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Multi-recycling of different concrete products: Effects on recycled aggregate's physical characteristics and compressive strength

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ABSTRACT

The utilisation of recycled aggregate from construction and demolition waste (CDW) as a replacement for fine and coarse natural aggregate has been increasing in recent years. The purpose of this study is to examine the feasibility and limitations of multiple recycling of concrete aggregates, which represents a novel contribution in understanding the extent to which CDW can be repeatedly reused. This research aims to reduce the amount of construction waste sent to landfill and reduce carbon emissions. An experimental investigation was carried out on eleven randomly selected natural aggregate concrete products available on the market. The parent concrete was used to create the first-generation recycled concrete aggregates by crushing with a hammer. Within the concrete products happened to have two different fibre-reinforced composites and one manufactured aggregate were examined as well. The investigation assessed the aggregate morphology, density and particle size distribution through three recycling cycles. The investigation found that increasing the number of recycling cycles for all types of aggregates increased the angularity, the volume of coarse aggregates and water absorption while fine particles was reduced giving way to mortar paste and the compressive strength of each subsequent concrete was reduced. By the end of the third recycling cycle, all aggregates turned into 80 % cement paste. The rate of physical and mechanical performance change decreased with each cycle but did not settle by the third cycle, thus a conclusive conclusion could not be formed, although the trend was noticed. The decrease was asymptotic with the number of recycling cycles. It was also discovered that the multiple recycling procedure replaced 80 % of the parent aggregate volume by the third recycling cycle and, for mixes containing fibres, it damaged 98 % of the fibres resulting in a full loss of fibre performance. These findings demonstrate that it is only possible to recycle concrete by a finite number of times before significant deterioration in quality occurs, limiting its long-term reuse potential.

1. Introduction

The Circular Economy (CE) is an economic model where resources are kept in use over and over and where their values are retained [1]. In the UK, the CE initiative targets all industrial sectors to make better use of resources. In the construction sector, the initiative is aimed at reducing the environmental footprint of buildings and, more importantly, to reduce generated waste. Recycling concrete

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waste to create new aggregate offers many benefits, for example, reducing the consumption of natural resources, saving land from long-term waste storage, and reducing transportation emissions. It is proven by researchers that crushing up old concrete to create new aggregate and reusing it to create new concrete is feasible for one cycle. However, multiple recycling of different types of concrete wastes has yet to be investigated. The concept behind repeatedly recycling concrete is that the natural aggregate concrete is crushed at the end of its useful life to produce coarse and fine recycled aggregates. The crushed Recycled Aggregate (RA1) is then used to replace the natural aggregate in new concrete, creating what is known as first-generation Recycled Concrete (RC1), as depicted in Fig. 1. After the end of the RC1 life cycle, the concrete is crushed again in order to produce recycled coarse and fine aggregates (RA2) that can be utilised to create a second generation concrete (RC2) and so on. In terms of Circular Economy, the cycle can be repeated numerous times, theoretically.

Aggregates occupy around 50–80 % of concrete by volume, depending on the application, consequently, the sustainability of buildings would be greatly impacted by recycling the concrete into new aggregate. On the other hand, demolished buildings generate billions of tons of mixed CDW every year that is not pure concrete and segregation might need to be considered in the future to preserve concrete purity. As reported by Saez et al. [3], the generation of CDW in the EU surpasses 850 million tonnes annually. Some EU nations have high disposal rates. According to the European Environment Agency [4] report: 47 % in Slovakia, 43 % in Cyprus, 30 % in France, 24 % in Sweden, 24 % in Croatia, and 21 % in Spain. According to the US EPA [5], 600 million tonnes of CDW were produced in the USA in 2018, 455 million tonnes were destined for other uses, and 145 million tonnes (24.1 %) were disposed of in landfills. According to Bilsen et al. [6], CDW accounts for approximately one-third of all waste produced in the EU and is the main source of waste by volume because of the scale of the construction industry and its reliance on raw materials. As per the European Parliament Directive 2008/98/EC [7], member states are mandated to achieve a CDW recovery rate of 70 % by 2020. However, the European Environmental Agency (2020) stated that the EU states mostly used CDW for backfilling and low-grade recovery applications to achieve this percentage.

The number of research studies on recycling coarse aggregate has grown exponentially in the last two decades. Early research focused on characterising the laboratory sample recycled aggregate physical properties such as specific gravity, moisture content, particle distribution and water absorption ([8,9,10]). Recent research focused on hardened concrete properties, including compressive and tensile strength, drying shrinkage, abrasion and freeze-thaw resistance [11,12]. The most recent advancement in recycled aggregate concrete is utilised for structural components of certain building elements. According to Fiol et al. [13]; Gayarre et al. [14]; Pedro et al. [15] and Thomas et al. [16] it is anticipated that this practice will increase in the near future.

It should be taken into account that Recycled Concrete Aggregate Concrete (RCAC) is influenced by the properties of parent concrete and the percentage of fine and coarse aggregate replacement. Key characteristics of repeatedly using Recycled Concrete Aggregate (RCA) in making multiple recycled concretes include:

- Density and water absorption: The density decreases while the water absorption increases for the first, second, and subsequent generations of recycled concrete aggregate. Huda et al. [17] observed that RC1 and RC2 resulted in a 10 % and 14 % decrease in density, respectively, while water absorption increased by 1.9 % and 4.2 % respectively. Salesa et al. [18,19], found that the dry density of high strength precast parent concrete reduced by 0.3 %, 1.19 % and 3.6 %, while water absorption increased by 11.6 %, 17 % and 20.3 % for RC1, RC2 and RC3 respectively.
- Attached mortar: According to Zhu et al. [20]; Thomas et al. [21]; Abed et al. [22] and Silva et al. [23], the amount of attached mortar of the laboratory samples subjected to multiple recycling increases as the number of recycling cycle increases.
- Workability of fresh concrete: The workability of multiple recycled aggregate concrete reduces with each recycling cycle, as a result of RCA's higher water absorption capacity when compared to NA. According to Salesa et al. [18,19], the workability decreased by 20.3 % and 27.5 % for RCA1 and RCA2 respectively for 100 % coarse aggregate replaced concrete.
- Compressive strength: The uniaxial compressive strength of repeated recycled aggregate concrete tends to decrease as the number of recycling cycles rises Huda et al. [17]. According to Abreu et al. [24], a 100 % substitution for a laboratory sample parent concrete coarse aggregate resulted in a decrease of compressive strength by 3.2 %, 4.7 %, and 13.1 % for RCA1, RCA2 and RCA3

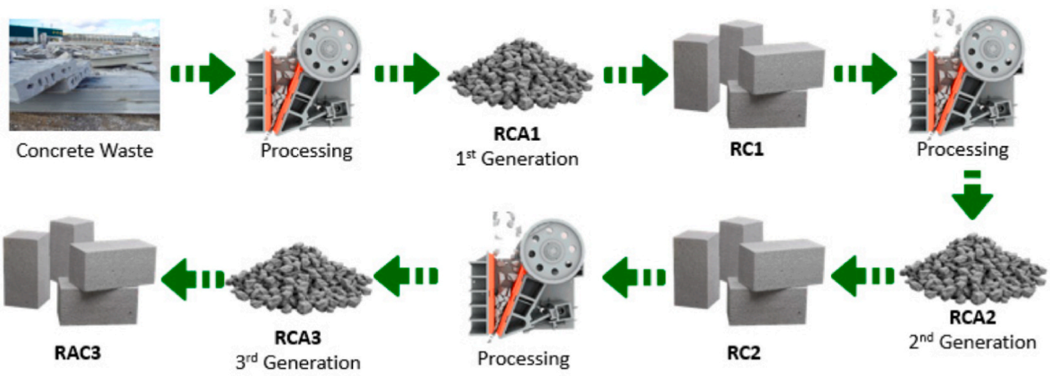


Fig. 1.1. Circular Economy scheme of repeated use of recycled concrete aggregate, Salesa et al. [2].

