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Comprehensive study on the most sustainable concrete design made of recycled concrete, glass and mineral wool from C&D wastes

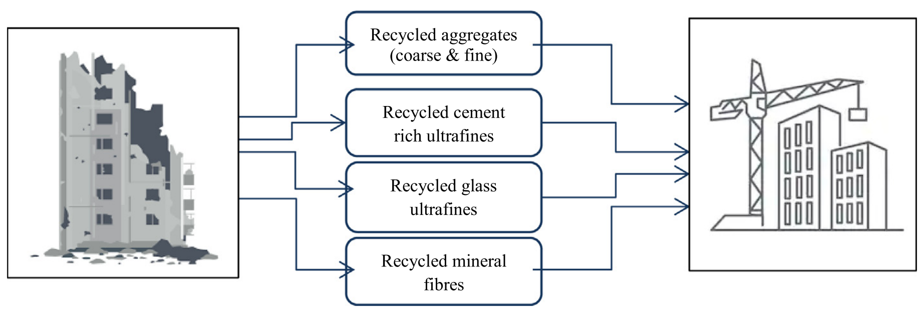
Abraham T. Gebremariam [a,*], Ali Vahidi [a], Francesco Di Maio [a], J. Moreno-Juez [b], I. Vegas-Ramiro [b], Artur Łagosz [c], Radosław Mróz [c], Peter Rem [a]

[a] *Delft University of Technology, Dept. of Engineering Structures, Resource and Recycling, 2628 CN Delft, Netherlands*
[b] *TECNALIA, Basque Research and Technology Alliance (BRTA), Astondo Bidea, Edificio 700, Parque Tecnológico de Bizkaia, 48160 Derio, Spain*
[c] *AGH University of Science and Technology, Faculty of Material Science and Ceramics, Department of Building Materials Technology, Mickiewicza 30, 30-059 Kraków, Poland*

HIGHLIGHTS

- The use of clean RCA and RFA in new concrete is a viable solution to assure circularity in the built environment.
- RCA and RFA can totally replace natural aggregates and sand, despite high water absorption.
- Recycled ultrafines are recommended as additives instead of cement replacement.
- Addition of RMF improves the tensile strength and modulus of elasticity of recycled concrete.
- RMF affect the workability of a concrete and are recommended at lower doses.

GRAPHICAL ABSTRACT



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ABSTRACT

This study focuses on formulating the most sustainable concrete by incorporating recycled concrete aggregates and other products retrieved from construction and demolition (C&D) activities. Both recycled coarse aggregates (RCA) and recycled fine aggregates (RFA) are firstly used to fully replace the natural coarse and fine aggregates in the concrete mix design. Later, the cement rich ultrafine particles, recycled glass powder and mineral fibres recovered from construction and demolition wastes (CDW) are further incorporated at a smaller rate either as cement substituent or as supplementary additives. Remarkable properties are noticed when the RCA (4–12 mm) and RFA (0.25–4 mm) are fully used to replace the natural aggregates in a new concrete mix. The addition of recycled cement rich ultrafines (RCU), Recycled glass ultrafines (RGU) and recycled mineral fibres (RMF) into recycled concrete improves the modulus of elasticity. The final concrete, which comprises more than 75% (wt.) of recycled components/materials, is believed to be the most sustainable and green concrete mix. Mechanical properties and durability of this concrete have been studied and found to be within acceptable limits, indicating the potential of recycled aggregates and other CDW components in shaping sustainable and circular construction practices.

1. Introduction

The constant craving for natural resources in the construction sector has posed a significant threat to the natural ecosystem. The construction sector is known for its increased demand for resources and energy. As such, it is one of the most

Abbreviations: CDW, construction and demolition wastes; C2CA, concrete to cement and aggregates; RCA, recycled coarse aggregates; RFA, recycled fine aggregate; HCP, hydrated cement paste; RCU, recycled concrete ultrafines; RGU, recycled glass ultrafine; RMF, recycled mineral fibres; EoL, End-of-Life; PSD, particle size distribution; SEM, scanning electron microscopy.

* Corresponding author.
E-mail address: a.t.gebremariam@tudelft.nl (A.T. Gebremariam).

