance of Recycled Aggregate Concrete Through Multiple Generation Recycling

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Abstract

Recycled Aggregate Concrete (RAC) represents a promising sustainable solution for the construction industry. Based on previous studies available in literature, that focused on multiple generations of concrete, we embarked on an in-depth investigation of this crucial topic. Instead of limiting the research to a single natural aggregate mix design, an extensive study was conducted encompassing four distinct concrete mix designs (C1, C2, C2D, C2M), some including steel or synthetic fibres. In total, specimens based on 12 concrete mix designs were prepared across the three generations of concrete. Each generation contained 4 mix designs.

The initial stage of the research involved the preparation of four unique concrete mixes: two variants of regular concrete (C1 and C2) with differing compressive strengths. Subsequently, we utilized the mix design yielding higher strength concrete (C2) to create fibre-reinforced concrete, incorporating synthetic (C2M) and steel fibres (C2D). These initial specimens underwent a number of property tests before being crushed and recycled into the generation of concrete, where the 4-16 mm fraction of aggregate was replaced, the crushed and sieved. This recycling process was repeated for each concrete type (e.g., C1 was used to create C1-Re, C2 for C2-Re, and so forth).

Throughout this comprehensive study, various experimental tests were conducted, including Crack Mouth Opening Displacement (CMOD), compressive strength, tensile splitting strength, modulus of elasticity, ultimate strain, water absorption, and water permeability tests on specimens from all generations. Findings revealed significant insights, notably an increase in compressive strength and a decrease in splitting tensile strength in subsequent generations of recycled concrete.

This research can considerably advance the understanding of RAC's performance over multiple recycling cycles and provides valuable insights into its mechanical and microstructural properties. The observed trends shed light on RAC's potential as a sustainable construction material, reinforcing its role in promoting environmentally responsible building practices.

1. Introduction and motivation

As human civilizations continue to expand and evolve, the construction industry has experienced remarkable growth and transformation. Today, our urban landscapes are characterized by an indispensable reliance on concrete for constructing buildings, residences, offices, healthcare facilities, and various other structures. Concrete has undeniably emerged as a fundamental construction material shaping the modern world. However, the ever-evolving demands of design, utilization, and industrial expansion have ushered in a recurring cycle of construction and demolition, leading to a surge in Construction and Demolition (C&D) waste, which has now emerged as a pressing concern. According to a report by the European Union (EU) on Resource Efficiency in the Building Sector, concrete constitutes a substantial portion of C&D waste [1]. This mounting C&D waste problem has contributed significantly to the global landfill crisis, with rates of 35% in Canada, 33% in the United States, 50% in the United Kingdom, and a staggering 65% in Hong Kong. This escalating trend in C&D waste generation has not only led to land scarcity but also prompted illegal waste disposal in many regions [2]. In response to this burgeoning crisis, the European Parliament, through its Waste Framework Directive, has mandated that all European Union countries reduce their C&D waste rates by 70%, stimulating a paradigm shift within the construction industry by transforming waste into a valuable resource [3].

Concrete, as one of the most widely used construction materials, requires substantial resource inputs during its production process. Furthermore, the concrete production industry is accountable for a significant portion, approximately 8%, of global carbon dioxide (CO2) emissions [4]. This environmental impact underscores the imperative for sustainable construction materials, as humanity grapples with environmental challenges. One promising solution gaining traction is Recycled Aggregate Concrete (RAC), which involves the utilization of recycled aggregates obtained from C&D waste as a viable substitute for natural aggregates. This shift towards RAC not only addresses the natural resource crisis but also offers a tangible solution for waste minimization. Nevertheless, the application of RAC in critical structural elements has raised concerns regarding its mechanical properties and durability [3].

In the realm of concrete improvement, reinforcing fibres have gained prominence for enhancing tensile strength and other key properties. These fibres can be instrumental in optimizing the characteristics of RAC, unlocking its full potential [2].

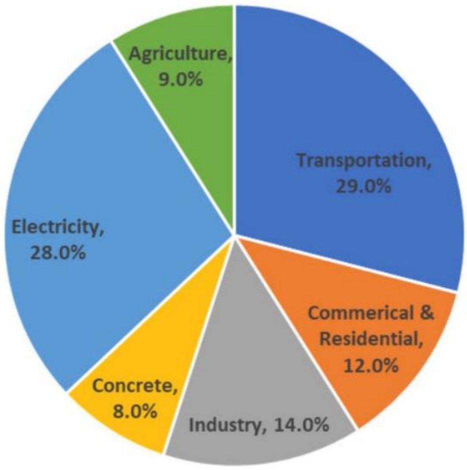


Figure 1.1 – Princeton Student Climate Initiative – 2020

This scientific paper seeks to provide an exhaustive review of RAC, comprehensively covering its mechanical properties, structural behaviour, durability, evolution across generations, and the impact of steel and synthetic fibres on its performance. By shedding light on the intricate interplay between fibres and recycled aggregates, this paper aims to serve as a valuable resource for enhancing mix design and construction practices, ultimately facilitating the development of high performance, more robust, and more durable RAC [3]. Drawing insights from a thorough analysis of existing scientific literature and experimental studies, this paper endeavours to explore the potential benefits, challenges, and opportunities associated with the adoption of RAC.

The investigated recycled concrete will be integrated into the design of an office building, the laboratory obtained mechanical properties will be used in calculations as a part of diploma work. This design will be aimed to provide solutions of recycled concrete usage and testing the applicability of the concrete.

2. Literature review

Prior to embarking on our research endeavour, a meticulous review of relevant scholarly works laid the foundation for our investigation. Among the significant contributions to the field, we delved into the research paper titled "Multi-recycling of Polypropylene Fibre Reinforced Concrete: Influence of Recycled Aggregate Properties on New Concrete," conducted by Tosic et al [5]. at the esteemed Polytechnic University of Catalonia. This seminal study navigated the intricate terrain of RAC across three distinct generations, all while incorporating the innovative use of polypropylene (PP) fibres. The research commenced with the first generation, wherein Natural Aggregate Concrete was meticulously examined, both in its fibre-reinforced and non-fibre-reinforced variants. Subsequently, the second and third generations of RAC were crafted, employing the remnants of the prior generation as a foundational material. These later generations also underwent scrutiny with and without the incorporation of PP fibres, mirroring the approach adopted in the initial phase. Throughout the course of this investigation, rigorous attention was directed toward comprehending the mechanical properties of concrete as it traversed these generational shifts.

The research probed into how recycled aggregates and the introduction of PP fibres contributed to the dynamic evolution of concrete characteristics. Notably, the study focused on the utilization of coarse fractions, specifically the 4/12 and 12/20 gradations, within the framework of RAC. To holistically assess the materials, a battery of tests was executed on the specimens, encompassing comprehensive examinations such as compressive strength tests, evaluations of modulus of elasticity, investigations into splitting tensile strength, and meticulous assessments of residual tensile strength. The findings gleaned from this rigorous investigation yielded valuable insights. They underscored the feasibility of employing RAC for structural applications, thus opening promising avenues for sustainable construction practices. However, the research also sounded a note of caution, emphasizing the need for precision in calculating water ratios in future studies. This is especially critical given the heightened porosity characteristic of Recycled Concrete Aggregate (RCA), particularly in scenarios involving embedded fibres and the addition of virgin fibres. These factors can exert a direct influence on the workability of concrete, thereby warranting precise consideration.

Furthermore, the study displayed a commendable awareness of environmental sustainability concerns by factoring in the energy consumption associated with recycling these aggregates. This holistic perspective underscores the research's commitment to not only advancing the understanding of RAC but also advocating for sustainable practices within the construction industry[5].

Another study was conducted in 2004 by Xiao et al in China and Germany [6]. The aim of that research was to study Mechanical properties of recycled aggregate concrete under uniaxial loading. Five specimens were prepared: concrete with natural aggregate, concrete with 30% recycled concrete aggregate (RCA) replacement, with 50%, 70% and 100% replacement. The specimens were moulded in 100*100*300mm and 100*100*100mm, and then tested for axial compression and vertical deformation were measured. In the case of Normal Concrete, the initial loading stages showed no visible cracks, but as the compression loading increased, small vertical micro-cracks gradually developed. Upon reaching the peak stress, the loading began to decrease slowly. At this point, several short vertical cracks emerged, eventually merging into inclined macro-cracks. The inclination angle of these macro-cracks with respect to the vertical loading plumb ranged from 58 to 648 degrees. On the other hand, Recycled Aggregate Concrete initially exhibited behaviour quite similar to normal concrete during the early loading stages. However, upon surpassing the peak stress, the first signs of vertical micro-cracks, short and thin in nature, became apparent. Continuing the test, an inclined macro-crack swiftly formed through the specimen, leading to an immediate decrease in load. In some cases, an audible cracking sound was heard. Once the macro-crack had formed, the specimen was self-supported and held together by friction between the cracks. Additionally, vertical, or slightly inclined branch cracks were observed in some samples, yet the loading remained stable. Most of the recycled aggregate concrete specimens did not spall and maintained their structural integrity throughout the test.

An interesting contrast between the two types of concrete is the inclination angle of the failure plane. In recycled aggregate concrete, this angle ranged from 63 to 798 degrees with respect to the vertical load plumb, significantly greater than that observed in normal concrete. Furthermore, the plastic deformation of recycled aggregate concrete was found to be less than that of normal concrete. Upon careful analysis of the failure plane, it was noted that fractures of the recycled and natural coarse aggregates were rarely seen in the recycled aggregate concrete specimens, suggesting a distinct shear mode as the prevailing failure mode, at least under the experimental conditions of this investigation. The stress–strain curves of RAC with RCA contents showed significant influences on RAC's behaviour. Irrespective of RCA replacement percentages, the shape of the SSC in RAC resembled that of natural aggregate concrete, indicating that the theory of plasticity could be applied in structural design. However, RAC exhibited higher strains under the same loads due to its lower elastic modulus. The stress-strain curves were divided into three parts: linear, nonlinear ascending, and descending branches. The ascending branch's curvature increased with higher RCA content, attributed to the presence of interfaces leading to micro-crack development. The slope of the descending branch decreased as RCA content increased, resulting in changes in stress–strain responses, including increased peak strain and reduced ductility. Regarding compressive strength, RAC's strength decreased with higher RCA content, except in the case of RC-30, where the f_c/f_{cu} ratio was higher than that of normal concrete. The average f_c/f_{cu} ratio of RAC was 0.81, 8% higher than normal concrete, but both fc and fcu were lower due to RCA presence. The elastic modulus (Ec) of RAC was lower than normal concrete, and it decreased with increasing RCA replacement percentage, with a 45% reduction at 100% RCA. The extent of this reduction varied in previous studies based on the elastic modulus of the RCA used. The peak strain in RAC increased with higher RCA content, with a 20% increase at 100% RCA, mainly due to the reduced elastic modulus, leading to greater deformation. An empirical formula was suggested for calculating the peak strain in RAC. The ultimate strain in RAC depended on the RCA replacement percentage, with a decreasing trend for small values of r and an increasing trend for large values of r.

As a conclusion, this study found out that RAC primarily fails in a shear mode, with a short failure process, inclined failure planes, increasing Recycled Concrete Aggregate (RCA) content affects stress–strain curves consistently, showing higher peak strain and reduced ductility, compressive strength in RAC decreases with higher RCA content, although the prism/cube strength ratio is higher than normal concrete, the elastic modulus of RAC is lower than normal concrete, decreasing further with more RCA content, peak strain in RAC is higher and increases with RCA content, an analytical expression, originally designed for normal concrete, was extended to approximate stress–strain curves for RAC, making it applicable in practical engineering with RAC.

One more study was conducted in China by Feng et al [7]. The study has focused on mechanical properties of HFRRAC (Hybrid Fiber reinforced recycled aggregate concrete) under cyclic loading. In total 6 mixes with different RCA, and fibre ratios were created, and casted into prismatic shape of 100 × 100 × 300 mm size. The tests that were run are: Monotonic loading tests involved loading specimens at a rate of 0.003 mm/s until they failed, using an electro-hydraulic servo testing machine with a 1000 kN capacity, following the Chinese code; Cyclic loading tests included loading specimens at 0.003 mm/s and unloading them to near-zero stresses with a rate of 10 kN/s; uniaxial compression experiments were carried out using the WAW-1000D testing machine; scanning electron microscopy (SEM) to examine the microstructure of various components of RAC, including RAC mortar, aggregate-mortar ITZs, and fibre-mortar ITZs. Cyclic loading revealed distinctive behaviours in specimens with and without fibres. Specimens lacking fibres predominantly displayed a dominant, penetrating crack leading to brittle failure. In contrast, specimens incorporating fibres demonstrated ductile failure, characterized by the presence of shear bands. The cyclic stress-strain properties exhibited distinct phases, commencing with stable microcrack propagation, transitioning to unstable macrocrack propagation, and gradually decreasing during the residual stress stage. Interestingly, the research found no substantial correlation between stiffness degradation and the rate of Recycled Concrete Aggregate (RCA) replacement.