respectively. On the contrary, an improvement in compressive strength was observed by Salesa et al. [18,19], when the RCA was of high strength and free of debris.
- Tensile strength: As with other properties, tensile strength tends to decline with each recycling cycle. Abreu et al. [24] reported that the decrease for RCA1, RCA2 and RCA3 was 9.1 %, 11.4 % and 15.1 % respectively when the replacement ratio of coarse aggregate was 100 % compared to the laboratory sample parent concrete.
- Elastic modulus: The elastic modulus of multiple recycled aggregate concrete tends to decrease with each recycling cycle since natural aggregate normally possesses a higher elastic modulus than cement mortar. A decrease of 4.3 %, 7.5 % and 13.8 % were reported by Salesa et al. [18,19], for RCA1, RCA2 and RCA3 respectively. Hamad et al. [25] concluded that, as a consequence, this will result in larger mid-span deflections in beams manufactured using RCA rather than NA.
- Multiple recycling performance: Silva et al. [23] experimented with crushed limestone aggregate concrete recycling for three cycles. The recycled coarse aggregates were obtained from multiple recycling of concrete with a design strength of 30 MPa in each cycle. They concluded that the recycled coarse aggregates exhibit a decline in quality as the number of recycling cycles increases. This leads to poorer durability and shrinkage performance in the final concrete. Furthermore, an asymptotic behaviour is demonstrated, indicating that the decline in performance tends to slow down as the number of recycling cycles increases. Further, Kim et al. [26] studied the recycled concrete fine powder effect on the physical characteristics of concrete for three recycling cycles. They found that particles smaller than 0.15 mm have a negative effect on porosity and density, and the mortar paste becomes very rough as the recycling cycles are increased. At a 10 % replacement ratio, the performance of the previous generation mortar with 30 % recycled concrete powders outperformed the mortar made with recycled concrete powders obtained from third-generation concrete, indicating the need for modification for proper utilisation of recycled concrete powders obtained from repeatedly recycled aggregate concrete.

Research on the recycling of concrete has primarily focused on replacing coarse aggregates only with recycled coarse aggregates made from laboratory samples or high-quality concrete. Limited research exists on the repeated recycling of fine and coarse recycled aggregates in concrete, particularly concerning lower-grade mixed construction and demolition waste. Therefore, the purpose of this study is to investigate the feasibility and limitations of multiple recycling cycles of both fine and coarse recycled aggregates derived from natural aggregate concretes available on the market. The study specifically examines aggregate morphology, density, and particle size distribution through three recycling cycles, as well as the resulting compressive strength of concretes, including mixes containing fibre-reinforced composites and manufactured aggregates. This research aligns with the London Mayor's Design for a Circular Economy guidance, which advocates for material reuse 'over and over' to retain materials at high value and extend the life of resources, particularly relevant in the context of large-scale concrete and CDW management.

2. Materials and experimental program

2.1. Methodology

The aim of this investigation is to examine the recyclability of end-of-life structural concrete elements for the purpose of concrete mix design based on BRE Design of normal concrete mixes [27]. Eleven randomly selected parent concretes were studied, including concrete roof tile, paving, high and low strength and lightweight concrete. The objective of this program is to analyse the multiple recycling impacts on the aggregate's morphology, water absorption, density, particle distribution, coarse aggregate content, compressive strength and fibre damage. Each recycled concrete was made with recycled aggregate from the previous concrete with the same composition and constituents as the cycle before using both coarse and fine particles for the three cycles.

2.2. Materials

Care was taken to source many different parent concrete samples representing the current built environment. Samples included:

- high-strength concrete: Hanson 40N and HPHS (high performance high strength),
- laboratory samples containing steel and basalt fibres: NA (natural aggregate) and NRCA100 (modern concrete recycled aggregate from construction site),
- concrete from old demolished buildings: All in RCA,
- normal strength concrete (CFA pile mix, Concrete roof tiles, Paving brick and Quartz stone)
- reclaimed aggregates (Factory recycled), and
- manufactured aggregate (CircaBuild)

Initial mixing was carried out for Quartz stone and CircaBuild manufactured lightweight aggregate to produce the parent concrete by mixing the virgin aggregate with 575 kg/m^3 of cement and 230 kg/m^3 of water. Concrete was crushed after 4 months to create the RCA1 aggregate. The recycled aggregate for the ready-mix Hanson 40N was created by following the mixing procedures found on the supply bag. All cubes were tested and crushed by hand using a sledgehammer. The first-generation recycled concrete aggregate (RCA1) appearance and mechanical properties used in the experiments are described in Table 1.

Two of the parent concrete obtained for the experiment were fibre-composite concrete. The Dramix 3D steel fibres at 1 % volume were mixed into limestone aggregate parent concrete and experimental basalt fibres were mixed with natural flint stone and sand concrete at 8 kg/m^3 volume. Both steel and basalt fibre geometry are shown in Fig. 2.1 and the basic fibre properties are detailed in Table 2.

2.3. Concrete mix design and properties

The concrete mix for all the recycled aggregates used in this study was based on the BRE Design of normal concrete mixes, BRE [27] using all coarse and fine particles from the crushing process at 100 % replacement ratio. Characteristic strength of fck,cube(28) = 35N/mm^2 was targeted with 0.4 w/c ratio and 230 kg/m^3 of water content. To establish a good comparison between all concrete mixes, water compensation method was used during the mix design. Absorbed water was controlled by oven-drying all the material and measuring the saturated surface dry density. Absorbed water was added to the mix during mixing, and a minimum of 10 min of mixing time was allocated to allow the aggregate to reach 90 % saturation. CEM II/B-V 32,5R Portland composite general-purpose cement conforming to BS EN 197-1 [28] was used for the concrete mixes at 575 kg/m^3 volume. Table 3 lists the mix design constituents in kg/m^3 for the three recycling stages in which RCA1, RCA2 and RCA3 are the 1st, 2nd and 3rd generation of mixes for each type of RA.

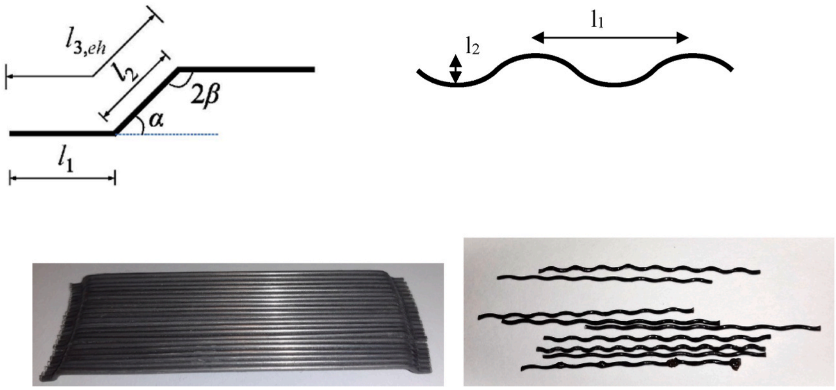
After mixing, the concrete was filled into 100 mm^3 moulds in accordance with BS EN 12390 [29]. After 24 h of casting, all samples were demoulded and stored in a temperature-controlled curing tank at 20 °C until testing.

2.4. Instrumentation and testing procedure

The testing was conducted in the Structures Laboratory in the Division of Civil Engineering at London South Bank University. Each

Table 2.1
Parent concrete description.