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resource-consuming sectors in Europe. It accounts for approximately half of all extracted materials, half of the total energy consumption, and one-third of water consumption [1]. The sector has been under pressure for its little effort in sustainable construction practices [2]. Concrete being an excellent construction material, it has to shoulder most of the blame. The major issues with concrete are its high embedded carbon footprint (e.g., CO_2), the need for large amount of natural resources, and the generation of large amount of waste after demolition. Thus, the increasing global construction activities urge to find sustainable resources that can replace natural resources in the production of concrete. Recycled aggregates and other mineral components retrieved from construction and demolition (C&D) activities are potential candidates in this regard. Consequently, there has been substantial effort in recycling concrete aggregates and other components that originate from construction and demolition activities.

The EU alone generated 374 million tons of construction and demolition waste (CDW) in 2016, and this accounts for approximately 25–30% of all wastes [3]. Although the EU has to some degree succeeded to achieve 70% of the recovery target set for 2020, the level of recovery is limited to low-grade applications such as backfilling and use as sub-base materials in road construction. Such applications are never circular because the functionality of the recycled materials differs from the original one. The rate of recovery must consider the intrinsic value of recycled materials and must aim for similar or higher value applications, for instance, in the manufacture of concrete. For this reason, there has been extensive research and effort on the recyclability of EoL concrete wastes back to construction purposes. Concrete made of recycled aggregates was often considered to display inferior properties than conventional concrete until several reports emerge on the advantages of using recycled aggregates [4]. Since then, much has been changed in favour of recycled aggregates. Now, we are in an era where structures and utilities are designed to meet not only serviceability requirements but also sustainability and circularity requirements. This makes recycling an interesting subject not only in terms of adopting sustainable construction practices but also in generating employment opportunities.

Over the last half-century, several methods have been developed to recycle EoL concrete waste, which is the major component of CDW. Most of these technologies are aimed to prove the possibility of recycling EoL concrete waste into a product that resembles the original components of concrete [5–10]. In most cases, the attempt is to classify recycled aggregates into three major grades: recycled coarse aggregates (RCA), recycled fine aggregates (RFA) and cement rich fine fraction. Selective fragmentation [11] and microwave-assisted beneficiation methods [10] are one of the technologies recently developed to recycle EoL concrete. It takes advantage of the difference in energy absorption capacity between mortar and aggregates, causing higher differential thermal stress at the interface between mortar and aggregate surface, leading to faster delamination of the adhering mortar. Although the method claims to improve the property of recycled aggregates and produce relatively clean coarse aggregates with minimum deterioration of the intrinsic qualities of the source material, the fact that the process uses high intensity electrical pulses to a material immersed in water leaves most of the cement into a sludge that needs to be landfilled or further treated. Similarly, the heating-rubbing method proposed by Shima et al. [8] claims to produce clean coarse aggregates and cement rich powder that can be either used as soil stabilizer or as an additive together with blast furnace slag cement. The strength and durability of concrete made of aggregates produced by this method were similar to the reference concrete. This method also claims satisfactory pumpability and castability of the recycled concrete. A waste free technology [7] that combines high-temperature furnace and grinding process claims to yield clean recycled aggregates and cement powder. This technology, however, exposes the concrete rubble at temperature 650 °C for about 1 h. Such longer residence time may render the method expensive and questions its feasibility. Nevertheless, the method produces high-quality recycled aggregate that could improve the strength of concrete by 10% without causing any significant deterioration of other parameters, such as water absorption, water permeability, and frost resistance. The smart crusher [9] is also one of the existing technologies that aim to liberate the hydrated cement powder through gentle crushing techniques. This method claims the property of recycled gravel and recycled sand produced by this method is as good as the natural ones. However, due to the continuous milling operation, it ends up with silica-rich powder instead of calcium-rich powder. Nevertheless, most of these technologies are challenging to be applied at the industrial level, mainly due to the high processing costs which make the recycled materials not competitive with inexpensive and abundant natural materials. Besides, C2CA technologies are among the suitable technologies that hold a quality-cost balance in recycling EoL concrete [12]. These technologies are composed of two innovative methods, namely ADR (Advanced Dry Recovery) and HAS (Heating Air classification System). ADR is used to sort and classify wet crushed concrete wastes into coarse (4–12 mm) and fine (0–4 mm) recycled aggregates [13,14]. The coarse fraction is composed of clean recycled aggregates with less amount of fines attached to it, hence can be directly used in the concrete mix. The fine fraction (0–4 mm) is thermally treated in the HAS and further classified into recycled sand and hydrated cement rich ultrafines/recycled concrete ultrafines (RCU).