Moreover, the presence of fibres effectively mitigated the stiffness degradation process. The study indicated that the RCA replacement rate and various fibre combinations had minimal influence on plastic strain and stress deterioration within the concrete specimens. Comparing Normal Aggregate Concrete (NAC) to Recycled Aggregate Concrete (RAC), it became evident that NAC exhibited superior maximum hysteretic energy dissipation. Nevertheless, the inclusion of fibres in RAC specimens led to improvements in hysteretic energy dissipation, with hybrid fibres showing a particularly noteworthy synergistic effect. Proposed constitutive equations effectively described the mechanical behaviour of HFRRAC under cyclic loading, offering a valuable framework for analysis. The research delved into the microstructure of the concrete specimens, revealing that specimens without fibres exhibited hydration products characterized by numerous holes and irregular cracks, which formed discontinuous gel blocks and ultimately reduced the mortar's strength. Conversely, specimens containing fibres displayed changes in the orientation of hydration products due to the presence of hybrid fibres. This structural alteration effectively restricted hardening shrinkage in the mortar, enhancing the density and structure of both the mortar and the interfaces between aggregate and paste. For simulating the compressive behaviour of HFRRAC, the study identified the suitability of the cohesive zone model. Moreover, the presence of fibres in the specimens resulted in the formation of a discontinuous skeleton structure and a shift in the original structure, leading to more convoluted fracture paths. In numerical simulations, the specimens predominantly failed through mixed fracture modes, with mode II fractures being the primary characteristic.

These investigations have illuminated the potential to enhance the performance of RAC through the addition of fibres, opening avenues for innovation and improvement in sustainable construction practices. The research has already revealed that the presence of fibres can substantially influence the failure modes and mechanical properties of RAC under various loading conditions. In particular, fibres have demonstrated the ability to shift the failure mode from brittle to ductile in cyclic loading scenarios, effectively mitigating stiffness degradation and improving energy dissipation. Moreover, the combination of recycled concrete aggregate (RCA) replacement rates and various types of fibres appears to have a nuanced impact on the behaviour of RAC, warranting further exploration to optimize their synergistic effects. Ultimately, this new research holds promise for advancing the understanding of how fibres can improve the mechanical and structural properties of RAC, making it a more sustainable and versatile material for modern construction applications [7].

The decision to embark on research in the field of RAC integrated with fibres arose from a pressing need to explore innovative avenues in sustainable construction materials. The aim of this research is to comprehensively investigate the mechanical properties of RAC, with a specific focus on the incorporation of fibres. Recognizing the potential to optimize RAC by introducing fibres, the research aims to shed light on the impact of this enhancement on critical aspects, including flexural and compressive strengths, ultimate strain (stress-strain behaviour), and modulus of elasticity. Additionally, the study seeks to delve into the properties of crushed recycled aggregate to discern the underlying factors influencing the material's performance. This research endeavour has been motivated by the desire to contribute to the development of greener, more resilient, and structurally sound building materials while promoting the sustainable use of recycled materials in the construction industry. By analysing these properties and their interplay, this research strives to pave the way for advancements in the application of RAC with fibres, offering substantial benefits for both the construction sector and environmental conservation.

As the world marches towards a greener and more sustainable future, this study's primary objective is to identify sustainable solutions for the construction industry. The results and findings presented in this paper hold significance for students, researchers, engineers, and policymakers alike, all of whom are dedicated to promoting and advancing the use of recycled aggregate concrete in pursuit of a more environmentally conscious and sustainable construction environment.

3. Research methodology

This study was performed in three phases, three generations of concrete were made. First generation concrete is the Natural Aggregate Concrete (NAC). Two mix designs of different targeted compressive strength were used, called C1 and C2. In addition to plain concrete of C1 and C2, the mix design of C2 was used to prepare Fibre Reinforced Concrete (FRC) once with steel fibres, second with synthetic macro fibres. Thus, the specimens for experimental testing were prepared using the following mix designs: C1, C2, C2D (steel fibres), C2M (synthetic fibres).

The specimens were tested for mechanical properties after 28 days and then crushed. Specimens were demoulded at age of one day, kept under water until the age of 7 days and then in laboratory ambient conditions.

After testing, the test specimens were crushed to prepare recycled concrete aggregate (RCA). The crushed aggregate of first generation of concrete was used to prepare the second-generation concrete. The coarse fractions of mix designs (4-16 mm) were replaced by RCA. Four types of second-generation RAC were produced. Crushed aggregates from the first generation of C1 concrete was used to produce the second generation of C1 concrete. Similar strategy was applied to other mixes. The mixes for the second generation of concrete have the following symbols: Re-C1, Re-C2, Re-C2D and Re-C2M, respectively.

After 28 days of curing (same as previously described), second round of testing were run, and the RAC were crushed, and coarse RCA was used for the third generation RAC. The mixes for the third generation of concrete have the following symbols: Re-Re-C1, Re-Re-C2, Re-Re-C2D and Re-Re-C2M, respectively.

The concrete specimens from each generation, and type were analysed for several tests to check their mechanical and microstructural properties: compressive strength, CMOD (Crack Mouth Opening Displacement), modulus of elasticity, splitting tensile strength, stress-strain behaviour, freeze-thaw resistance, water absorption, water permeability under pressure. The number of specimens, and dimensions made for each test are listed in Table 3.1. The specimens were then crushed using a jaw crusher. Afterwards, crushed aggregates were sieved through 4-16 mm sieves. The aggregates were tested for apparent density and water absorption after 1 and 24 hours.

Table 3.1 – Number of specimens for mechanical properties testing

Test type	Dimensions [mm]	Amount [pieces]
CMOD	70 × 70 × 250	3
Compressive strength	150 × 150 × 150	4
Splitting tensile	100 × 200	3
Freeze-thaw resistance	100 × 100 × 100	6
Stress-strain behaviour	70 × 70 × 250	3
Modulus of elasticity	100 × 200	3
Water permeability	150 × 150 × 150	3
Water absorption	100 × 100 × 100	3

3.1 Experimental test types

To study the properties of Recycled Aggregate Concrete (RCA), following tests were done:

- Compressive strength
- Splitting tensile
- Flexural behaviour (CMOD – Crack Mouth Opening Displacement)
- Modulus of elasticity
- Water permeability
- Stress-strain behaviour
- Freeze-thaw resistance
- Water absorption.

3.2 Materials

As binder the cement type CEM I 52.5 N was used. The natural aggregate (NA) was quartz aggregate of fractions: 0/4, 4/8, 8/16 (Figure 3.2.1). The steel fibres used were Dramix 3D 65/35BG, length of 35 mm, and diameter of 0.55 mm. The polypropylene fibres were used of MAPEI brand, Mapefibre IT25, of the length of 25 mm, and 0.54 mm of diameter (Table 3.2.1).

Figure 3.2.1 – NA:0/4 (left), 8/16 (right) fractions

Table 3.2.1 – Characteristics of steel and synthetic fibres

	Diameter [mm]	Length [mm]	Tensile strength [N/mm^2]	Young's modulus [N/mm^2]
Dramix 3D 65/35BG	0.55	35	1345	210
Mapefibre IT25	0.54	25	480	4 000

The following mix designs were used for the first generation of the concrete (Table 3.2.2-3.2.3).

Table 3.2.2 – Mix design for C1 concrete mix, Generation I (i.e., first generation)

Material	Type		Mass, kg/m^3	Volume, l/m^3
Aggregates	0/4 mm	45%	832	315
	4/8 mm	20%	370	140
	8/16 mm	35%	647	245
Cement	CEM I 52.5 N		293	95
Water	m_w/m_c =	65.0%	190	190
Superplasticizer cem. m%	Glenium C300	0.00%	0.0	0
Air			--	15
All			2332	1000

Table 3.2.3 – Mix design for C2 concrete mix, Generation I

Material	Type		Mass, kg/m^3	Volume, l/m^3
Aggregate	0/4 mm	45%	832	315
	4/8 mm	20%	370	140
	8/16 mm	35%	647	245
Cement	CEM I 52.5 N		375	121
Water	m_w/m_c =	43.0%	161	161
Superplasticizer cem. m%	Glenium C300	0.61%	2.3	2.29
Air			--	15
All			2388	1000

The mix design for C2D and C2M are same as for C2, but with added fibres content: 5 kg/m^3 of synthetic fibres, and 43 kg/m^3 of steel fibres. The dosages were defined, as they have the same volume.

3.3 Mixing of concrete

For each generation 4 different mixes were made: C1, C2, C2D, and C2M. The concrete was mixed in a 100 ℓ capacity pan type mixer with activator (Fig. 3.3.1).

Figure 3.3.1 – Concrete mixing machine

After mixing the consistency of the fresh concrete is tested by the flow table test. There is a desired diameter for each mix design, for us this diameter was around 490-540 mm for the first generation (consistency class F4) (Fig. 3.3.2).

Figure 3.3.2 – Flow table test

Afterwards, concrete was poured into forms listed in the Table 3.1. After 24 hours specimens were unmoulded and placed into water basin for water curing process for 6 days. 28 days after mixing and moulding, the specimens are ready to be tested.

4. Experimental investigation

4.1 Compressive strength test

Firstly, all specimens were collected and compression strength testing machine matching EN 12390-3 standards was used. The specimens were loaded in machine until failure, and maximum force was recorded. The testing machine was cleaned prior to each specimen testing from all the leftover pieces of preceding specimens. The test specimens were used in cube shape of 150×150×150 mm dimension (4.1.1). Force was applied at a rate of 11.25 kN/s, this was calculated by the following formula: $R = A * s$.

A – area of surface [mm^2]

s – constant rate of loading [$N/mm^2/s$], taken as 0.5 $N/mm^2/s$

For each mixture four specimens were tested, and average value was calculated.

Figure 4.1.1 – Installation of compressive strength test

4.2 Splitting Tensile test.

For this test specimens were taken in prism shape, in accordance with EN 12390-1, of 100mm diameter, 200 mm height (4.2.1). Force was applied at a rate of 1.57 kN/s, this was calculated by the following formula: $R = \frac{s \times \pi \times L \times d}{2}$.

S – constant rate of loading [N/mm^2/s]

L – length of the specimen [mm]

d – diameter of cross section [mm]

In total 3 specimens were tested for each generation, and average value was calculated accordingly.

Figure 4.2.1 – Installation of splitting tensile strength test

4.3 CMOD test

CMOD – Crack Mouth Opening Displacement was performed to study tensile behaviour of concrete in terms of residual flexural tensile strength. This is mostly made to test the fibres embedded in the concrete. For this test 3 prismatic specimens of each generation were used, in the dimensions of 70 × 70 × 250 mm. The test was done according to EN 14651:2005+A1:2007 standard. Testing machine meeting the machine class 1 requirements in EN 12390-4. Each specimen was notched, of 5 mm width and 15 mm height through the width of specimen at midspan. The specimen was then placed into the testing machine , and the load was applied only after making sure that all loading and supporting rollers are resting evenly against the test specimen (Fig. 4.3.1).

Figure 4.3.1 – CMOD testing

4.4 Modulus of elasticity test

The test was performed by EN 12390-13 standard. A machine matching a standard of EN 12390-4 is used in this test. The specimens are prepared in prismatic shape, according to EN12504-1 standard, for this test specimens of dimensions 70 × 70 × 250 mm, the surface of the specimen is marked with paint for appropriate contrast, as the stain is measured by a contactless (video) technique. The specimen is subjected to a compressive force (Fig. 4.4.1).

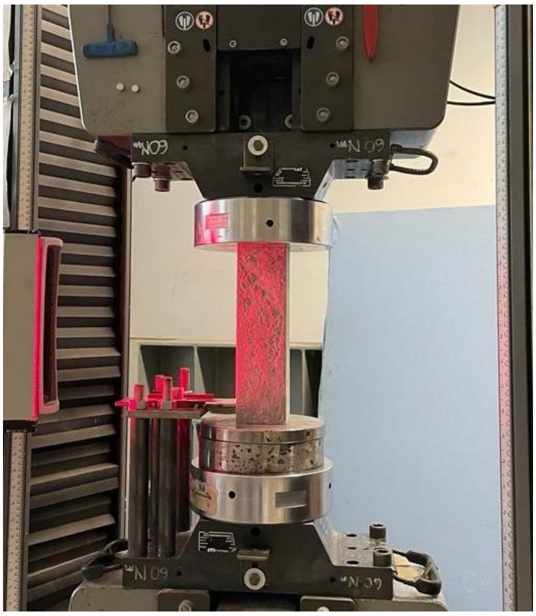


Figure 4.4.1 – Modulus of elasticity testing

4.5 Water Permeability test

This test was performed according to EN 12390-8. The dimensions of specimens tested: 150 × 150 × 150 mm cube shaped. The test specimens were place into the apparatus, and water was applied under pressure (500±50 kPa) on the surface of concrete for 72±2 hours (Fig. 4.5.1). After 72 hours, the specimen was removed from the machine, the surface was wiped, after the specimen was split in half, the water penetration on the cross-section was measured, so that the water penetration can be assessed.

Figure 4.5.1 – The water permeability test setup.

4.6 Stress-strain behaviour test

The ultimate strain is a measure of how much a concrete specimen can deform in compression before it breaks. Specimens with 100 mm diameter and 200 mm height were used. The surface was covered with paint, marking points, using which computer would detect the movement and deformation. Furthermore, three deformation measuring instruments (LVDT) are arranged symmetrically with respect to the central axis of the specimen (Fig. 4.6.1). Compression force is applied during this test. The test was repeated on three specimens for each concrete type.