Aggregate type	Crushed concrete aggregate attributes
Hanson 40N	Ready mix concrete supplied in 20 kg bags, high strength concrete containing $D_{\max}$ = 8 mm flint coarse aggregate and washed sand fine aggregate, $f_{ck,cube}$ = 62N/mm^2 tested at 28-days with the recommended water volume by the manufacturer. Once the cubes were tested they were crushed with a hammer to create 0–20 mm recycled aggregate. The recycled aggregate is angular; mortar paste is firmly attached to coarse aggregate. Contains minimal fines. Saturated surface dry density 2.29 g/cm^3.
NA natural aggregate with, 8 kg/m^3 basalt waves	Laboratory test sample natural flint stone coarse aggregate 5–14 mm nominal size and washed sand fine aggregate 0–5 mm nominal size concrete mix with 60 mm long basalt fibre waves, $f_{ck,cube}$ = 35N/mm^2. The recycled aggregate is sub-angular with increased fines content, during crushing the aggregate split along the aggregate-mortar paste interface. Saturated surface dry density 2.21 g/cm^3.
NRCA100 1 %3D with Dramix steel fibres	Construction site concrete waste, 0–20 mm recycled aggregate processed with a sledgehammer. The donor concrete contained limestone coarse and washed sand fine aggregates, 50 % GGBS, Xypex crystalline admixture and superplasticizer, $f_{ck,cube}$ = 56N/mm^2. The recycled aggregate is very angular with minimal fine content. During crushing the failure line often lies through the limestone coarse aggregate particles. Saturated surface dry density 2.14 g/cm^3 for the first generation recycled aggregate.
CFA pile mix P280	Construction site concrete waste during pile cropping, 0–20 mm recycled aggregate processed with a sledgehammer. Donor concrete contained 30 mm limestone coarse aggregate with washed sand containing 280 kg/m^3 cement and 50 % GGBS used for CFA female piling (primary pile), $f_{ck,cube}$ = 4N/mm^2 at 1–2 days, $f_{ck,cube}$ = 10–12N/mm^2 at 7-days, uncompacted during construction. The recycled aggregate contains a high surface area regarded as a new stone surface because of the original maximum size limestone aggregate. The recycled aggregate contains an increased volume of internal pores within the cement paste because of no compaction was carried out during casting. Saturated surface dry density 2.29 g/cm^3.
Concrete roof tiles	Fine flint aggregate, unknown strength; tiles are broken up with a hammer to create 0–20 mm recycled aggregate. The recycled aggregate is very angular and contains an increased volume of fines. Saturated surface dry density 2.05 g/cm^3.
Paving brick	Fine flint aggregate, unknown strength; bricks are broken up with a hammer to create 0–20 mm recycled aggregate. The recycled aggregate is very angular. Saturated surface dry density 2.32 g/cm^3.
HPHS, high performance high strength concrete	0–20 mm recycled aggregate crushed with a hammer. The parent concrete contained 20 mm limestone coarse aggregate and washed sand. High-strength modern concrete for high-performance applications containing 50 % GGBS, $f_{ck,cube}$ = 41N/mm^2 at 5 days. The recycled aggregate contains minimal volume of fines. During crushing the failure line often lies through the limestone coarse aggregate particles. Saturated surface dry density 2.5 g/cm^3.
Quartz stone	0–20 mm natural quartz coarse and fine aggregate, $f_{ck,cube}$ = 42N/mm^2. Once the cubes were tested they were crushed with a hammer to create 0–20 mm recycled aggregate. Saturated surface dry density 2.28 g/cm^3.
All in RCA	32 mm flint coarse aggregate concrete waste from historical concrete building, sourced during structure demolition, containing both coarse and fine aggregate, $f_{ck,cube}$ = 13–23N/mm^2. Structural members were crushed with a jaw crusher. The recycled aggregate contains a high surface area regarded as a new stone surface because of the original maximum size of flint aggregate. Saturated surface dry density 2.07 g/cm^3.
Factory recycled	Washed and cleaned 14 mm recycled mixed stone and concrete waste mixed with recycled sand, purchased from a local recycling plant. Saturated surface dry density 2.48 g/cm^3. The aggregate's origin is not known and may have never been part of a cast concrete.
CircaBuild aggregate from Carbon8	2/6 d/D carbonated manufactured waste product containing mainly CaO and SiO. The aggregate contained 10 % CO_2 intake, compressive resistance 12.5N/mm^2, dry density 1400 kg/m^3, water absorption 25 %. The aggregate was mixed with cement and water, and tested at 28-days, $f_{ck,cube}$ = 19N/mm^2, no fines added to create the parent concrete. Once the cubes were tested they were crushed with a hammer to create 0–20 mm recycled aggregate. During crushing the failure line often lies along the surface of the coarse aggregate. Saturated surface dry density 1.85 g/cm^3.



(a) (b)

Fig. 2.1. (a) Dramix 3D and (b) Basalt wave fibre shapes.

Table 2.2
Dramix 3D and 5D fibre properties.

Fibre property		3D	Basalt
Tensile strength: f_u, (N/mm^2)		1600	4150–4800
Young's Modulus E, (GPa)		210	93–110
Wire ductility, (%)		1.5	3.1
Length l_f, (mm)		60	60
Diameter d_f, (mm)		0.9	0.75
Aspect ratio, (l/d)		65	80
Surface finish		Bright, Glued	Smooth
Hook/wavelength (mm)	l_1	2.1	6
	l_2	2.5	2
Hook angle (°)	β	67.5	
	α	45	

Table 2.3
Mix design for multiple recycled concrete aggregate experiments.

Aggregate type and constituents (kg/m^3)	RCA1		RCA2		RCA3	
	RA weight	Absorbed water	RA weight	Absorbed water	RA weight	Absorbed water
Hanson 40N	1347	32	1261	134	1242	155
NA + Basalt waves	1313	57	1267	103	1274	134
NRCA100 1 %3D	1286	17	1228	131	1258	149
CFA pile mix P280	1346	38	1314	113	1290	111
Concrete roof tiles	1250	41	1222	125	1254	134
Paving brick	1360	45	1280	121	1153	123
HPHS	1432	22	1304	103	1290	116
Quartz stone	1340	55	1297	116	1273	129
All in RCA	1258	107	1261	114	1249	122
Factory recycled	1423	32	1315	98	1291	102
Carbon8 CircaBuild	1166	227	1211	213	1191	177

test was conducted on around 15 kg of parent concrete. An average of three samples per test was reported. The saturated surface dry density test was conducted in accordance with BS EN 1097-6 [30]. The particle size distribution test was performed in line with BS EN 933-1 [31], dry sieving method, Clause 7.2. All aggregate was deemed to be "All-in" aggregate. Compressive strength tests were conducted on Controls MCC8 hydraulic testing machine in accordance with BS EN 12390 Testing hardened concrete, Part 3 Compressive strength of test specimens on 100 mm cube samples at 7 and 28-days (BSI 2019). The samples were cured in a temperature-controlled curing tank and air-dried before testing. The samples were weighed on a scale capable of 1 g reading. A loading rate of 3500N/s was used on the large plate testing rig. The jacking force was applied until the specimen failed. The failure force and shape of failure were noted in (kN). The compressive strength values were calculated by dividing the failure force by the area of the specimen (N/mm^2).

2.5. Results and discussion

2.5.1. Recycled concrete aggregates morphology and surface texture

The recycled aggregate's morphological characteristics were analysed based on their shape, angularity and surface texture in accordance with BS EN 933-4 [32] throughout three recycling stages. The aggregate morphology affects the workability and mechanical performance of concrete. In Table 2.4, Fig. 2.2 to 2.12 shows the aggregates used in the experiments for the three recycling cycles. Fig. 2.2 (a)–2.10 (a) images in the series show the crushed RA1 recycled aggregate for the first nine different types of aggregates sourced for this study. Fig. 2.2 (b)–2.10 (b) images in the series show the aggregate before the third recycling concrete mixing was made (RA3). Fig. 2.11(a) and (b) show the RA1 coarse and fine aggregates for Factory recycled aggregate, and Fig. 2.11 (b) shows the RA3. For Carbon8 Fig. 2.12 (a) shows the virgin aggregate, Fig. 2.12 (b) shows the first-generation recycled aggregate and Fig. 2.12 (c) shows the aggregate before the third recycling concrete mixing was made (RA3).