The suitability of coarse recycled aggregates and their performance in recycled concrete has been well studied. While most researchers believe the presence of attached mortar on the surface of aggregates is the major bottleneck of RCA for structural applications [15,16], others believe RCA can be equally used for structural applications [17–19]. Recycled fine aggregates (RFA), however, are least favoured for concrete applications. The detrimental factors that influence the use of recycled fine aggregates are the amount of adhered cement paste, their angular shape, and its high water absorption. These properties affect the strength and durability of recycled concrete adversely. To offset such weaknesses, different methods have been used to enhance the performance of recycled aggregates. Xuan et al. [20] has examined the durability of recycled aggregates by treating with CO_2 during curing and found a greater beneficial impact on the durability of recycled aggregates. This method is valuable to offset the inherent properties of recycled aggregates, such as high water absorption and high permeability. Cartuxo et al. [21] also suggested the use of superplasticizers to improve the workability, porosity, and also found an increase in compressive strength of concrete made of recycled fine aggregates. It was also indicated that the use of mineral admixtures such as fly ash along with recycled fine aggregates would improve the workability and strength of recycled concrete [22]. The use of sodium silicate and silica fume has also been suggested as a method of enhancing the mechanical properties of recycled aggregates [23]. Nevertheless, most of the property or strength enhancing methods may not be welcomed by the concrete industries, as it merely increases the time needed to cast the concrete which is directly related to the cost of production.

To maximize the utilization of resources from C&DW and reduce the carbon footprint of a product, research has been conducted to incorporate cement-based products manufactured with recycled ultrafine resources from CDW. Recycled concrete ultrafine particles are mainly composed of hydrated cement products and silica particles generated while crushing the EoL concrete wastes. Due to their small particle size and suitable composition, their potential use as partial replacement of cement or as an additive has been recently studied. According to some studies, the existence of self-cementing properties of recycled fine aggregates (<0.15 mm) is related to the amount of unhydrated cement and C2S adhered to the product, which varies depending on the age, grade, and amount of cementitious materials in the original concrete [19]. Nevertheless, the presence of about 24% unhydrated cement in the recycled ultrafine product was found to be responsible for its hydraulic reactivity when reused again [24]. On the other hand, less than 4% unhydrated cement was reported along with recycled concrete ultrafine products [25], which suggests little hydraulic property of the product. The same study recommends that 25% of cement can be replaced with recycled concrete ultrafine product without affecting the strength of mortar. Besides, the use of recycled concrete ultrafine products as a substitute for limestone filler may also be a practical solution [25]. Recycled concrete ultrafine particles have demonstrated their suitability in new eco-products, providing a technical and environmentally viable solution to the ecosystem [26]. Thus, incorporating ultrafines retrieved from CDW as supplementary cementitious materials (SCM) in new cement or as an addition to the material are observed to display pozzolanic properties. Moreno-Juez et al. [26] have demonstrated the feasibility of using ultrafine recycled concrete particles processed by HAS technology by replacing directly up to 5% of the cement during the manufacturing of concrete. In doing so, it reduces the curing and setting times, improves mechanical properties at early age, and reduces the clinker content of cement by 5–7%. Apart from this, some researchers have studied the possible use of recycled concrete ultrafine products as raw meal in the production of cement by replacing 30% of the raw meal [27], to produce a clinker with a mineralogical composition very close to the commercial clinker.

The objective of this study is, therefore, to examine the influence of clean recycled aggregates, ultrafine particles (cement rich powder and glass powder), and mineral fibers recovered from CDW on the performance of concrete. Furthermore, assess how much EoL material can be incorporated into a new type of concrete product that holds a balance between strength, durability, and sustainability. In this study, a concrete made by adding several recycled components from CDW activities is presented. With the intention of using most of the construction and demolition wastes (CDW) back to the construction sector, recycled products such as recycled aggregates (both coarse and fine), recycled cement paste, recycled glass powder, and recycled mineral fibres are used in a new concrete mix. Recycled products (RCA, RFA and RCU) processed by C2CA technologies are the primary components used to replace natural aggregates. This study also encompasses new perspectives of using glass powder and mineral wool due to their potential pozzolanic activity and the possibility of improving properties such as cracking and mechanical resistance of concrete, a subject only a few studies have addressed [28,29]. To this end, as much reclaimed materials from C&D activities are utilized to come up with the most green and sustainable concrete design. Such product not only does save the use of natural resources but also the CO_2 emissions associated with concrete production.