Figure 4.6.1 – Testing for stress-strain behaviour

4.7 Freeze-thaw resistance test

To test the durability of the concrete in cold and moist environment, freeze-thaw test was performed. For each mixture 6 specimens were taken: 3 reference ones, and 3 that were undergoing freeze-thaw cycles. The dimensions of specimens were taken as 100 × 100 × 100 mm cubes. The specimens were first measured: dimensions, and initial dry weight. Then they were placed into a water tank in room temperature until full saturation. After those three specimens were placed into freeze-thaw machine, while the reference ones were kept under water. For each mixture 56 freeze-thaw cycles were run. The specimens were undergoing change of temperature between -20°C and +20°C.

4.8 Water absorption test

A water absorption test for concrete is conducted to determine the amount of water that concrete can absorb. The primary purpose of this test is to assess the porosity of concrete and its ability to resist the penetration of water. For this test cube specimens of dimension 100 × 100 × 100 mm are taken, 3 specimens per mixture. First, the specimens are measured by their dry mass, then the specimens are place into oven at 60°C until they are completely dry, the dried mass is also noted. Then, the specimens are placed into water tank and kept there until complete water saturation.

4.9 Crushing and testing of aggregates.

After testing the first (and second) generation of concrete, the specimens were crushed using the jaw-crusher machine (Fig. 4.9.1).

Figure 4.9.1 – Jaw crusher machine

The crushed aggregates were then sieved through sieving machine (Fig. 4.9.2).

Figure 4.9.2 – Sieving machine

The sieved aggregates are then used for the next generation of concrete.

5. Results and discussion

5.1 Compressive strength test results

The test was carried out for all three generations, and maximum load value was recorded from the machine. Compressive strength was then calculated by the formula: $\sigma_c = \frac{F}{A}$.

F – Maximum load [kN]

A – Cross-section of the specimen [mm^2]

The density of the specimen was calculated by the following formula: $\rho = \frac{m}{V}$.

m – mass of the specimen [g]

V – volume of the specimen [mm^3]

Results for all three generations will be given below in graphs and tables comparing each mixture's compressive strength through three generations, Fig. 5.1.1-5.1.4 and Table 5.1.1-5.1.3.

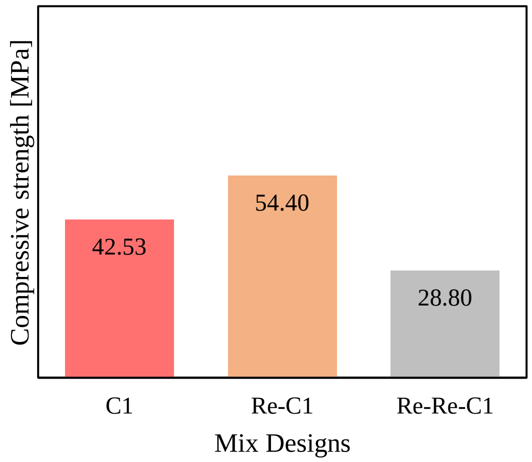


Figure 5.1.1 – C1 mixtures compressive strengths

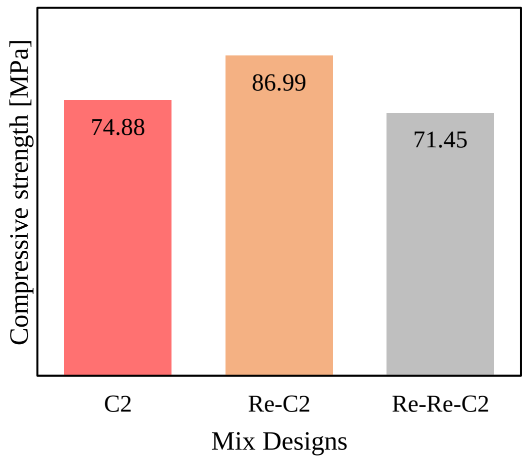
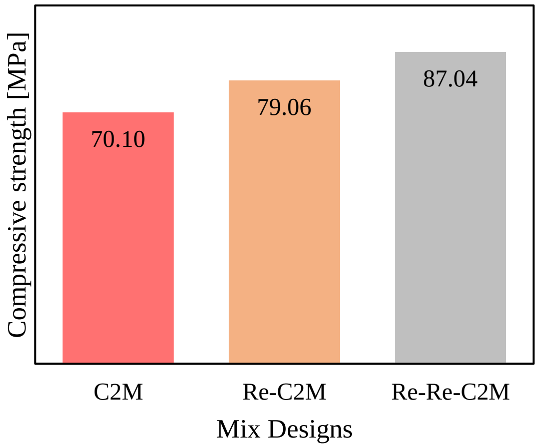


Figure 5.1.2 – C2 mixtures compressive strengths



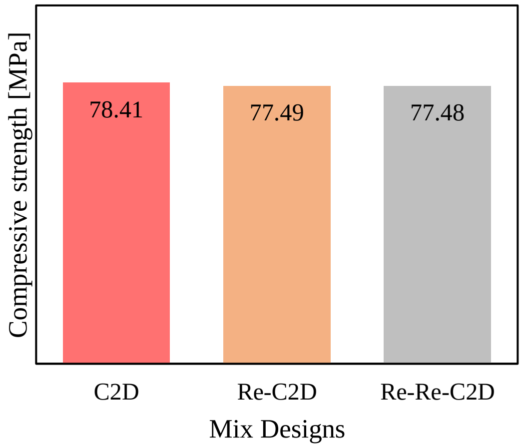
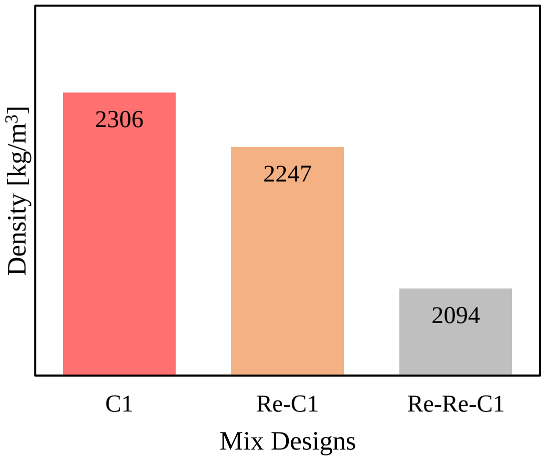


Figure 5.1.3 – C2M mixtures compressive strengths *Figure 5.1.4 – C2D mixtures compressive strengths*

The density of specimens is presented in Figures 5.1.5-5.1.8.



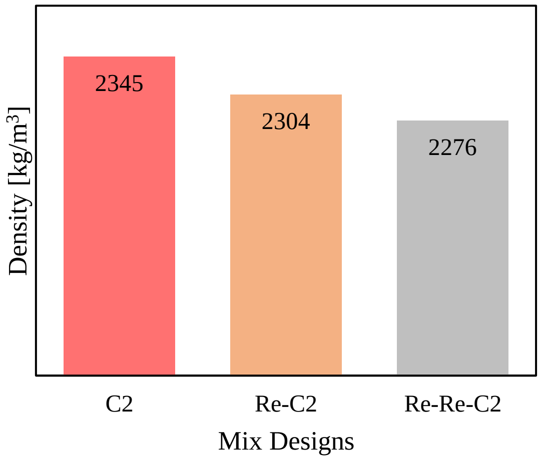
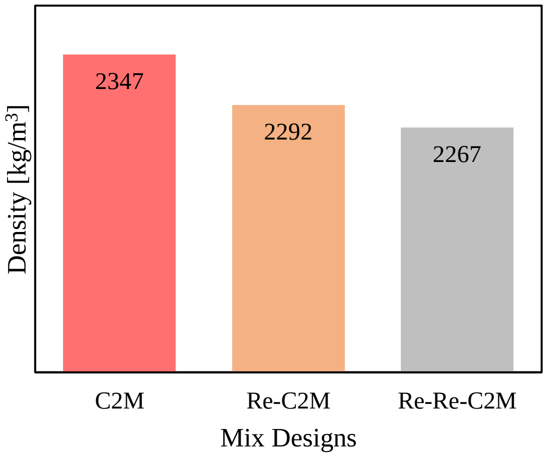


Figure 5.1.5 – Density of C1

Figure 5.1.6 – Density of C2



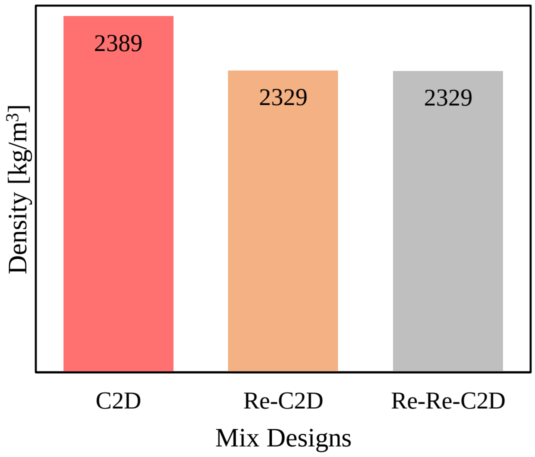


Figure 5.1.7 – Density of C2M

Figure 5.1.8 – Density of C2D

Table 5.1.1 – Results of compressive strength test of the first generation

Specimen	Force [kN]	Compressive strength [MPa]	Density [kg/m^3]
C1 I	954.0	42.53	2306.2
C2 I	1689.5	74.88	2345.0
C2D I	1774.5	78.41	2388.5
C2M I	1573.0	70.10	2346.6

Table 5.1.2 – Results of compressive strength test of the second generation

Specimen	Force [kN]	Compressive strength [MPa]	Density [kg/m^3]
C1 I	1207.0	54.40	2247.1
C2 I	1969.0	86.99	2304.0
C2D I	1726.3	77.49	2329.3
C2M I	1777.5	79.06	2291.7

Table 5.1.3 – Results of compressive strength test of the third generation

Specimen	Force [kN]	Compressive strength [MPa]	Density [kg/m^3]
C1 I	637.5	28.80	2094.2
C2 I	1607.3	71.45	2276.0
C2D I	1726.3	77.48	2328.9
C2M I	1974.0	87.04	2267.1

Based on the laboratory results, the increase in compressive strength results can be noticed from the first to the second generation. However, results for the third generation RAC show that compressive strength values have decreased for C1 and C2 mixtures. Meanwhile C2M and C2D results do not show decrease in the last generation, steady result for C2M and slight increase in value or C2D. Density results, on the contrary, have a steady trend through generations – a decrease in density value, this is one of the qualities of the RCA: high porosity. Further the water tightness of the specimens will be checked. Below the failure state of specimen is presented (Fig. 5.1.9).

Figure 5.1.9 – Compressive strength test, specimen failure

5.2 Splitting Tensile strength test results.

In the below, results of the splitting tensile strength tests are presented – for each generation separately (Tables 5.2.1-5.2.3).

Table 5.2.1 – Results of splitting tensile strength test of the first generation

Specimen	Force [kN]	Splitting tensile strength [Mpa]
C1 I	128.7	4.11
C2 I	141.0	4.47
C2D I	254.0	8.02
C2M I	154.0	4.89

Table 5.2.2 – Results of splitting tensile strength test of the second generation

Specimen	Force [kN]	Splitting tensile strength [Mpa]
C1 I	101.0	3.27
C2 I	136.7	4.40
C2D I	218.0	6.93
C2M I	171.3	5.44

Table 5.2.3 – Results of splitting tensile strength test of the third generation

Specimen	Force [kN]	Splitting tensile strength [Mpa]
C1 I	86.3	2.75
C2 I	161.3	5.15
C2D I	211.3	6.69
C2M I	177.3	5.65

The results of splitting tensile strength test showed a considerable decrease for C1 and C2, however the specimens with embedded fibres have showed only slight decrease in strength value, thus maintaining relatively high splitting tensile strength throughout generations. The failure state of the test specimen is presented below (Fig. 5.2.1)

Figure 5.2.1 – Splitting tensile test, specimen after failure.

5.3 CMOD test results

The CMOD test was performed on all mixes, taking 3 samples from each mix. Below the results for all mixes are presented (Fig. 5.3.1-5.3.12).