From the images below we can conclude that the first-generation recycled aggregates were spherical with sharp jagged edges and equal axial lengths. Especially, NRCA100 1 %3D, CFA pile mix P280 and HPHS were found to be spherical with highly angular particles in the coarse fraction. These mixes contained limestone aggregate with a tensile strength between 5 and 25 MPa, [33]. The crushed limestone parent aggregate was often visible on the surface of the coarse aggregate particles with a new surface because of the crushing action and weak tensile capacity of the parent coarse aggregate. During the crushing of the parent concrete, the weaker limestone aggregate suffered a failure zone that further divided the original grains. It was noticed that the parent cement matrix has an exceptional bond to the crushed limestone. Angular aggregates have a higher specific surface area than smooth rounded aggregates. With a greater specific surface area, the angular aggregate may show higher bond strength than rounded aggregates. According to Ostrowski et al. [34], the sharper edges of the irregular particles could create more noticeable stress concentrations at the mortar paste's tip, reducing the concrete's resistance to breaking when new concrete is created and resulting in a lower compressive strength.

The Hanson 40N, NA with basalt waves, Quartz stone and All in RCA aggregates were containing flint and quartz stone. These first-generation recycled aggregate mixes were rounded because of the parent concrete's coarse particles. These intact particles were visible on the surface of the RA1. The parent coarse aggregates were found to be rounded with a very smooth surface. It was anticipated that the cement paste in the parent concrete did not bond well with the weathered and smooth surface of the tough natural particles; hence, after crushing the parent concrete, the cement paste separated from the surface of the parent coarse aggregate. The natural surface of the recycled aggregate could help the next-generation cement paste bond to the aggregate's surface again. In the case of All in RCA aggregate, the weak cement paste crumbled off the surface leaving an old mortar film attached to the coarse particles. All in RCA parent concrete contained larger than 20 mm aggregates. When the parent concrete was crushed these large particles were split creating a new surface for the next generation of cement paste to bond.

The recycling plant produced Factory recycled aggregate morphological characteristic was equal to natural aggregate as seen in Fig. 2.11. The coarse particles are cubical with rounded surfaces resembling natural aggregate. Contamination (>1 %) was found within the parent aggregate and included plastics, brick and wood splinters. This could adversely affect the new concrete's compressive strength.

The first-generation Carbon8 recycled aggregate produced an interesting combination. The manufactured lightweight aggregate had a low compressive strength. During crushing the adhered mortar paste peeled off a thin layer of the Carbon8 aggregate making the aggregate surface angular from the cement paste. The parent aggregate surface after the crushing was new creating a clean surface for the next generation cement paste to bond. The recycled aggregate had identical lengths on all three axes and a consistent cubical dimension.

The third-generation aggregates are represented in Fig. 2.2 to 2.12 right-hand image. The main distinct feature of the third-generation recycled aggregates is the increased volume of cement paste and the lack of parent coarse aggregate. The reason for the parent aggregate reduction is the constant replacement of all particles by cement paste during recycling. As a result of the increased mortar, the entrapped void volume also increased. Furthermore, the third-generation aggregate's morphological characteristics are cubical/flaky and very angular with jagged sharp edges. Under close inspection, micro-cracks are present in the larger particles. The morphological characteristics are the result of the increasing mortar paste. According to Deng et al. [35], the compressive performance and design of concrete mixes are significantly influenced by the morphological properties of coarse aggregates, including surface roughness, angularity, and shape. It can be concluded that in a finite number of recycling cycles the whole aggregate will be replaced by mortar paste fully. As demonstrated by Factory-recycled coarse aggregate, additional grinding of the recycled aggregate can lower the angularity and more importantly, the mortar content. Furthermore, the continuous recycling technique resulted in virtually all of the colour pigments being lost from the Paving brick and Roof tile recycled aggregates.

The constant crushing cycle gradually decreased the parent coarse aggregate size. It was foreseen that in a finite number of recycling cycles, the coarse parent aggregate portion will progressively turn into fine particles even with careful removal of cement paste. Similarly, Thomas et al. [36] concluded that by the 6th recycling cycle, the parent aggregate will completely disappear and the produced concrete will become mortar. The types of crushers used in the production of recycled aggregate and the acquisition of various morphological parameters have been demonstrated by Rajan and Singh [37] could improve the parent aggregate volume in the new mix. They revealed that regular particles with a spherical morphology are the most desired owing to their smaller specific surface area. However, the research did not discuss the angularity of the aggregate and as we can conclude from Fig. 2.2 to 2.12, all RA3 recycled aggregates were highly angular. Furthermore, elongated and flat particles tend to orient in a single plane and have a greater specific area and when irregular particles make up between 25 and 50 % of the aggregate's overall content, their impact on the aggregate's durability is the greatest. Zielinski [38] noted that when the proportion of irregular particles in the aggregate material reaches 50 %, the durability of the aggregate decreases by 55 %. Therefore, both the granulometric distribution and the morphology of

Table 2.4
Visual comparison of morphology and surface texture of first and third generation aggregates.

	First generation aggregate (a)	Third generation aggregate (b)
Figure 2.2. Hanson 40N		
Figure 2.3. NA with basalt waves		
Figure 2.4. NRCA100 1%3D steel fibres		

Figure 2.5. CFA pile mix P280

Figure 2.6. Concrete roof tiles

Figure 2.7. Paving brick

Figure 2.8. HPHS

Figure 2.9. Quartz stone

Figure 2.10. All in RCA

Figure 2.11. Factory recycled

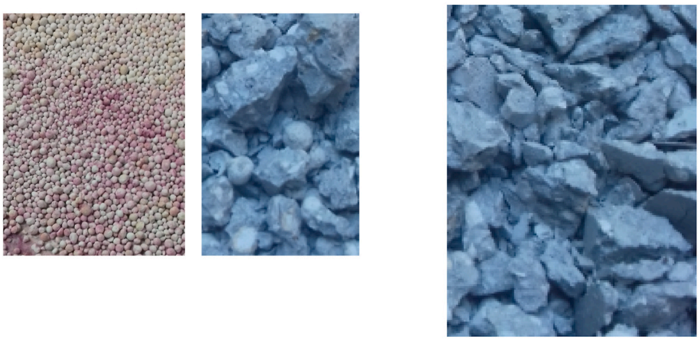


Figure 2.12. Carbon8

the particles are equally important when we discuss the quality of the recycled aggregate.

2.6. Loss of parent aggregate volume

Fig. 2.13 shows the decreasing parent aggregate volume tendency vs. the number of recycling cycles in terms of the w/c ratio. The concrete mixture in this research contained 575 kg/m^3 cement, and 230 kg/m^3 water, resulting in a total volume of 0.4125 m^3 and a W/C ratio of 0.4. The remaining volume of 0.5875 m^3 in one cubic metre of concrete was the fine and coarse aggregate volume with different densities. Consequently, it can be concluded that by replacing coarse and fine fractions at a 100 % rate at each recycling cycle, only 58.7 % recycled concrete aggregate is utilised for the next cycle of concrete with the current mix design. Further, the second and third-generation recycled concrete aggregate concrete contained only 34.5 % and 20.3 % parent concrete aggregate by volume, respectively. The parent recycled concrete aggregate percentage is projected to be only 7 % by the fifth recycling cycle as shown in Fig. 2.13 by a dotted line, with mortar paste from previous recycling stages accounting for the remaining 93 %.

The mix design was projected to 0.3 and 0.5 W/C ratio mixes. Considering a 0.3 w/c ratio concrete mix design with 575 kg/m^3 cement content the first and fifth-generation recycled concrete aggregate concrete would contain 64.5 % and 11.2 % parent concrete by volume, respectively. While this provides a theoretical means of estimating the influence of w/c ratio, further experimental work is needed to validate its impact on aggregate performance and the long-term behaviour of multiple recycled concretes. It can be concluded that the recycled aggregate concrete mix design has a significant impact on the composition of the concrete at each stage of recycling and that after a limited number of mixes, the concrete would eventually transform into cement paste with a decelerating decline rate.