2. Materials

In this study, different products from C&D activities are used to formulate green and sustainable concrete. Recycled concrete aggregates are produced by using ADR and HAS technologies [12]. Thus, clean and high quality recycled coarse aggregates (4–12 mm), recycled fine aggregates (0.25–4 mm) and recycled ultrafines (<0.125 mm) are produced by a combination of ADR and HAS technologies (called C2CA technology). While both the coarse and fine aggregates are used to replace natural coarse and fine aggregates completely, the amount of ultrafines used to replace cement is limited at 5% (by wt.) based on a previous study conducted on mortars [26]. Recycled aggregates are sourced from a demolished bridge in the Netherlands; on the other hand, river gravel and sand are used as natural aggregates. Other CDW components such as recycled glass ultrafines (RGU) and recycled mineral fibres (RMF) are obtained from construction and demolition activities in Finland and are incorporated into the mix design at 3% and 0.5%, respectively, either as cement substitution or as an additive. Recycled glass samples are prepared by grinding flat glass into powdered form and collecting the ultrafine fraction (RGU) in the cyclone, whereas RMF are prepared by grinding insulation material collected from C&D activities into short fibres of length <2 mm. CEM III/A 42.5R type cement has been used in this study, as it is widely used type in precast industries in the Netherlands. Isoflow 755 (Cemex) superplasticizer is used to adjust the consistency of concrete.

3. Experimental methodology

3.1. Property of materials

The properties of recycled aggregates produced by C2CA technology were evaluated to assess their conformity for concrete production. The particle size distribution of both RCA and RFA are examined based on the standard method EN 933-1. The water absorption and the specific gravity of aggregates were determined based on standard EN 1097-6, where the saturated and surface dried particle density of coarse and fine recycled aggregates were measured by using a Pycnometer method. The Los Angeles abrasion loss was determined using the standard EN 1097-2. The particle size of RCU and RGU has been analysed by Mastersizer 3000 laser diffraction particle size analyser, and their chemical composition has been analysed by using x-ray fluorescence (XRF) spectroscopy.

3.2. Concrete mix design

The experimental approach for the mix design is categorized into three steps. In the first step, the impact of recycled coarse and fine aggregates is studied by completely replacing all natural aggregates with recycled aggregates. At the second step, the impact of recycled ultrafines is studied at a small percentage of use, either by replacing either cement or limestone (as a replacement or as an additive, respectively); lastly, the influence of mineral fibres is studied by incorporating a small fraction of mineral fibres that are obtained from C&D activities. In all cases, a strength class of C30/37 and exposition class XC4 (corrosion induced by carbonation) are assumed in the mix design. Details are described below:

3.2.1. Influence of recycled coarse and fine aggregates

At this level, the performance of ADR coarse and HAS fine products has been investigated by totally replacing natural coarse aggregates (NCA) and natural fine aggregates (NFA) with recycled coarse aggregates (RCA) and recycled fine aggregates (RFA). Three samples are designed. The first one is a reference recipe (C-Ref), which is composed of natural coarse and natural fine aggregates. In the second sample (C-100-0), the coarse natural aggregates are completely substituted with recycled coarse aggregates. In the third recipe (C-100-100), both natural coarse and fine aggregates are entirely replaced with RCA and RFA. Table 1 indicates the mix composition concrete samples. As far as the quantity of aggregates is concerned in Table 1, the lower volumetric density of recycled aggregates is reflected by a difference in the amount of natural

Table 1
Mix composition of both reference and recycled concrete for 1 m$^{3.}$

Components		C-Ref	C-100-0	C-100-100
Cement (kg)	CEM III/A 42.5R	335	335	335
Filler (kg)	Limestone	145	145	145
Fine aggregates (kg)	NFA (0–4 mm)	750	682	0.0
	RFA (0–4 mm)	0.0	0.0	567
Coarse aggregates (kg)	NCA (4–12 mm)	907	0.0	0.0
	RCA (4–12 mm)	0.0	882	881
Water (kg)		161	161	161
Superplasticizer (% cement)		0.65	0.75	1.3

and recycled aggregates used in the mix design. Based on the strength and substitution rate, the sample containing higher amount of secondary materials is further investigated in the next step to accommodate more recycled products that are generated from C&D activities.