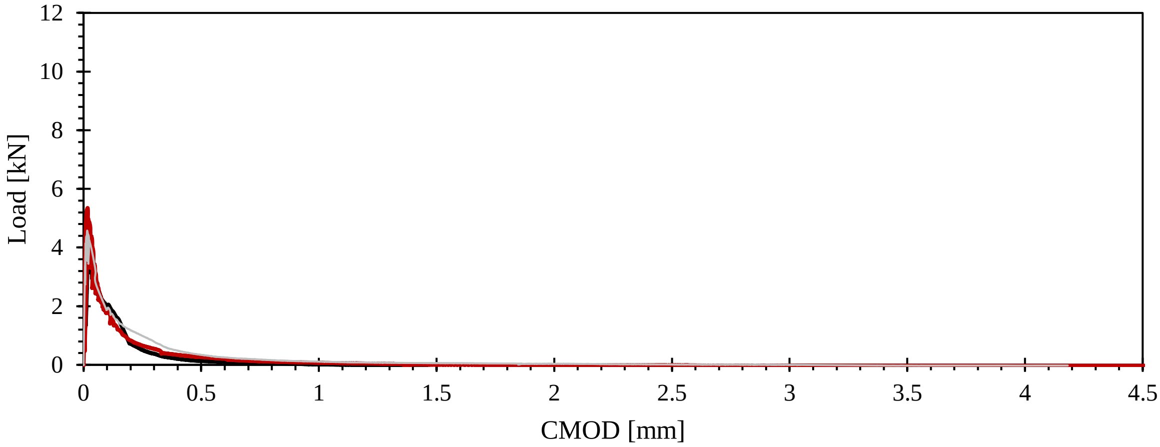


Figure 5.3.1 – CMOD C1, Generation I (i.e., first generation)

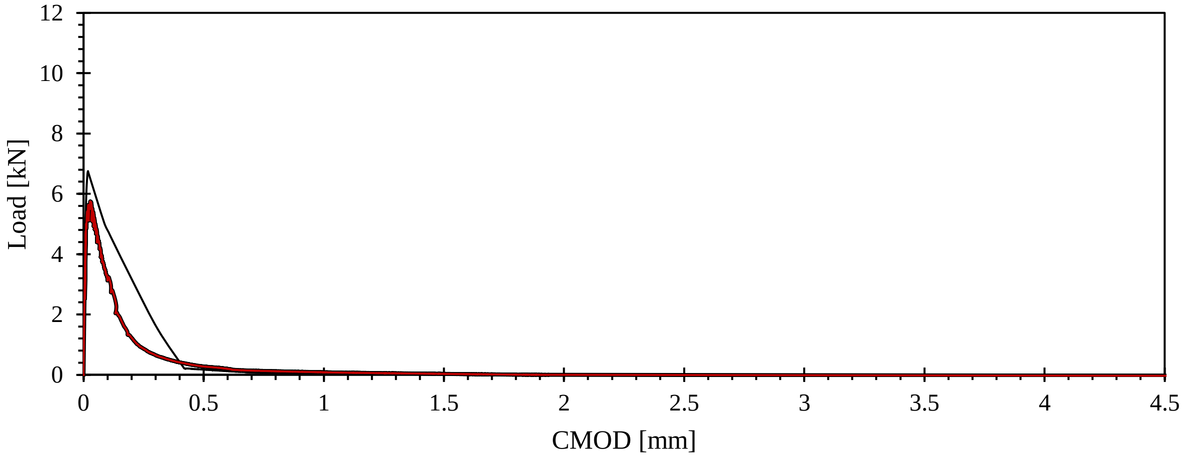


Figure 5.3.2 – CMOD C2, Generation I

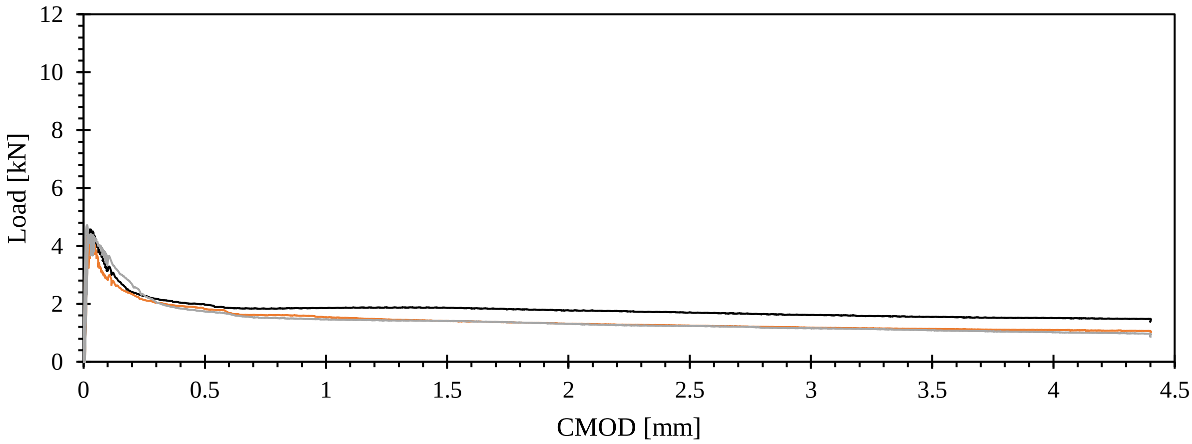


Figure 5.3.3 – CMOD C2M, Generation I

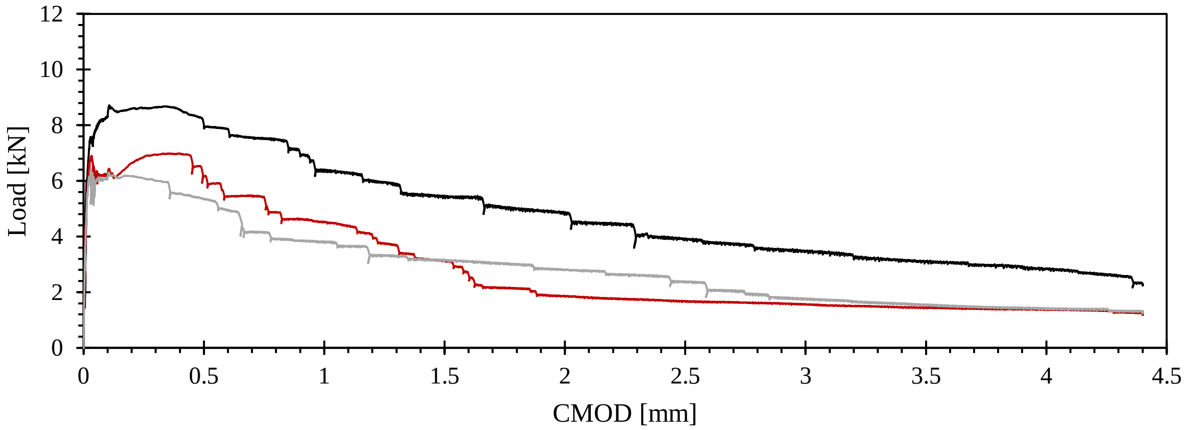


Figure 5.3.4 – CMOD C2D, Generation I

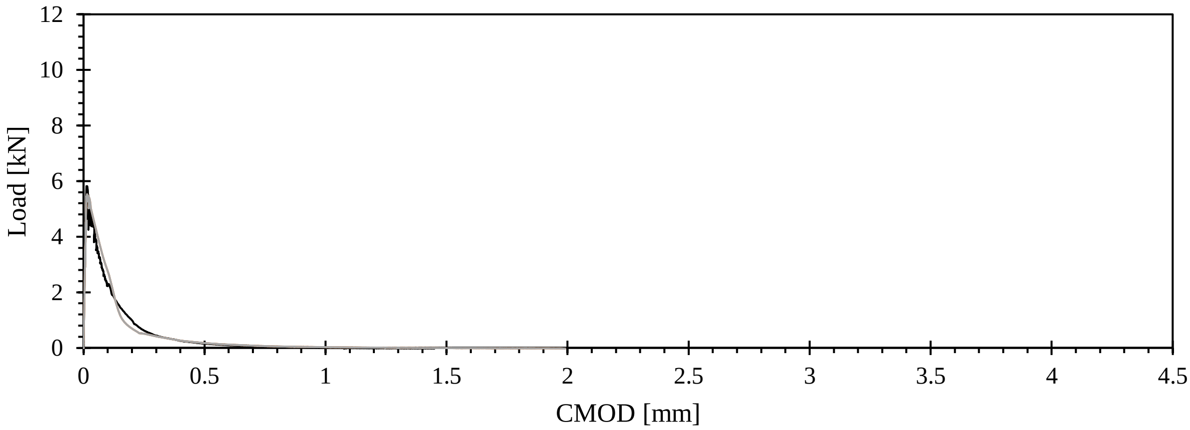


Figure 5.3.5 – CMOD C1, Generation II (i.e., second generation)

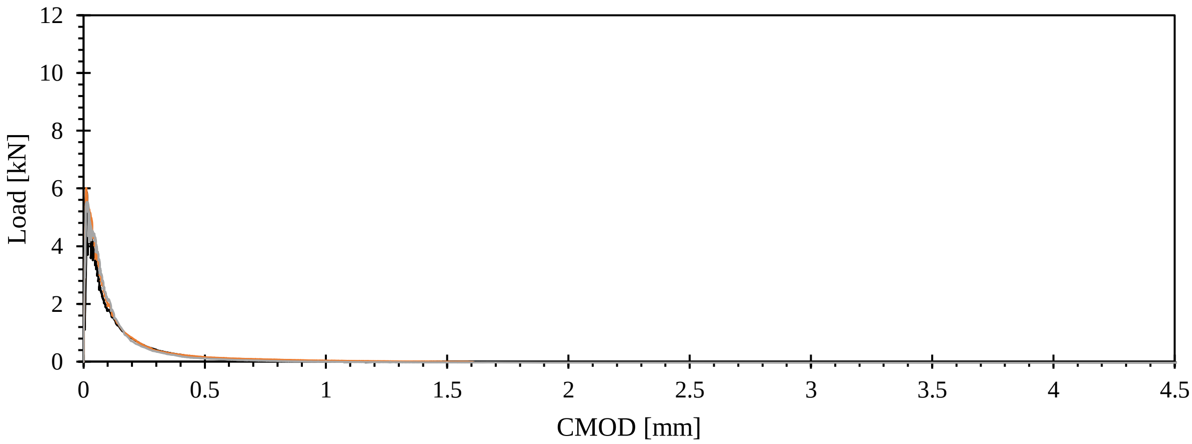


Figure 5.3.6 – CMOD C2, Generation II

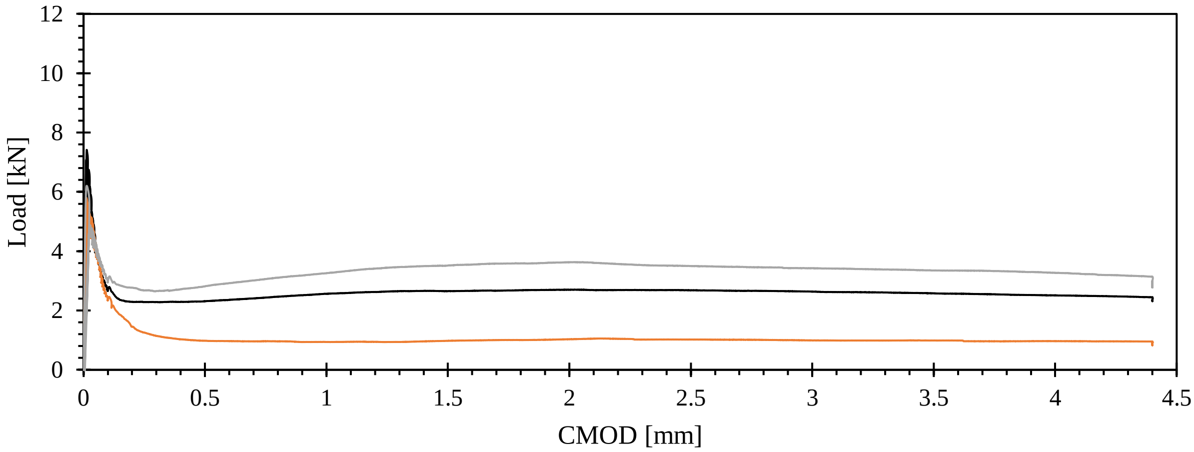


Figure 5.3.7 – CMOD C2M, Generation II

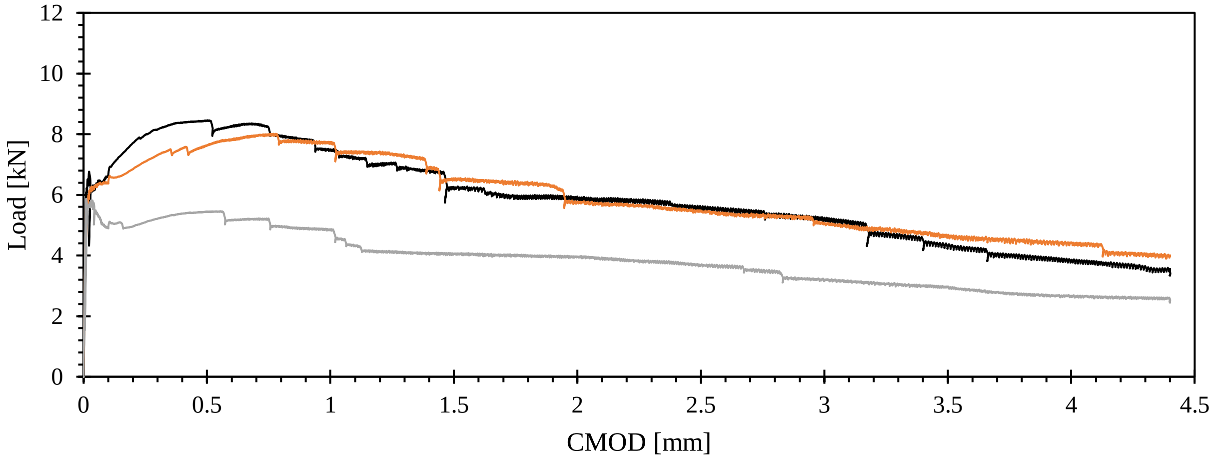


Figure 5.3.8 – CMOD C2D, Generation II

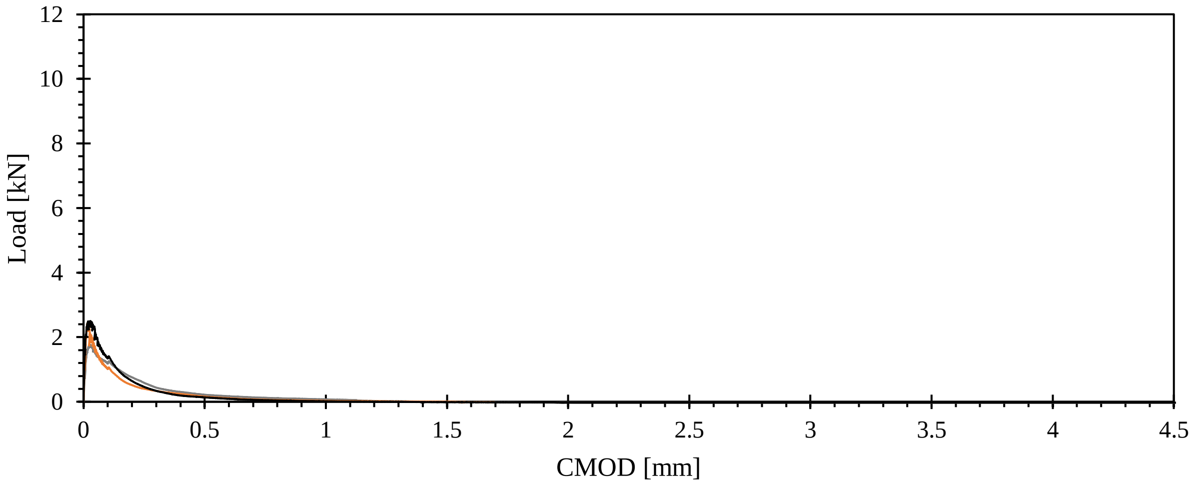


Figure 5.3.9 – CMOD C1, Generation III (i.e., third generation)