The results support Silva et al. [23] findings, in which the decrease in durability and shrinkage performance of multi-recycled concrete tends to slow down as the recycling cycles increase because of the increasing mortar content. Thomas et al. [36] experimented with coarse limestone aggregate replacement concrete with a 0.55 w/c ratio for three recycling cycles. It concluded that the RCA3 showed almost twice as much mortar as first-generation recycled aggregate. Similarly, Kasulanati et al. [39] found that the mortar content was increased by 21 % and 12 % for the second and third-generation aggregate when all particles were used. Most of the studies conducted by researchers utilised coarse aggregate only with natural sand as fine aggregate. The multiple aggregate replacements in recycled aggregate concrete result in the loss of parent concrete volume because of the new binder and mixing water added at each recycling stage. The volume of aggregate loss for the next generation of concrete may be calculated using Equation (1) assuming no voids present in the mix:

$$RCA1\ volume\ loss = RC1\ V_C + RC1\ V_W \tag{1}$$

where:

V_c Volume of cement.

V_W Volume of water.

2.7. Multiple recycling effects on the particle distribution

Fig. 2.14 shows the particle size distribution of the parent concrete recycled aggregate. The grading tolerance was derived from BS 882 [40] Table 5 (BS 2002). The table applies to all-in-particle aggregates with a maximum particle size of 20 mm. The particle distribution is an important factor in concrete mix design. The percentage of aggregates passing the 600 μm sieve defines the fine and coarse portion of the mix. The sieve analysis test result indicated that for the RCA1, only the Paving stone and All in RCA meet the gradation specification for all in aggregate according to BS 882 [40] Table 5. The reason for the non-conformance in most of the recycled aggregates is the lack of particles below 0.6 mm; and for Hanson 40N, NRCA100 1 %3D, Concrete roof tiles, HPHS, Quartz stone and Factory recycled aggregates the lack of particles below 5 mm.

Aggregates lacking fine particles are uniformly graded or open-graded depending on the size and aggregate volume distribution. Uniform-graded or open-graded aggregates are undesirable for concrete production because of the poor particle packing ability. Furthermore, it can be concluded that the production method using a sledgehammer does not result in a high volume of fine material. It was discovered during crushing that the higher-strength concrete samples were bound together by the cement paste even at small sizes resulting minimal quantity of fines, whereas the lower-strength aggregates produced a considerable amount of fine particles due to because of bond, as seen in the All in RCA aggregate. Therefore, gradation is a critical property to achieve maximum particle packing for each type of aggregate and the aggregate production method can be used to control the volume of fractions.

Table 5 specifies the coarse sand component to be between 35 % and 55 %. The sieve analysis test result indicated that the first-generation recycled aggregates (NA + basalt waves, CFA pile mix, Paving brick, All in RCA and Carbon8) had enough particles to comply with the standard. The remaining first-generation aggregates had less than 35 % of particles smaller than 5 mm resulting in a lower particle packing density. The standard also specifies that only 5 % of aggregates by weight can remain on the 20 mm sieve. It was discovered that because of insufficient crushing of the NRCA100, CFA pile mix P280 and HPHS recycled aggregates, the approach generated over 5 % particles larger than 20 mm. The outcomes may have been prevented by having better grading control.

Fig. 2.15 and 2.16 show the particle size distribution for the second and third-generation recycled aggregate, respectively. The sieve analysis test result indicated that for the second and third-generation recycled aggregates, no recycled aggregates meet the gradation specification for all in aggregate according to BS 882 [40] Table 5 (BSI 2002). The reason for the non-conformance is the lack of particles below 5 mm. Only third-generation Carbon8 aggregates had above the lower limit coarse sand particles. It was noted that

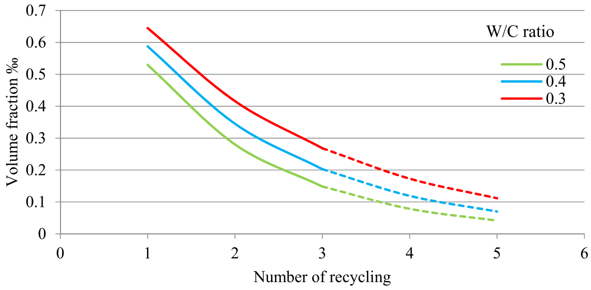


Fig. 2.13. Aggregate volume decrease vs. number of recycling cycles.

particles below 600 μm were almost non-existent throughout the various aggregate ranges. Upon closer inspection, it was discovered that the smaller particles were integrated into the cement paste. The bond between the sand particles and cement paste cannot be broken by the hammering action because of the surrounding larger particles. It was estimated that the third-generation recycled aggregates cannot be processed with a slow-moving jaw crusher because of the limitation of the jaw outlet opening. Multiple crushing stages are required to remove the adhered mortar paste. The jaw crusher can be used for primary and secondary crusher handling the coarse aggregates and utilising the cone crusher for the tertiary stage to produce fine sand recycled aggregate. To remove unwanted mortar paste a ball mill may be employed.

The optimisation of aggregate gradation arises from the maximum particle packing requirement and the desire to improve the mechanical and durability properties of concrete. Aggregates containing low-volume fine particles are known to be open-graded. Concrete containing open-graded aggregates cannot be compacted sufficiently. This results in many air pockets in the hardened concrete, reducing the density and performance. Yogita et al. [41] experimented with open-graded aggregate and found that this type of aggregate is represented by a horizontal line on the gradation graph in the fines size range and a curve near vertical in the coarse size range. Similarly, as shown in Fig. 2.15 and 2.16, we can conclude that the aggregate open-graded properties increased with increasing recycling ratio; therefore, multiple-stage crushing is required to produce the desired well-graded aggregate for recycling.

2.8. *The impact of multiple recycling on density*

Table 2.5 shows the dry and saturated densities of aggregates used in the experiments throughout three recycling cycles. Comparing first to second to third-generation recycled aggregate; there is a slight decrease in dry density as a result of increased mortar content. The highest density was recorded for HPHS and Factory recycled aggregate at 2.46 t/m^3 and 2.42 t/m^3 respectively. The results show that on average the second-generation normal-weight recycled aggregates had a 14 % reduction in dry density compared to first-generation recycled aggregates, and a further 3.3 % density reduction was observed on average for the third-generation recycled aggregates. On the contrary, the lightweight Carbon8 first-generation recycled aggregate density was measured at 1.45 t/m^3, the second-generation aggregate density was increased by 8.3 %; and a further 1.27 % density increase was observed for the third-generation recycled aggregate. The reason for that is the lightweight aggregate gained mortar volume from the remixing which is heavier than the manufactured aggregate.

The first-generation aggregate density was greatly influenced by the parent concrete mix composition including cement and water content, fine aggregate volume and compaction method. Additionally, in the case of All in RCA aggregate, the higher volume of fines further influenced the dry density of the first-generation recycled aggregate. When the uniform concrete mix was introduced for the first generation recycled aggregate concrete the density change became more consistent. This is due to the first-generation recycled concrete being designed with an identical volume of water, cement, and aggregate depending on SSD weight. For the following recycling stages, each subsequent recycled aggregate and concrete mix was prepared in the same way, gradually reducing the parent aggregate influence and turning each mix into a cement grout mix. The gradual change is shown in Fig. 2.17, where we can conclude

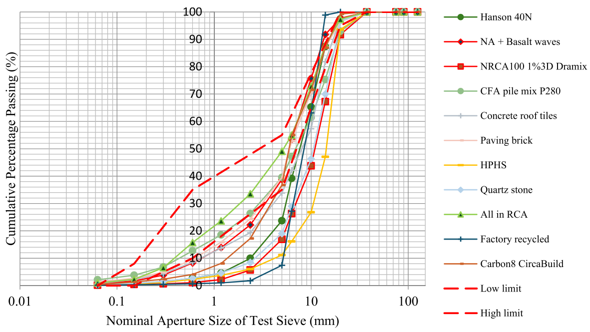


Fig. 2.14. Particle size distribution, first-generation recycled concrete aggregate.