3.2.2. Influence of recycled ultrafine powders

Based on the above recipe, sample C-100–100 is chosen, and further modification of the recipe was made to include recycled concrete ultrafines (RCU) processed by HAS and recycled glass ultrafine (RGU) powder processed by grinding the flat glass collected from C&D activities. The particle size of RCU is <125 μm and RGU is <200 μm and both are expected to have some cementitious property. Consequently, they are incorporated in the concrete recipe at low percentages. Based on the preliminary study on the RGU, its usage has been limited to only 3%. Whereas RCU is used at 5% and 10%, either as an additive (A) or as cement substitution (S). Thus, C-100-100-5/3A contains 100% RCA, 100% RFA, and ultrafines (5% RCU + 3% RGU, as additives). The same is true for C-100-100-5/3S, except that the ultrafines (5% RCU + 3% RGU) are considered as cement substitution. Table 2 summarizes the composition of the mix along with substitution rates.

3.2.3. Influence of recycled mineral fibres from insulating mineral wool waste

Based on the second stage, the impact of recycled mineral fibres (RMF) is studied by incorporating a limited amount of RMF into sample C-100–100-5/3A and C-100–100-5/3S. Table 3 shows the mix design for the most sustainable concrete composed of recycled products from C&D activities. The main objective at this stage is to assess the reinforcing potential of mineral fibres on the final property of the concrete. As the presence of these fibres strongly influences the workability of concrete, their dosage is limited to only 0.5% by weight, which is still significant by volume due to its lower bulk density. Thus, C-100–100-5/3–0.5RMF-A denotes a sample made by fully substituting NCA and NFA with RCA and RFA, respectively. Besides, it consists of 5% RCU and 3% of RGU and 0.5% RMF, added as an additive (Limestone replacement). On the other hand, C-100-100-5/3-0.5RMF-S stands for similar composition as C-100-100-5/3-0.5RMF-A except that RCU, RGU and RMF are added as cement replacement (S).

Table 3
The final composition of concrete made by incorporating most components from C&D activities (RCA, RFA, RCU, RGU and RMF).

Components		C-100-100-5/3-0.5RMF-A	C-100-100-5/3S-0.5RMF-S
Cement (kg)	CEM III/A 42.5R	335	307
Ultrafine (kg)	RCU	16.75	16.75
	RGU	10.05	10.05
Microfibres (kg)	RMF	1.675	1.675
Filler (kg)	Limestone	117	145
Fine aggregates (kg)	NFA (0–4 mm)	0.0	0.0
	RFA (0–4 mm)	566	566
Coarse aggregates(kg)	NCA (4–12 mm)	0.0	0.0
	RCA (4–12 mm)	881	881
Water (kg)		161	161
Superplasticizer (% cement)		1.15	1.25

3.3. Specimen preparation and test methods

Concrete specimens were prepared according to the mix design given in Tables 1–3. Two stage mixing method was adopted for casting the concrete specimen [30]. To accommodate the difference in water absorption of recycled aggregates, an appropriate moisture adjustments are made. Concrete cubes, cylinders and prisms are prepared according to EN 12390-1&2. Fresh and hardened concrete properties are analysed based on standard test methods. In the fresh state, the workability is examined (using the Abram's cone) according to EN 12350-2 and the specific density is examined according to EN 12350-6. After proper curing of the specimen, the mechanical properties and durability of the hardened concrete have been examined based on standard test methods. The compressive strengths of the hardened concrete cubes were tested at the ages of 2, 4, 7, 28 and 90 days, according to EN 12390-3. The modulus of elasticity (EN 12390-13), the ten-

Table 2
The mix composition of concrete samples that incorporate RCU and RGU at the second stage.

Components		C-100-100	C-100-100-5/3A	C-100-100-10/3A	C-100-100-5/3S	C-100-100-10/3S
Cement (kg)	CEM III/A 42.5R	335	335	335	308	291
Ultrafine (kg)	RCU	–	16.75	33.50	16.75	33.50
	RGU	–	10.05	10.05	10.05	10.05
Filler (kg)	Limestone	145	118	101	145	145
Fine aggregates (kg)	NFA (0–4 mm)	0.0	0.0	0.0	0.0	0.0
	RFA (0–4 mm)	567	566	566	566	566
Coarse aggregates(kg)	NCA (4–12 mm)	0.0	0.0	0.0	0.0	0.0
	RCA (4–12 mm)	881	881	881	881	881
Water (kg)		161	161	161	161	161
Superplasticizer (% cement)		1.3	1.15	1.32	1.25	1.5