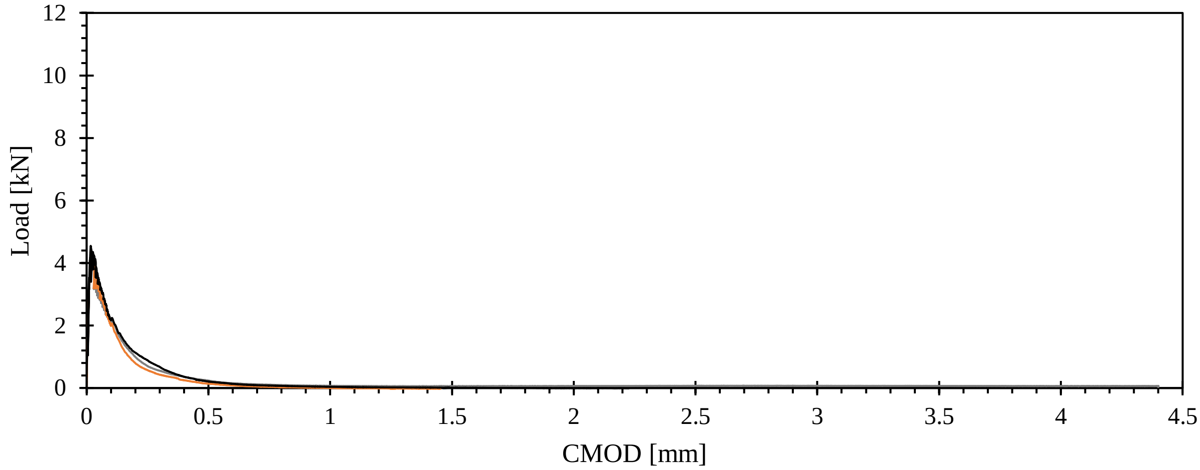


Figure 5.3.10 – CMOD C2, Generation III

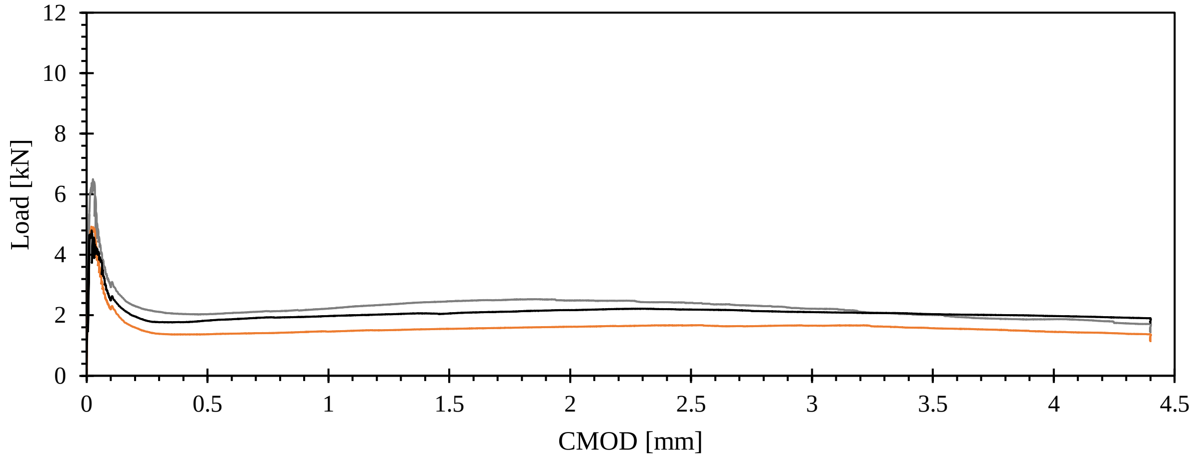


Figure 5.3.11 – CMOD C2M, Generation III

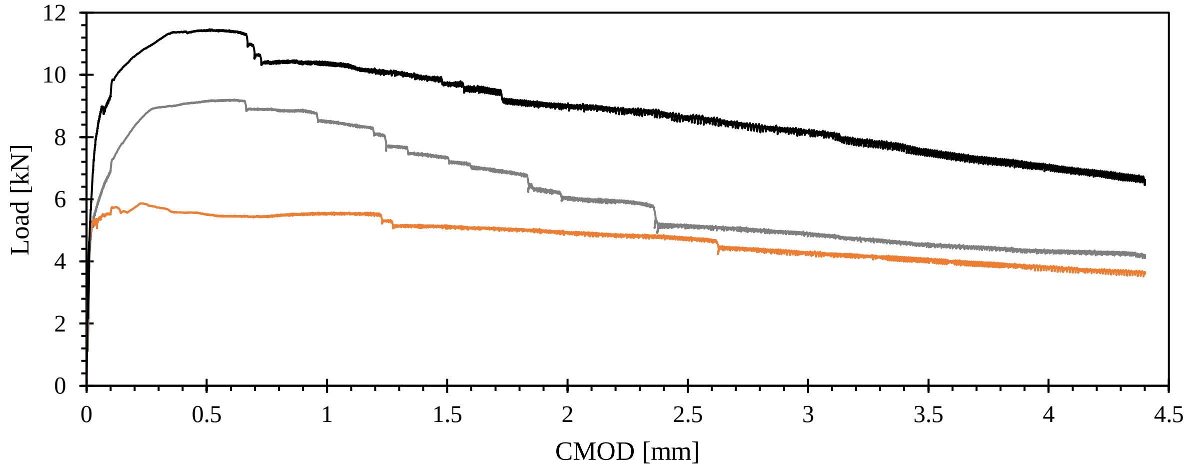


Figure 5.3.12 – CMOD C2D, Generation III

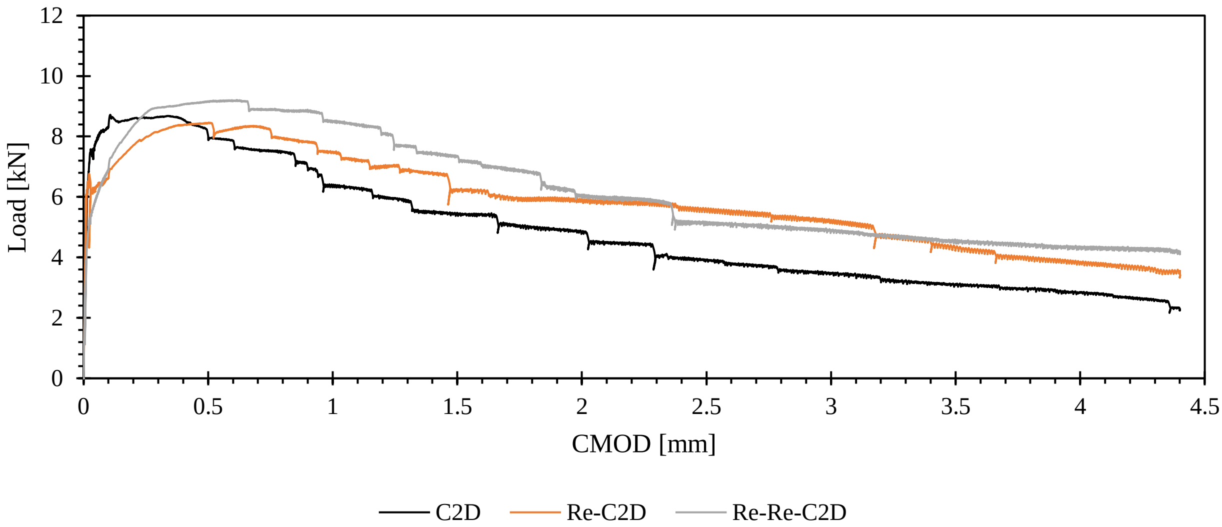


Figure 5.3.13 – CMOD C2D, Re-C2D, Re-Re-C2D

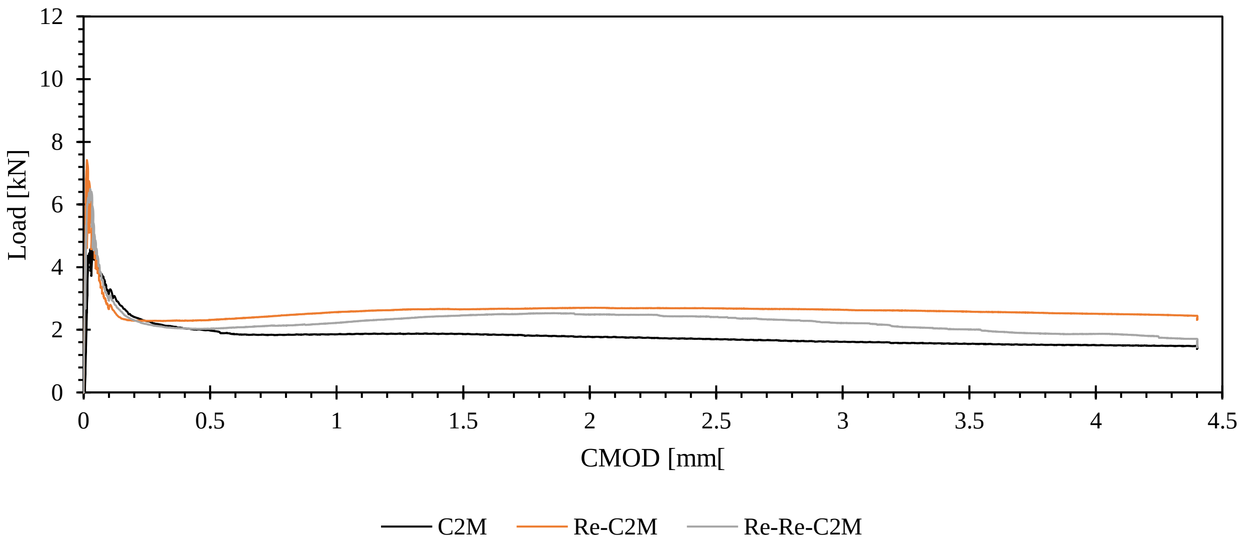


Figure 5.3.13 – CMOD C2M, Re-C2M, Re-Re-C2M

Based on the results, high maximum load for C2D can be observed in all three generations. Moreover, the CMOD graph for this mix has a special pattern, due to steel fibres, because they alter material behaviour and fracture characteristics of concrete, resulting in complex interaction between steel fibres and concrete. Test specimens after failure are shown in Fig. 5.3.13.

Figure 5.3.13 – CMOD test specimens after failure

5.4 Modulus of elasticity test results

The elastic modulus (EMod) test was performed on all mixes, taking 3 samples from each mix. The data for stress and strain values were collected, secant modulus of elasticity was calculated using formula form the standard:

$$E_{C,0} = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_a^m - \sigma_b^m}{\varepsilon_{a,1} - \varepsilon_{b,0}}$$

σ_a^m – upper stress [MPa]

σ_b^m – lower stress [MPa]

$\varepsilon_{a,1}$ – strain from upper stress [mm/mm]

$\varepsilon_{b,0}$ – strain from lower stress [mm/mm]

Hereby the results for all generations are presented (Table 5.4.1):

Table 5.4.1 – Elastic modulus

Mixture	E [GPa]
C1	34.47
C2	44.69
C2M	40.45
C2D	42.45
Re-C1	29.79
Re-C2	36.94
Re-C2M	34.08
Re-C2D	32.96
Re-Re-C1	25.78
Re-Re-C2	36.57
Re-Re-C2M	29.15
Re-Re-C2D	32.27

The results in graph form are presented as well, showing behaviour of each mixture's behaviour in each generation (Fig. 5.4.1-5.4.4).