Table 2.5
Dry density and SSD density of aggregates.

Aggregate type and density (t/m^3)	RCA1		RCA2		RCA3	
	SSD	Dry density	SSD	Dry density	SSD	Dry density
Hanson 40N	2.29	2.23	2.08	1.83	2.03	1.75
NA + Basalt waves	2.21	2.10	2.10	1.91	2.11	1.87
NRCA100 1 %3D	2.14	2.11	2.00	1.76	2.07	1.80
CFA pile mix P280	2.29	2.22	2.21	2.00	2.15	1.95
Concrete roof tiles	2.05	1.98	1.98	1.76	2.06	1.82
Paving brick	2.32	2.24	2.13	1.9	1.81	1.60
HPHS	2.50	2.46	2.19	2.00	2.15	1.94
Quartz stone	2.28	2.17	2.17	1.96	2.11	1.87
All in RCA	2.07	2.17	2.08	1.87	2.05	1.83
Factory recycled	2.48	2.42	2.21	2.03	2.16	1.97
Carbon8 CircaBuild	1.85	1.45	1.96	1.57	1.91	1.59

Table 2.6
Change in fibre condition during recycling stages.

	1st recycle (%)		3rd recycle (%)	
	Basalt	Steel	Basalt	Steel
Intact fibres	66	1	2	0
Bent fibres	8	99	3	100
Attached fibres	54	45	42	34
Split or broken fibres	17	0	5	0
Broken half fibres	11	8	98	98

that by finite recycling times, the recycled aggregate dry density will be uniform. As a result, the density of the final generation recycled aggregate could depend on the w/c ratio and compaction method used for the final generation recycled aggregate concrete.

The decrease in dry density is associated with an increase in porosity and water content at saturated surface dry density (SSD). Table 2.5 shows the SSD and the aggregates used in the experiment. The densities of recycled aggregates were greatly dependent on the composition of the parent concrete and its porosity, since the recycled aggregate retains the adhered mortar paste. The SSD density of the concrete products used in this experiment fluctuated considerably for the first-generation recycled aggregate. The highest density was recorded for HPHS and Factory recycled aggregate at 2.5 t/m^3 and 2.48 t/m^3 respectively. On average, the SSD density decreased by 7 % for the second-generation normal-weight recycled aggregate and a further 2.3 % decrease was measured for the third-generation aggregates. The highest third-generation aggregate density was recorded for Factory recycled aggregate at 2.16 t/m^3. On the other hand, the second-generation Carbon8 lightweight recycled aggregate had increased in density by 6 % but had reduced density for the third-generation recycled aggregate by 2.5 %. From Table 2.5 we can also conclude that the recycled aggregate SSD density rate of decrease was reduced by increasing the number of recycling stages. It was estimated by the 5th or 6th round of the recycling cycle the SSD density change would stabilise. At that time, the recycled aggregate would solely consist of cement paste and the parent aggregate influence on SSD density would completely diminish. For comparison, Kasulanati et al. [39] highlighted that the recycled concrete aggregate from the third-generation cycle indicated nearly twice as much mortar as the material from the first generation. It is evident that the concrete has a limited capacity for recycling multiple times when all-in aggregate particles are used for the next-generation mix.

Fig. 2.18 shows the water content development for three recycling stages. The highest water content for normal weight first generation aggregate was measured for NA + Basalt waves and equally for Quartz stone and All in RCA aggregates at 5.08 % and 4.76 % respectively. On average, 3.39 % water content was measured for the first-generation normal weight aggregate, which was increased by 232 % and a further 13 % for the second and third-generation recycled aggregate, respectively. It is important to note that within the concrete range used for the study, there were well compacted high strength parent concrete products with high density, such as Hanson 40N, HPHS and the NRCA100 1 %3D Dramix; therefore, it was expected that the first-generation aggregates were showing very low water content. As the recycling number increased for these mixes, so did the lower-strength mortar content resulting in higher porosity.

The low-density Carbon8 CircaBuild first-generation aggregate water content was 27.7 %. As the number of recycling cycles increased, the water content decreased by 12.3 % and a further 18.5 % because of the increasing volume of mortar paste to 19.8 % water content. From the third-generation aggregate results, we can conclude that the aggregate water absorption capacity was between 10 % and 20 %. It is expected with further recycling cycles the results will stabilise, as the aggregate will turn into cement paste.

2.9. The impact of multiple recycling on fibre effectiveness

Fibre effectiveness was assessed by appearance after the parent concrete was crushed to create the next generation of recycled aggregate. The process involved counting all the fibres in the crushed concrete and categorising fibre appearance in RA1 and RA3 aggregates. To classify fibre damage by appearance, five categories were devised. It was found that the crushing procedure damaged a

Table 5
Grading limits for all in aggregate (BSI 1992).

Sieve size	Percentage by mass passing BS sieves for nominal sizes			
	40 mm	20 mm	10 mm	5 mm
50 mm	100	–	–	–
37.5 mm	95–100	100	–	–
20 mm	45–80	95–100	–	–
14 mm	–	–	100	–
10 mm	–	–	95–100	100
5 mm	25–50	35–55	30–65	70–100
2.36 mm	–	–	20–50	25–100
1.18 mm	–	–	15–40	15–45
600 µm	8–30	10–35	10–30	5–25
300 µm	–	–	5–15	3–20
150 µm	0–8	0–8	0–8	0–15

high portion of the fibres within the first-generation aggregate, and all the fibres suffered some form of alteration within the third-generation aggregate resulting in a loss of fibre effectiveness. Table 2.6 shows the fibre condition during the first and third recycling cycles.

The largest volume of intact basalt fibres was found in the first recycled aggregate batch. The high flexibility of the basalt fibre enabled 66 % of the fibres to endure the crushing process without permanent damage. Contrary to the basalt fibres, only 1 % of the steel fibres were completely intact after the first crushing process. After the third crushing process, only 2 % of the basalt fibres were found to be completely intact and 100 % of the steel fibres were found to have suffered some form of damage. Fibre damage is irreversible and accumulative as the recycling cycle increases. Overall, the results show that after the third recycling cycle, both fibre types had lost full effectiveness compared to new fibres.

After the first and third recycling, 8 % and 3 % of the basalt fibres were found to become permanently bent beyond the elastic limit respectively. By close inspection, the surface of the individual fibres was intact; therefore, the internal structure of the fibres had suffered irreversible damage. Composite materials are known to have a substantially smaller plastic range than steel. It was hypothesised that during production, the epoxy resin did not permeate the full fibre cross-section, allowing individual fibres to slide on top of each other and form the bent shape. This also implies that the fibres in the core are not fully involved in the load-bearing process because of a lack of bond and that the exterior fibres are passing the stress to the inner fibres via friction. On the other hand, 99 % of the steel fibres were subjected to loads greater than their elastic limit during the first crushing operation, and all the fibres were damaged after the third recycling. Most of the fibres were found to be bent out of straight and the hook geometry of the 3D fibre was out of shape. The recycling process gradually reduced the effective length of the steel fibre; hence, the fibre's primary function of bridging micro-cracks had been significantly diminished.

Following crushing, fibres were found to be embedded into aggregate particles. For the first-generation aggregate, 54 % and 45 % of basalt and steel fibres were discovered embedded in the mortar paste, respectively. The attached fibres appeared to be increasing the particle size along at least one of the major axes of the aggregate and had difficulty falling through a much larger sieve size. This could result in an incorrect particle size distribution assessment. This phenomenon only affected larger particles that had enough mortar paste surrounding the fibre to keep the fibre trapped. In comparison to the first-generation aggregate, the third-generation aggregate had 23 % less attached fibre. Larger aggregate particles, on the other hand, might have contained undiscovered smaller fibres that were completely enclosed by mortar.