sile strength (EN 12390-6), the flexural strength (EN 12390-5), Abrasion resistance (EN 1338 - Annex G), water absorption (PN B-06250), water permeability/depth of water penetration (EN 12390-8), accelerated carbonation (EN 12390-12) and shrinkage (ASTM C 157) of the hardened concrete are examined. For each test, an average of three specimen are used at each curing age. Lastly, the porosity of hardened concrete was examined with mercury porosimeter PoreMaster 60 in the range of pore diameters from 3.3 nm to 250 μm. Due to the size of the measuring cell (diameter 10 mm, length 20 mm), smaller fragments were extracted from the concrete for the best possible measurement and accuracy. At the initial stage of measurement, the apparatus was degassed at ambient temperature until a vacuum of 10 mmHg is reached. The detailed results of measurement are presented in graphical diagrams of cumulative (summation) curves of pore size distributions and differential curves of pore size distributions, as shown in Fig. 4. The microstructure of fibre reinforced concrete is examined by scanning electron microscopy (SEM), where the concrete micro sections are prepared from the internal part of the concrete specimen after being dried at laboratory conditions for three days. A FEI Nova NanoSEM 200 ultra-high resolution scanning electron microscope with a Schottky type field emission gun equipped with an EDAX/EDS analyser is used for our purpose.

4. Results and discussion

4.1. Properties of recycled aggregates and other C&D components

The physical properties of recycled and natural aggregates are examined based on standard methods (EN 933-1 for particle size distribution (PSD) and EN 1097-6 for water absorption and the specific density of aggregates). As shown in Fig. 1, some adjustment has been made on the particle size of the NCA to assume similar particle size distribution as that of RCA. As the objective of this study is also to examine the influence of the fine products (RFA) processed by HAS, it was not necessary to make particle size adjustments for the fine fraction. Thus, neither finer fractions are removed from RFA nor NFA are compensated with finer fractions. Recycled fine products are applied to the mix as they are produced from HAS.

Table 4 displays some physical properties of natural and recycled aggregates. As shown in the table, recycled aggregates show higher water absorption and lower particle density compared to the natural aggregates. This is attributed to the mariginal amount of mortar present on the aggregates surface which increases the porosity.

The particle size distribution of RCU and RGU has been analyzed along with commercial cement that is used in this study. As shown

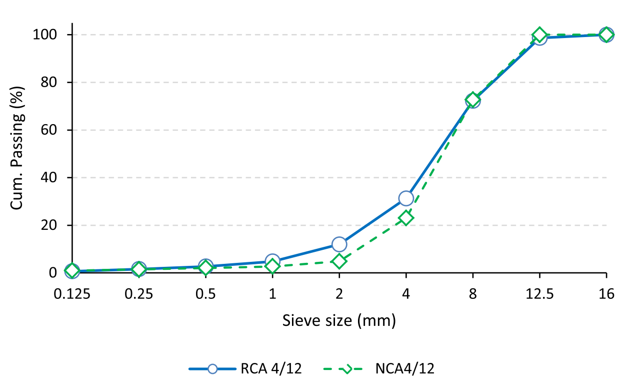

Fig. 1. Particle size distribution of recycled coarse and natural coarse aggregates.

in Fig. 2, RCU product contains smaller particles compared to RGU, yet both ultrafines are coarser compared to the PSD of cement.

The chemical and mineralogical composition of RCU, RGU and RMF are shown in Table 5, as well as the main physical properties are given in Table 6.

As shown in the Table 5 and Table 6, the ultrafine recycled materials employed in this study are silica-based materials with different particle sizes and densities. The RCU product comprises rounded particles of low to medium sphericity with similar chemical and physical properties to the commercial cement. Indeed, RCU has high silica content, lower calcium content, and are coarser compared to the commercial cement. The glass powder RGU is composed of sharp-edge particles of low to medium sphericity with coarser particle size distribution than RCU. Lastly, the recycled mineral fibres are composed of vitreous glass fibres with thickness ranges from 2 to 15 μm and a length of 2 mm.

4.2. Fresh concrete properties

As the mix design shows in Tables 1–3, the slump is designed to comply with S4 according to EN 206. To keep the designed slump (S4), the consistency loss due to the addition of recycled aggregates is monitored by the use of superplasticizers. Superplasticizer additions are based on the weight percentage of cement and limestone powder. The workability and fresh concrete density are shown in Table 7. As more cement or limestone is substituted, the decrease in workability is compensated by the addition of plasticizers. There is no clear correlation between the amount of plasticizers used and the degree of substitution. It is barely based on a preliminary test performed on the consistency prior to casting samples. The average bulk density of fresh concrete for each mix design is also shown in Table 7. The fresh density shows a decreasing trend while increasing the amount of recycled components, which could be justified by the lower density of recycled aggregates due to its higher porosity, which is in line with previous studies [31]. The water absorption after 24 h (WA24) reveals that, as the amount of recycled components in the mix design increased, either more water is needed or more plasticizers are used to compensate the consistency.