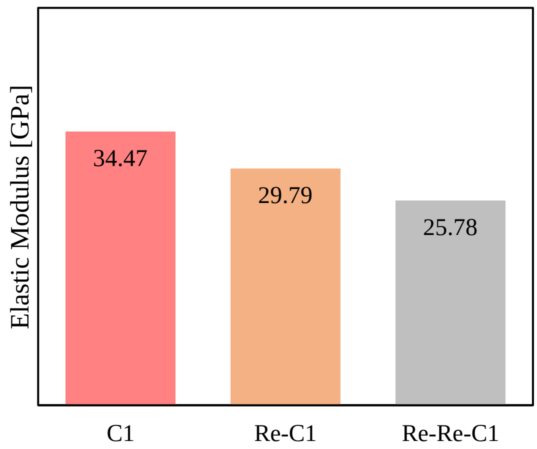


Figure 5.4.1 – Emod C1

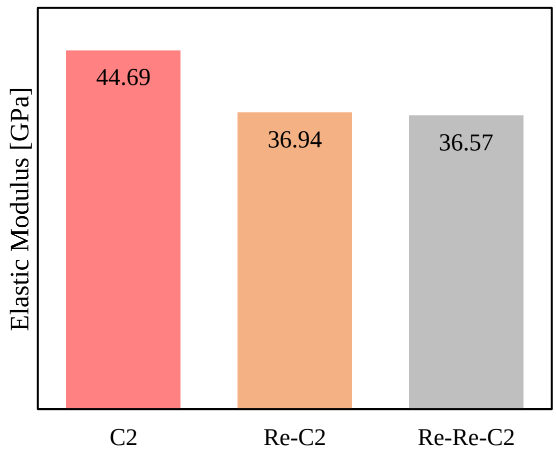


Figure 5.4.2 – Emod C2

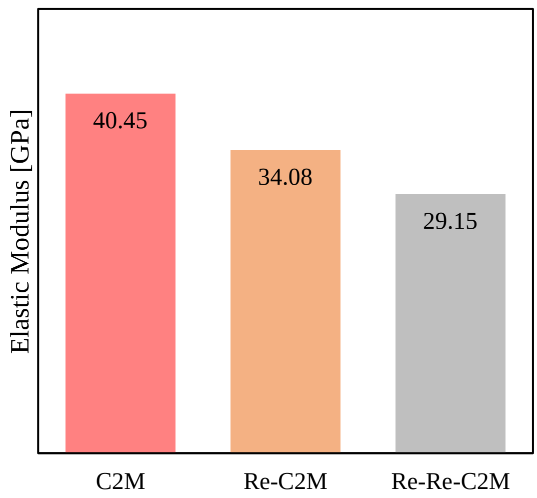


Figure 5.4.3 – Emod C2M

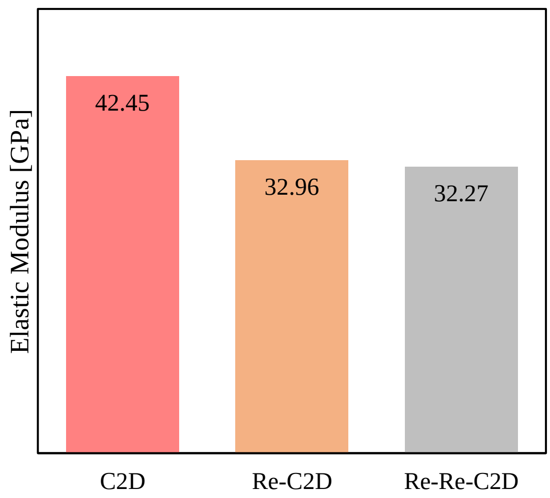


Figure 5.4.4 – Emod C2D

As can be observed, C1 mix has the lowest results. C2 and C2M have around same values, while C2D has the highest outcomes. Throughout generations the decrease in elastic modulus is also observed. This observation is supported on by the studied literature, similar test was already conducted on RAC, and elastic modulus value decreased through generations [8].

5.5 Water Permeability test results

Water permeability test was done on each mixture type, taking three specimens from each. The specimens were left for 72 hours under 5 bars pressure of water. Afterwards the specimens were halved, and water penetration level was measure using calliper. Hereby results are shown for all four mixes in all three generations (Fig 5.5.1-5.5.4).

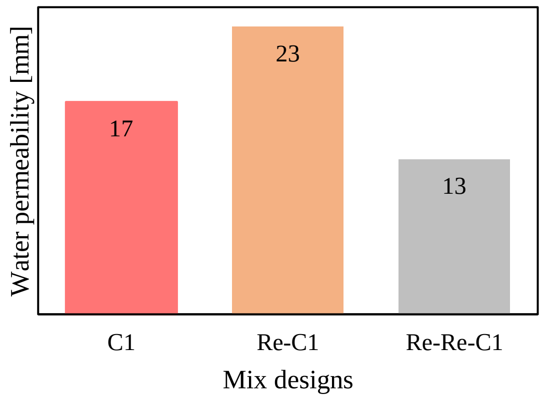


Figure 5.5.1 – Water permeability C1

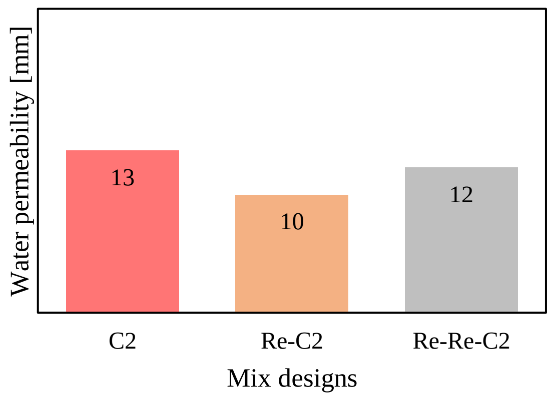


Figure 5.5.2 – Water permeability C2

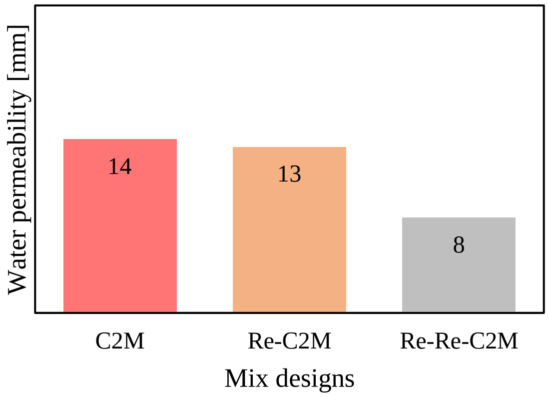


Figure 5.5.3 – Water permeability C2M

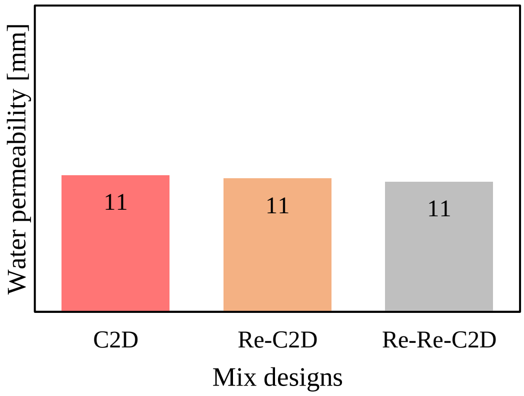


Figure 5.5.4 – Water permeability C2D

The change in C1 mixture through generations shows the higher water penetration level. However, unlike C1, specimens of C2, C2M, and C2D has shown a minor decrease in their values. Example of split open specimen is presented in Fig. 5.5.5.

Figure 5.5.5 – Water permeability test, specimen split open

5.6 Stress-strain behaviour test results

Ultimate strain test was performed on all three generation of concrete. The data is presented in graphs (Fig. 5.6.1-5.6.12).