The majority of basalt fibre damage was discovered to be split and broken fibres. Within the first-generation aggregate, 17 % of the basalt fibres were observed to be split along their lengths. The fibre splitting was the result of a normal force applied to the fibre's main

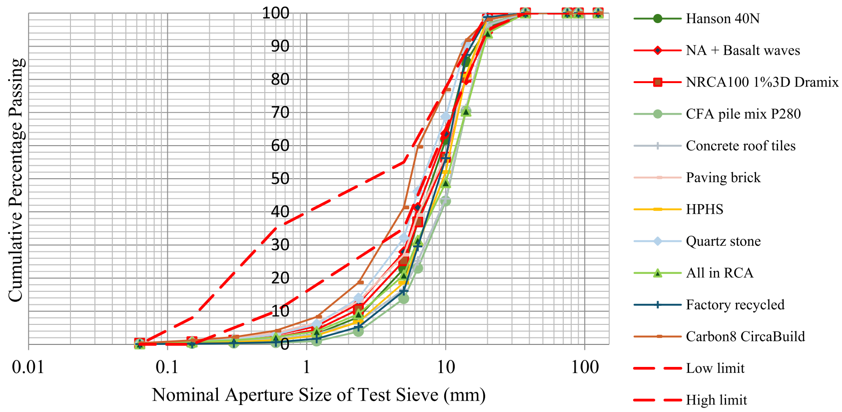


Fig. 2.15. Particle size distribution, second-generation recycled concrete aggregate.

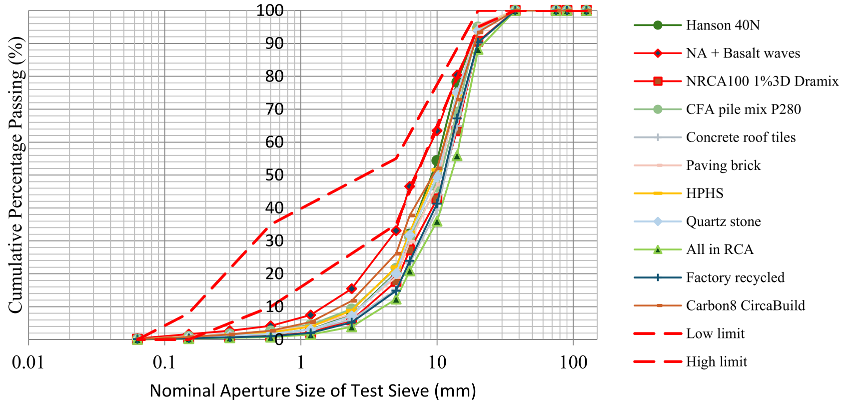


Fig. 2.16. Particle size distribution, third-generation recycled concrete aggregate.

axis. Most of the fibres encountered strong shear forces, resulting in partly severed fibres. This type of failure was only observed in basalt fibres, while steel fibres can withstand significantly higher normal forces. 11 % of the basalt fibres experienced large enough shear force to shear the fibre into multiple pieces. By design, fibres are anchored to the mortar paste by the fibre hook. When the aggregate is subjected to tensile and shear force the brittle aggregate transfers the load to the fibre resulting in complete fibre failure. As the recycling cycles increased the volume of broken fibres increased to 98 % for both basalt and steel fibres resulting in a complete loss of fibre efficiency.

2.10. *The effect of different recycled concrete aggregates on the uniaxial compressive strength*

The normal concrete compressive strength development at an age of *t* can be described by the expression given in BS EN 1992-1-1, Clause 3.1.2 (6), also shown in Equations (3) and (4) below (BSI 2023).

$$\beta cc(t) = exp\left\{ s\left[1 - \left(\frac{28}{t} \right)^{1/2} \right] \right\} \tag{3}$$

$$fcm(t) = \beta cc(t)\, f_{cm} \tag{4}$$

where:

s cement type coefficient

t time in days.

The concrete's compressive strength at normal curing conditions depends on the type of cement used for the mixing. In this experiment, all concrete mixes were made and cured identically, with the recycled aggregate acting as the only variable. The unit weight of hardened concrete and compressive strength results for 7 and 28-days are presented for the tested mixes in Figs. 2.19. 2.20 and 2.21. The uniaxial compressive strength results show that the compressive strength increased for all recycled aggregate mixes between 7 and 28-days for first, second and third-generation concretes. The largest strength increase for the first-generation concrete was observed for Factory recycled aggregate concrete at 138 %, and the largest increase for the third-generation concrete was observed for CFA pile mix P280 at 42 %. The results show that by increasing the number of recycling cycles, the strength increase between 7 and 28-days was reduced by 34 % on average for the normal weight aggregates. The possible reason for the decreased strength gain

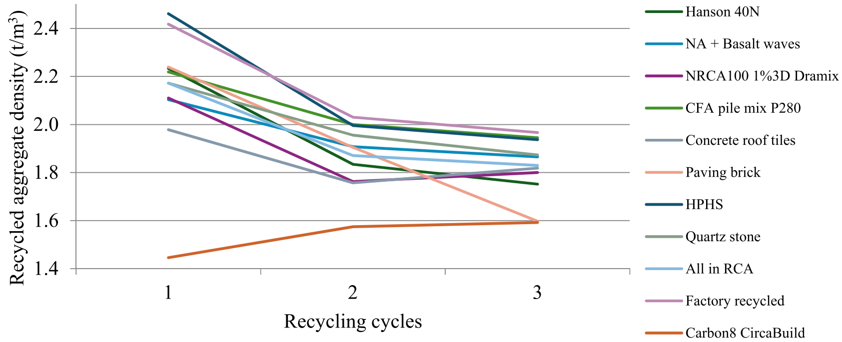


Fig. 2.17. Dry density trend.

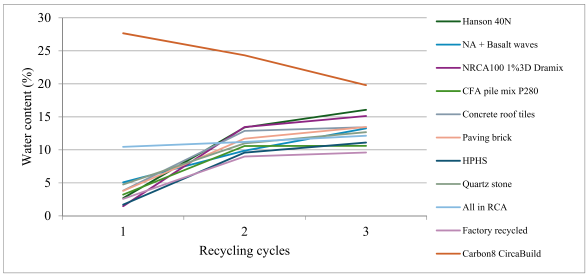


Fig. 2.18. Water content.

between the 7 and 28-day results of the first-generation recycled concrete is the influence of the parent concrete aggregate in the early-generation recycled concretes. The influence seems to diminish as the number of cycles increases and the aggregate mix becomes more homogeneous.

Using the expression provided by Equations (3) and (4) the 7-day results are 16 % lower by average than the predicted value for most of the first generation of normal-weight concrete mixes. One exception was Factory recycled concrete; the 7-day result was 85 % lower than the value proposed by Equations (3) and (4). For the third-generation normal weight aggregate concrete on average the 7-day result was 4.5 % lower than the predicted value in Equations (3) and (4), with one exception, the NA + Basalt waves concrete the 7-day result was 19 % lower. Therefore, we can conclude that the strength estimate based on the Eurocode 2 formula cannot be applied to the normal-weight recycled aggregate concrete without adjustments. Nevertheless, based on the limited number of results used in this experiment, a close approximation cannot be drawn because of the high variability of the parent concrete and the limited number of samples made. The other possible explanation for the low 7-day and consequently 28-day compressive strength result is because of oven drying the aggregate. The oven-drying method was used to establish the dry density and moisture content of the recycled aggregate for the next-generation concrete. As Du et al. [42] pointed out the dehydration of ettringite and C–S–H gel because of high temperature leads to changes in the compositions of hydration products and the contraction in their volume after cooling down. Micro cracks can form and spread in the interface between paste and aggregate because of the differences in their thermal characteristics. The aggregate undergoes recovery upon cooling to room temperature, but the paste shrinkage resulting from water loss cannot be reversed. This damages and often completely breaks the bond between the aggregate and cement paste. These physicochemical alterations modify the aggregate's microstructure, which modifies the next-generation concrete compressive behaviour. The research results also contradict de Brito et al. [43], who claimed that the recycling process could be replicated with no further limitations on compressive strength or workability.