4.3. Hardened concrete properties

4.3.1. The influence of recycled coarse and fine aggregates

The average compressive strength for both recycled concrete and reference concrete obtained at different curing days is displayed in Fig. 3. The compressive strengths of all mixtures increases with age. As shown in the figure, all concrete mixtures developed a consistent rate of strength gain up to 90 days. The concrete mix made of 100% coarse recycled aggregates (C-100-0) displays similar compressive strength until 28 curing days as the reference concrete (C-Ref), with little increase at 28 days and a small decrease in value at 90 days of curing. At 28 days of curing the compressive strength of C-100-0 slightly surpasses the reference concrete (C-Ref) by 3% before dropping to 6% at 90 days.

For the concrete mixture that is entirely made of recycled fine and coarse aggregates (C-100-100), the rate of increase in compressive strength is faster at later ages than earlier ages. It can be clearly seen that after two days of hardening, upto 12% difference in compressive strength was noticed between C-Ref and C-100–100. This difference, however, decreases with curing time. After 28 days of hardening, the difference in compressive strength drops to approximately 1.8%. After 90 days, C-100-100 has shown only 5% decrease in compressive strength compared to the reference concrete (C-Ref). This difference can be considered as insignificant, as the sustainability benefit offsets it. All in all, the obtained results

Table 4
Physical properties of recycled aggregates (processed by C2CA technology) and natural aggregates.

Aggregate property	RCA	RFA	NCA	NFA
Particle density (g/cm^3)	2.26	2.18	2.49	2.62
Water absorption (%)	6.2	7.6	2.3	0.3
L.A. Abrasion loss (%)	26	–	21	–

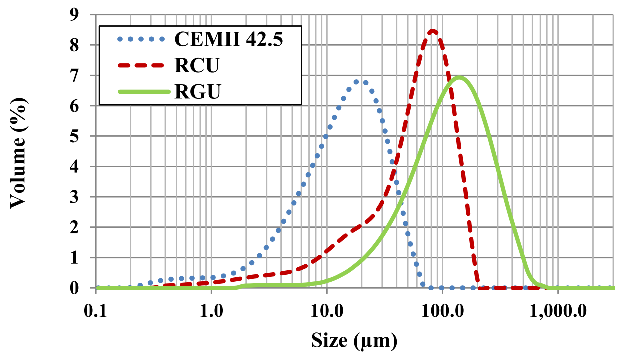

Fig. 2. Particle size distribution of recycled concrete ultrafines (RCU) and recycled glass ultrafines along with cement.

Table 5
Chemical and mineralogical composition of the ultrafine particles used in this study.

Chemical composition %	CEM III	RCU	RGU	RMF
SiO_2	30.52	55.91	70.30	59.68
Al_2O_3	8.84	6.04	1.07	1.59
CaO	47.80	20.5	9.64	7.07
Fe_2O_3	1.14	2.3	0.92	0.44
MgO	5.42	2.1	3.64	0.15
SO_3	2.19	1.61	0.24	0.52
Na_2O	0.28	2.14	13.26	14.27
K_2O	0.71	1.06	0.26	0.9
TiO_2	0.78	0.41	0.07	0.06
P_2O_5	0.07	0.09	–	0.01
LOI	1.55	7.42	0.43	5,42
Mineralogical composition %		*RCU*	*RGU*	*RMF*
Amorphous content		36.68	100	100
Calcite ($CaCO_3$)		8.25	–	–
Quartz SiO_2		48.66	–	–
Others		4.4	–	–

Table 6
Physical properties of the ultrafine particles used in this study.

Physical properties	CEM III	RCU	RGU	RMF
Particle density (g/cm^3)	2.95	2.54	2.5	2.46
Specific surface area (cm^2/g)	4234	2649	674	5976
D10 (µm)	1.55	10.3	33.0	Microfibers
D50 (µm)	21.5	57.9	111.7	Length < 2 mm
D90 (µm)	45.7	117.8	277.8	Ø = 2 to 20 µm

have fulfilled the criteria for the strength class (C30/37) for the established exposure class (XC4).

The concrete mix, C-100-100 is entirely made of recycled fine and coarse aggregates. Considering all components of the concrete mix, C-100-100 has got an overall substitution rate of 75% by weight or 79.7% by volume. This means 75% (by wt.) of the concrete (C-100-100) is composed of recycled aggregates compared to C-100-0, which is only 43% (by wt.). This concrete is, therefore,

Table 7
Fresh concrete properties.