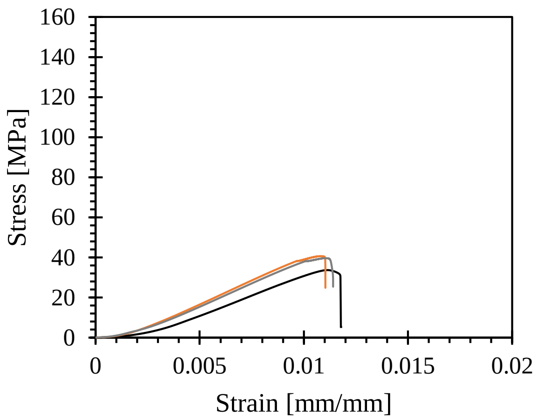


Figure 5.6.1 – Ultimate strain C1

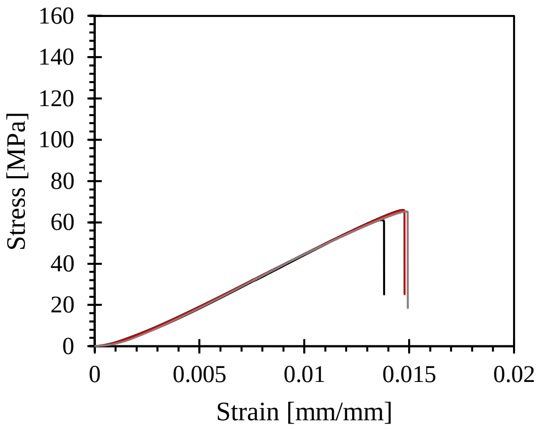


Figure 5.6.2 – Ultimate strain C2

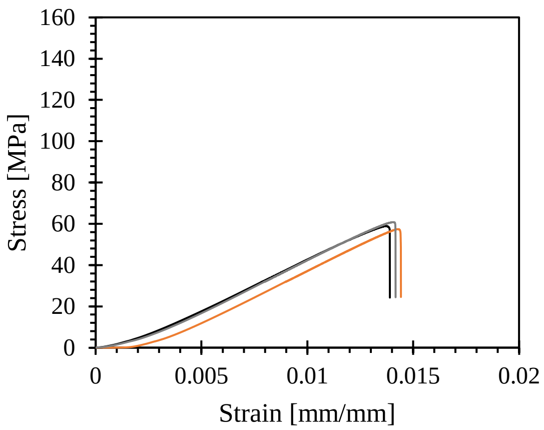


Figure 5.6.3 – Ultimate strain C2M

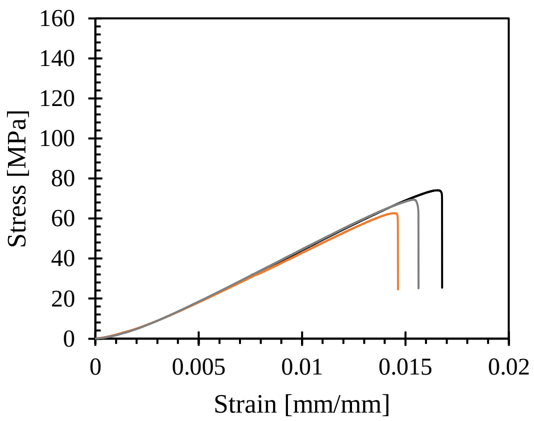


Figure 5.6.4 – Ultimate strain C2D

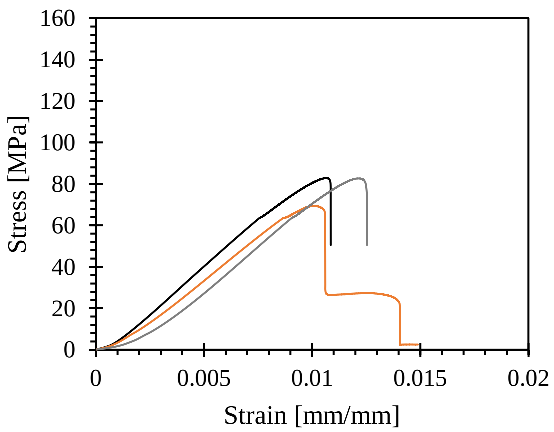


Figure 5.6.5 – Ultimate strain Re-C1

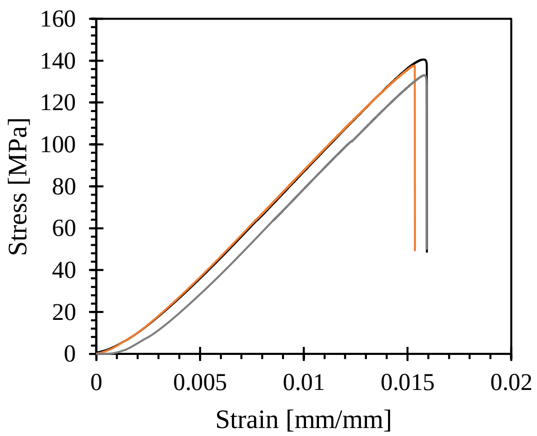


Figure 5.6.6 – Ultimate strain Re-C2

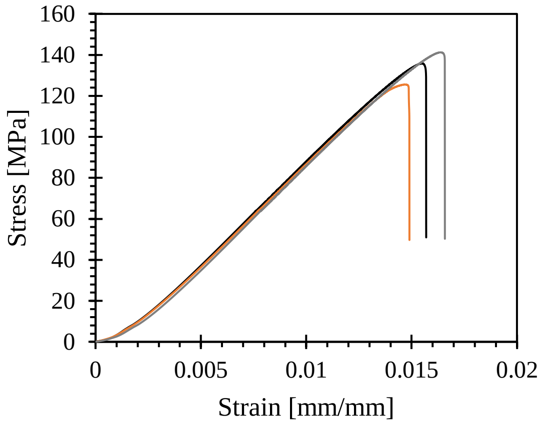


Figure 5.6.7 – Ultimate strain Re-C2M

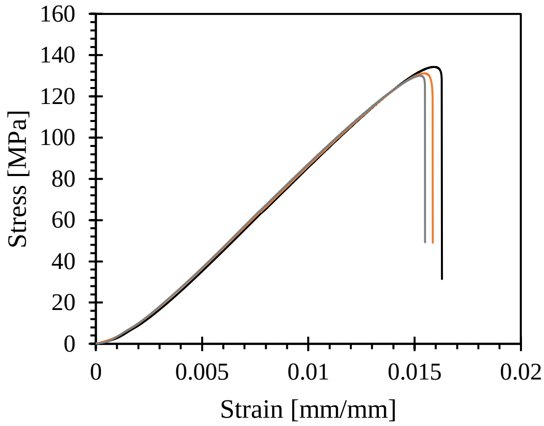


Figure 5.6.8 – Ultimate strain Re-C2D

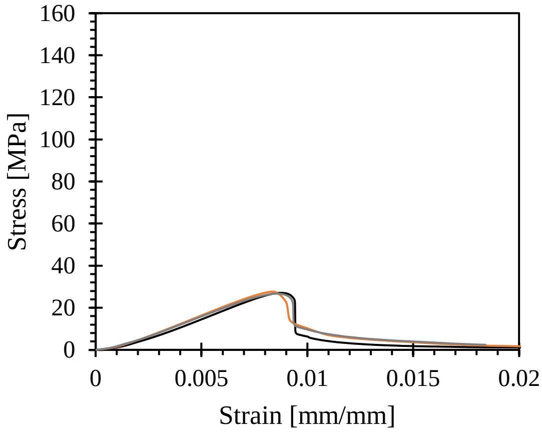


Figure 5.6.9 – Ultimate strain Re-Re-C1

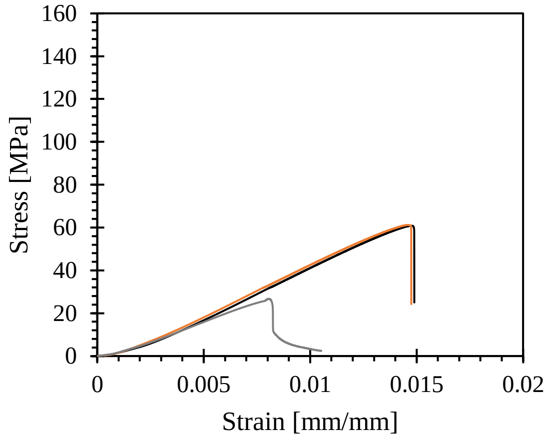


Figure 5.6.10 – Ultimate strain Re-Re-C2

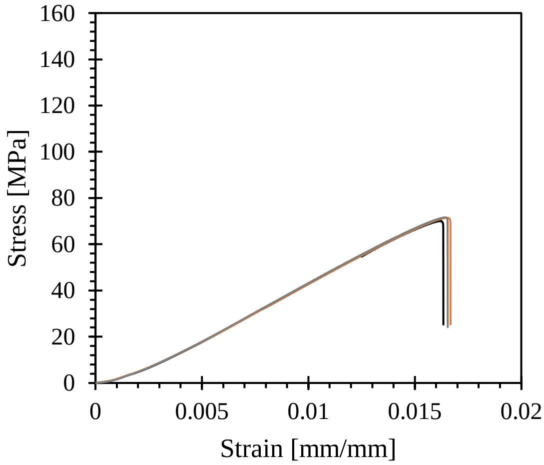


Figure 5.6.11 – Ultimate strain Re-Re-C2M

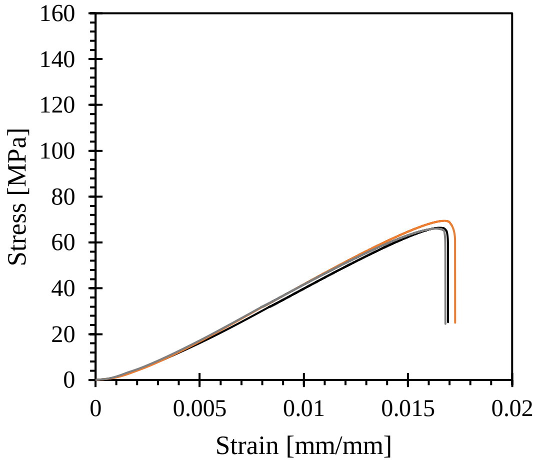


Figure 5.6.12 – Ultimate strain Re-Re-C2D

The difference of stress-strain behaviour can be seen in three generations. Ultimate strain value increases in the second generation for all mixtures, however it drops again in the third generation. Meaning that recycling has its effect on concrete's elasticity.

5.7 Freeze-thaw resistance test results

Freeze-thaw resistance test was performed on all three generations, each generation went through 56 freeze-thaw cycles. The results can be seen below for generations I and II (Table 5.7.1-5.7.2), the freeze-thaw cycles for the specimens of generation III are undergoing in the time of submission of this paper.

Table 5.7.1 – Freeze-thaw testing results, Generation I

		Compressive strength [MPa]
C1	Reference	44.3
	Freeze-thaw	35.2
C2	Reference	76.0
	Freeze-thaw	69.7
C2D	Reference	82.3
	Freeze-thaw	78.8
C2M	Reference	74.9
	Freeze-thaw	60.8

Table 5.7.2 – Freeze-thaw testing results, Generation II

		Compressive strength [MPa]
C1	Reference	46.9
	Freeze-thaw	40.8
C2	Reference	83.7
	Freeze-thaw	85.1
C2D	Reference	76.0
	Freeze-thaw	68.9
C2M	Reference	77.5
	Freeze-thaw	74.5

According to the results above, one can conclude that the RCA appears to have no major detrimental effect on the freeze-thaw resistance of concrete, as the decrease in compressive strength due to the freeze-thaw cycles in case of the second generation concrete is not higher than for those of first generation concrete.

Failure mode of specimen can be seen below (Fig. 5.7.1).

Figure 5.7.1 – Freeze-thaw specimen failure under compressive stress

5.8 Water absorption test results

Water absorption testing for 3 generations have shown following results:

Table 5.8.1 – Water absorption testing results, Generation I

	Dry mass [g]	Dried mass [g]	Saturated mass [g]	Water content [m%]
C1	2314	2274	2352	3.44
C2	2336	2310	2348	1.66
C2M	2363	2300	2350	2.19
C2D	2391	2366	2413	2.00

Table 5.8.2 – Water absorption testing results, Generation II

	Dry mass [g]	Dried mass [g]	Saturated mass [g]	Water content [m%]
C1	2218	2161	2278	5.41
C2	2317	2285	2342	2.49
C2M	2290	2258	2321	2.80
C2D	2287	2253	2318	2.91

Table 5.8.3 – Water absorption testing results, Generation III

	Dry mass [g]	Dried mass [g]	Saturated mass [g]	Water content [m%]
C1	2095	2007	2147	6.96
C2	2262	2211	2274	2.85
C2M	2318	2254	2297	1.94
C2D	2290	2272	2331	2.58

Below we can see comparison of water content for each mix through generations (Fig. 5.8.1-5.8.4).

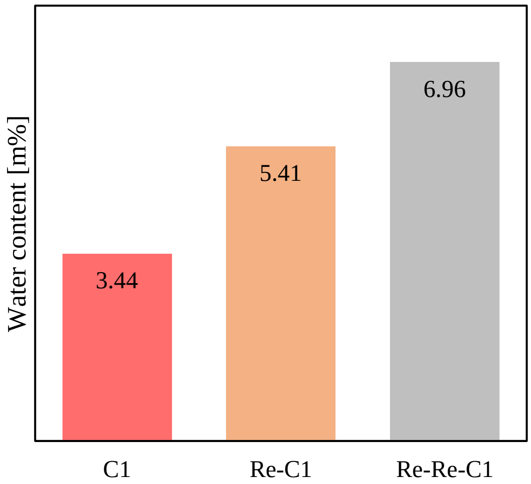


Figure 5.8.1 – Water content C1

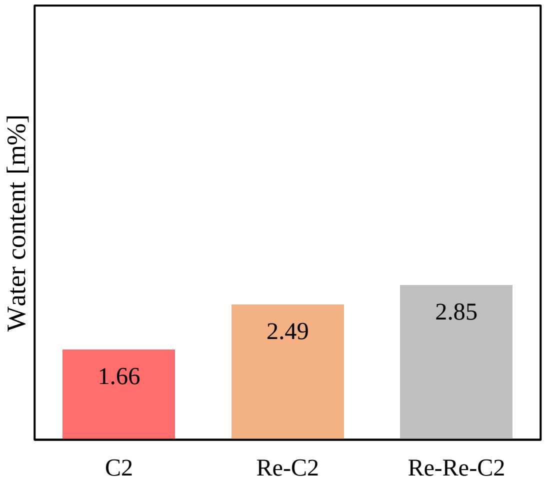


Figure 5.8.2 – Water content C2

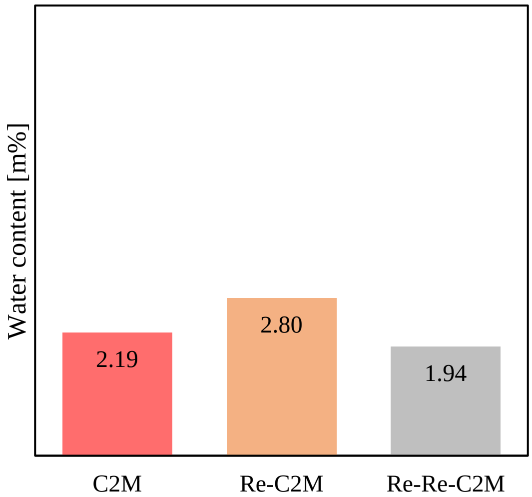


Figure 5.8.3 – Water content C2M

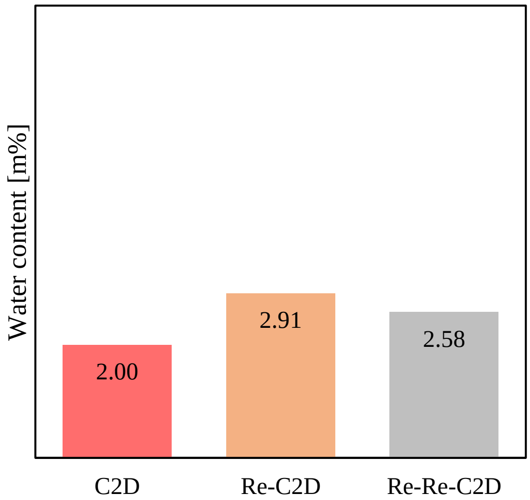


Figure 5.8.4 – Water content C2D

Based on the results in tables, can be seen that water absorption has increased among mixtures through generations, since the water content has increased. This shows the porous nature of RAC. The lowest increase in water absorption was among specimens with embedded fibres. The second generation of C1 had visual surface deterioration, specimens of remaining mixtures did not develop similar traits (Fig. 5.8.5).

Figure 5.8.5 –Surface deterioration C1, Generation II

5.9 Test results of crushed aggregates

Generation I and Generation II concretes were crushed and sieved after being tested. The crushing was done in jaw-crusher machine (Figure 4.9.1). The sieving was done after that using sieving machine (Fig. 4.9.2), (Fig. 5.9.1).

Figure 5.9.1 – Crushed and sieved aggregates C1: 0/4 (left), 4/16 (right)

For sieving, sieves of sizes: 16 mm and 4mm were used, as RCA were substituting only 4/16 grade aggregate in new concrete mixture. Figure 5.9.2-5.9.5 represent grading curves for each mixtures RCA.