The lightweight Carbon8 aggregate 7-day compressive strength results for the first-generation concrete were 6 % higher than predicted by Equations (3) and (4). For the third-generation concrete, the 7-day compressive strength result was 1.6 % lower than the value proposed by Equations (3) and (4). The test results are in good correlation with the Eurocode 2; however, because the second-generation concrete's 7-day compressive strength result is 15 % higher further testing is recommended before the conclusion can be drawn. On the other hand, the parent Carbon8 aggregate does not contain different mortar paste and cement replacement materials that could interfere with the results; therefore, one of the possible explanations for the uniform results gained from the Carbon8 aggregate testing is because of the consistent mix used in the experiment.

Particularly compressive strength results and the coarse aggregate loss results highlight the practical challenges of keeping concrete aggregates in circulation indefinitely. While repeated recycling aligns with the principle of material retention advocated in the Design for a Circular Economy guidance by the Greater London Authority, our findings suggest that material quality inevitably deteriorates after multiple cycles. This raises important considerations for design strategies that emphasize reuse and adaptability before down-cycling, so that the highest-value use of concrete materials can be preserved for as long as possible.

While the experimental results confirm that concrete can only be recycled a finite number of times before significant deterioration occurs, the practical application of these findings must be considered in the context of real building lifespans. Most reinforced concrete structures are designed for service lives of 50–100 years, meaning that the opportunity to recycle concrete multiple times within a century is limited. However, the large aggregate volumes involved in demolition events present a significant source of recycled material even from a single cycle. Our findings therefore highlight that, although multiple recycling may be theoretically possible, in practice, the first and second recycling cycles are the most realistic within typical planning horizons. Beyond this, selective demolition, material segregation, and reuse strategies aligned with circular economy principles become more critical to extend the value of concrete resources before quality loss becomes prohibitive.

3. Conclusion

An experimental study was conducted to investigate the circular economy concept of various concrete products. In line with the London Mayor's Design for a Circular Economy framework, which calls for materials to be reused "over and over" at their highest value, this research provides empirical evidence that concrete can only be recycled a finite number of times before performance degradation limits its structural applications. These results underline the need for circular design approaches that not only promote recycling but also prioritize disassembly, selective demolition, and material segregation, thereby extending the useful life of concrete

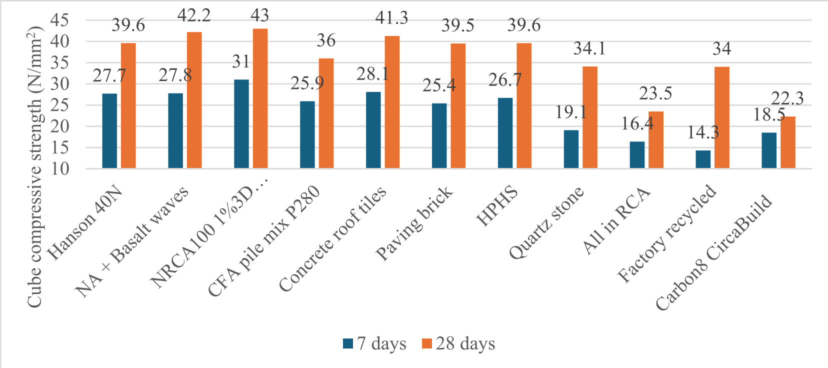


Fig. 2.19. First-generation recycled aggregate compressive strength.

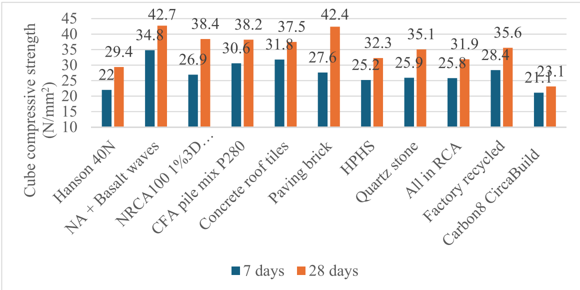


Fig. 2.20. Second-generation recycled aggregate compressive strength.

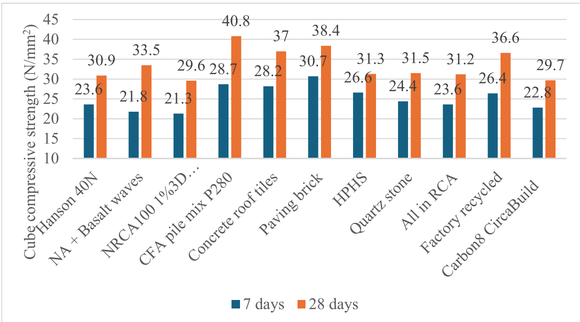


Fig. 2.21. Third-generation recycled aggregate compressive strength.

before it reaches its recycling limits. The experimental research referred here aimed to demonstrate the technical feasibility of repetitive recycling of coarse and fine aggregates that were obtained from structural concrete elements and concrete products for the production of new concrete. From the experimental results, the following conclusions can be drawn:

- Though there hasn't been much research done on multi-recycled aggregate concrete up till now, it's becoming more and more important for sustainability. It has been noted that as the number of recycling cycles increases, the mechanical properties of various recycled concrete aggregates decrease.
- The morphological characteristics of recycled aggregate are mainly dependent on the parent aggregate type for the RCA1. The higher-strength parent concrete's recycled aggregate was spherical with edges sharp from the brittle cement paste. The low-strength aggregate is round, mainly resembling the parent aggregate properties.
- The multi-recycling favoured the smooth weathered flint aggregates because of the high resistance to crushing. This feature allowed the coarse aggregate particles to remain intact during the crushing process, while the smooth surface enabled the cement paste to peel away from the coarse particles. Further, the mix design and the parent aggregate particle distribution have equal importance on the multiple-recycling concept.

- The third-generation recycled aggregate is very angular because of the brittle cement paste. The parent aggregate characteristic almost disappeared and consequently, the morphology of the last-generation concrete was influenced by the brittleness of the cement paste.
- The parent aggregate loss by each recycling stage depended on the mix design. For all in aggregate mixes with a 0.4 w/c ratio the third-generation recycled aggregate contained only 20 % parent aggregate. The increase or decrease of w/c ratio could delay or accelerate the natural aggregate replacement, respectively; however, eventually, all parent aggregates would be lost after a finite number of recycling cycles.
- Multiple crushing and recycling processes produce an open-graded aggregate with a low volume of fines and a high coarse aggregate content. As the number of recycling cycles increases, the particle grading reveals an increase in coarse particles and a decrease in fines. The well-graded aggregate produces denser concrete; consequently, coarse and fine aggregates must be carefully graded to produce dense concrete using a multiple-stage crushing process for recycled concrete materials. Further tests are required to verify the well-graded multiple times recycled concrete compressive strength.
- A more uniform and predictable compressive strength concrete can be gained by producing a similar concrete mix to the parent concrete throughout the recycling cycles.
- The formula-based strength prediction in BS EN 1992-1-1, Clause 3.1.2 (6) [44] cannot be used, without modification, for normal-weight recycled aggregate concrete. However, because of the high variability of the results, a close approximation cannot be made based on the limited number of results used in this experiment; therefore, further research is required in that field.
- Multiple crushing and reusing of the fibre-reinforced aggregate resulted in ever-increasing fibre damage and a complete loss of fibre effectiveness for both basalt and steel fibres.

The majority of structural concrete regulations often use mechanical and physical characteristics as verification standards. According to all of the test results included in this research, multiple-recycled concrete has qualities that make it appropriate for use as structural concrete. However, density and compressive resistance are lost with each recycle, therefore this paper's quantification of the loss is the greatest contribution.

CRediT authorship contribution statement

Robert Kovacs: Writing – original draft, Methodology, Conceptualization. **Rabee Shamass:** Supervision. **Vireen Limbachiya:** Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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