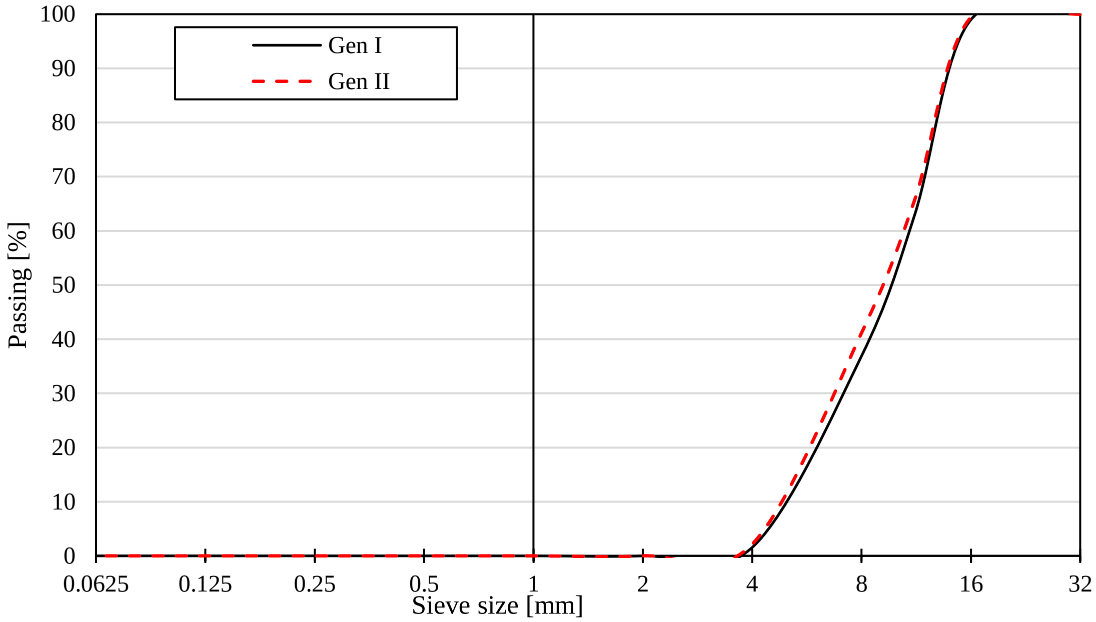


Figure 5.9.2 – C1 grade curve Gen I-II

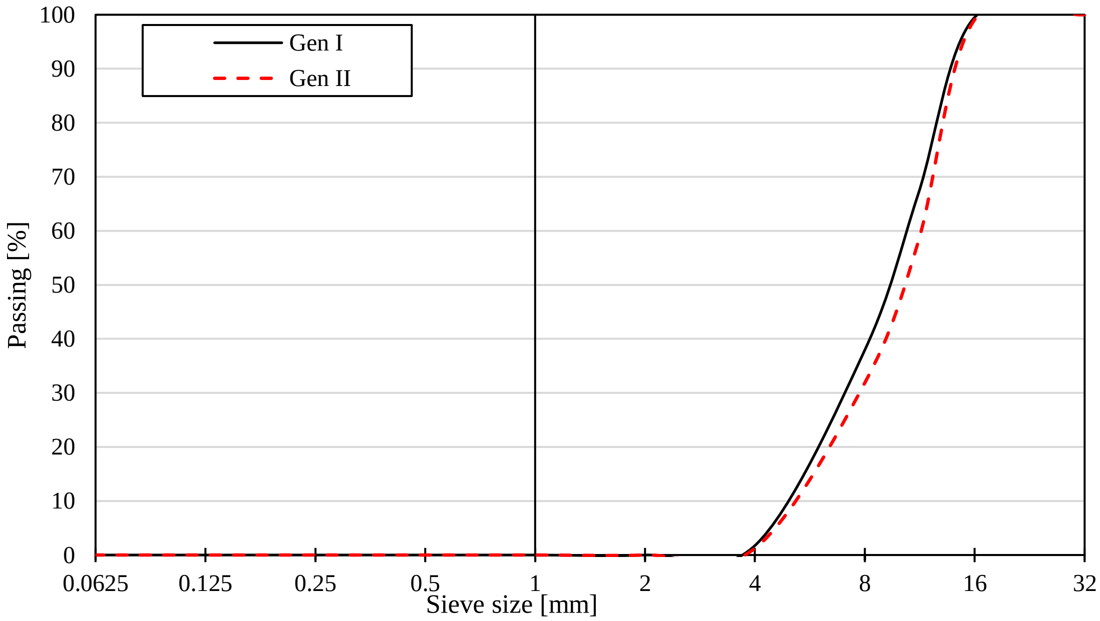


Figure 5.9.3 – C2 grade curve Gen I-II

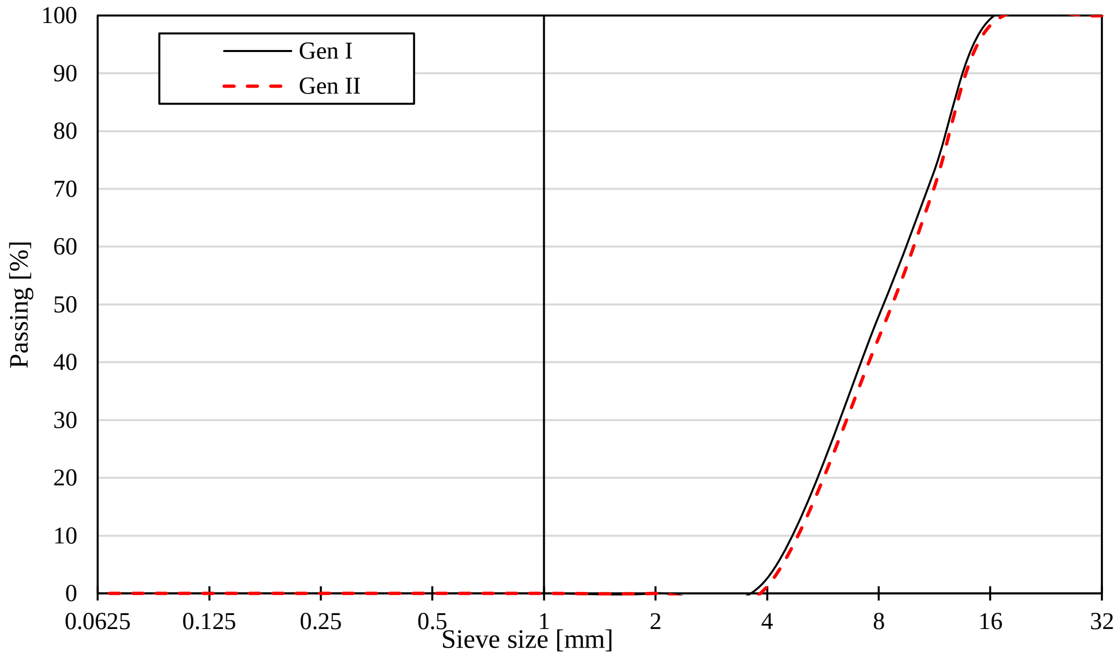


Figure 5.9.4 – C2M grade curve Gen I-II

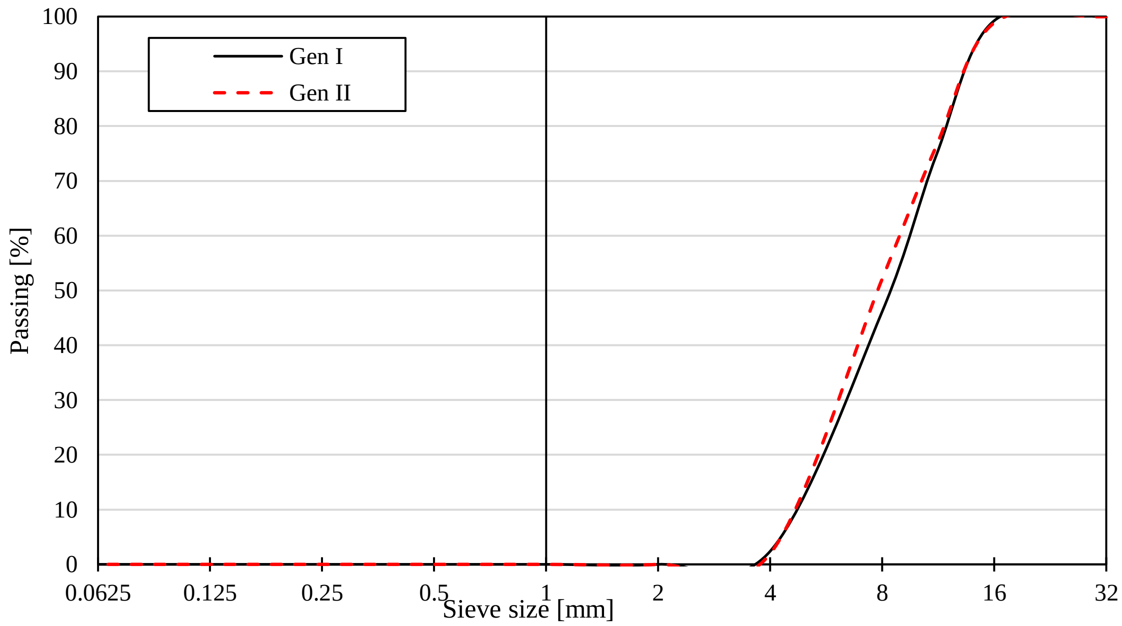


Figure 5.9.5 – C2D grade curve Gen I-II

The RCA of C2M and C2D were filtered from "free" fibres. For C2M RAC floating method was used, the aggregates were washed in water tank, and free PP fibres floating on the water surface were collected (Fig. 5.9.6).

Figure 5.9.6 – Filtering of free PP fibres from C2M RCA

The free steel fibres in RCA of C2D were collected using a different method, the magnet was used to collect free fibres. Firstly, RCA was sieved again using 4 mm sieve, then free fibres were collected by the magnet (Fig. 5.9.7).

Figure 5.9.7 – Filtering of free steel fibres from C2D RCA

After all was done, the 4/16 grade RCA were tested for the porosity and density using pycnometer (Fig. 5.9.8). The RCA were washed from fine particles and dried in the oven at 50°C before the testing.

Figure 5.9.8 – RCA in pycnometer – apparent density test

Hereby the Tables 5.9.1-5.9.2 present results for 2 generations of RCA, density of aggregates.

Table 5.9.1 – Water absorption, aggregate density, RCA generation I

	C1	C2	C2M	C2D
Dry body density [g/m3]	2.346	2.389	2.384	2.462
Water absorption (30min) [m%]	3.53	2.74	2.40	2.64
Water absorption (60min) [m%]	3.60	2.93	2.43	2.72
Water absorption (final) [m%]	4.13	3.37	2.45	2.89

Table 5.9.2 – Water absorption, aggregate density, RCA generation II

	C1	C2	C2M	C2D
Dry body density [g/m3]	2.179	2.296	2.367	2.311
Water absorption (30min) [m%]	7.37	4.11	3.74	3.99
Water absorption (60min) [m%]	7.40	4.13	3.77	4.02
Water absorption (final) [m%]	7.81	4.47	4.06	4.89

The collected data helped to build a new mix design for concrete mixtures of generations I and II (Table 5.9.3-5.9.4).

Table 5.9.3 – Mix design for C1 RAC, Generation II

Material	Type		Mass, kg/m³	Volume, l/m³
Aggregates	0/4 mm	45%	832	315
	4/16 mm – RCA C1	55%	903	385
Cement	CEM I 52.5 N		293	95
Water	m_w/m_c =	65.0%	190	190
Air		--	15	
All			2218	1000

Table 5.9.4 – Mix design for C2 RAC, Generation II

Material	Type		Mass, kg/m³	Volume, l/m³
Aggregates	0/4 mm 4/16 mm RCA C2	45% 55%	832 920	315 385
Cement	CEM I 52.5 N		375	121
Water	m_w/m_c =	43.0%	161	161
Superplasticizer cem. m%	Glenium C300	0.61%	2.3	2.29
Air		--	15	
All			2291	1000

For Generation II C1, RCA of C1, and for Generation II C2, RCA of C2 were used accordingly. The mix designs for Generation II C2M and C2D were same as for Generation II C2, but again fibres were added to the mixture. For the Generation II and III the volume of the total mixture has been decreased, this is because the third generation was the last one.

6. Conclusions

Based on the extensive research conducted on the mechanical properties and performance of Recycled Aggregate Concrete (RAC) through multiple generations of recycling, several key conclusions can be drawn. These conclusions shed light on the potential of RAC as a sustainable construction material and its role in promoting environmentally responsible building practices:

1. There is an initial increase in compressive strength from the first generation to the second generation. This can be attributed to the improved particle packing and enhanced bonding between recycled aggregates and fresh cement paste. However, a decrease in compressive strength is observed from the second generation to the third generation. This reduction may be due to the cumulative effect of increased voids and reduced quality of recycled aggregates over multiple recycling cycles. The density of specimens decreased through three generations, which is consistent with the trend of decreasing compressive strength.
2. For specimens without fibres, the splitting tensile strength decreased with successive generations, likely due to the degradation of the recycled aggregates. In contrast, specimens with fibres showed an increase in splitting tensile strength over multiple generations, indicating that fibre reinforcement can mitigate the degradation of tensile strength in RAC. Important to note that RAC had more fibres from generation to generation, since new portion was added to mixture on top of already embedded ones in RCA.
3. In general, the CMOD test results show a decrease in the peak load for each mixture type through successive generations. This suggests that the multiple recycling cycles have a detrimental effect on the crack resistance and tensile strength of RAC.
4. The modulus of elasticity decreases with each recycling generation. This reduction indicates that the stiffness of RAC diminishes as a result of multiple recycling cycles.
5. Water absorption increased in each generation, suggesting greater porosity and increased susceptibility to moisture penetration. However, specimens with fibres showed a slight decrease in water content in the third generation.

In conclusion, the research on multiple generations of RAC provides valuable insights into the material's mechanical and microstructural properties. While there are some positive trends, such as the initial increase in compressive strength and improved freeze-thaw resistance in the second generation, it is clear that the sustainability and performance of RAC can be affected by multiple recycling cycles. To maximize the benefits of RAC, careful consideration of mix design, the use of reinforcement like fibres, and monitoring of properties over successive generations is essential. This research underscores the potential of RAC as a sustainable construction material, emphasizing the importance of responsible recycling practices and further investigation into its long-term performance.

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