Sample type	Superplasticizers (% wt)	Consistency (mm)	WA24 (kg)	Fresh density (kg/m3)
C-Ref	0.65	180	23	2295
C-100-0	0.75	195	57	2254
C-100-100	1.3	190	95	2194
C-100-100-5/3A	1.15	190	95	2184
C-100-100-10/3A	1.32	185	95	2175
C-100-100-5/3S	1.25	170	95	2156
C-100-100-10/3S	1.5	190	95	2185
C-100-100-5/3A-0.5RMF-A	1.15	170	95	2169
C-100-100-5/3S-0.5RMF-S	1.25	190	95	2160

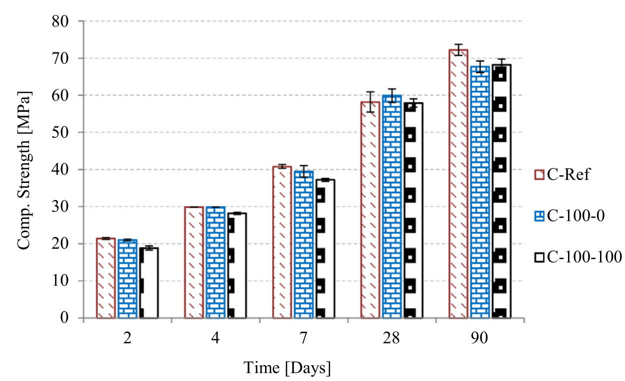

Fig. 3. Compressive strength of recycled concrete and reference concrete.

the most sustainable and green, among other concrete mixes in this group.

According to literature, there is no complete consensus in research results on the amount of RCA that can be used in concrete mixtures. Hence, the performance of concrete made with recycled coarse aggregate varies depending on the extent of substitution. It has been reported that replacing natural coarse aggregates with recycled coarse aggregates displayed better compressive strength [32]. On the other hand, it is not recommended to use beyond 30% replacement of coarse aggregates [30,33,31]. Nevertheless, this study revealed the positive effect of using recycled coarse and fine aggregates produced by ADR and HAS technology.

Once the strength of the most sustainable concrete (C-100-100) is understood and found to be within the design limits for structural applications, further tests were performed on this concrete and compared with the reference concrete. Table 8 summarizes some of the measurements done on the hardened concrete. Based on the measurements, recycled aggregates (C-100-100) display inferior properties compared to the reference concrete (C-Ref). Such reduction in property (depth of water penetration, abrasion resistance and modulus of elasticity) simply means concrete made of recycled aggregate performs less than the reference conventional concrete but within limits for structural applications.

The presence of adhered mortar on the surface of recycled aggregates influences the pore system making it more liable to the ingression of foreign substances into the internal structures of concrete. Mercury intrusion porosimeter (MIP) has been used to evaluate pore size distributions in concrete. Although the method seems to be controversial for measuring pore size distribution in hydrated cement systems [34], it provides a reasonable threshold diameter of the intrudable pore volume that may

Table 8
Comparison of measurements among the reference concrete and recycled concrete at 28 days.

Type of test		Standard	C-Ref	C-100-100
Water penetration (mm)		EN 12390-8	10.5	13.8
Density of hardened concrete (kg/m^3)		EN 12390-7	2197	1990
Abrasion resistance (mm)		EN 1338-Annex G	17.2	19.1
Modulus of elasticity (GPa)		EN 12390-13	31.1	27.1
Porosity	%		11.21	13.03
	Modal pore diameter (μm)		0.07	0.01
	Total volume, open (cm^3/g)		0.04	0.09

constitute useful comparative indexes of the concrete pore. As shown in Table 8, concrete made of recycled coarse and fine aggregates (C-100–100) tend to have smaller pore diameter but higher percentage of pore volume compared to reference aggregates. This contributes to a decrease in the mechanical properties of the recycled concrete. Fig. 4 displays the pore volume and pore size distribution of recycled concrete and reference concrete at 28 days, showing recycled concrete (C-100-100) is composed of smaller pores but large in volume compared to the reference concrete (C-Ref). In fact, porosity has a direct relationship with the amount of recycled aggregates [35,36]. Depth of water penetration test revealed that concrete made of recycled aggregate displays a higher depth of water penetration. This may result from the poor combination of new cement matrix with the secondary aggregate grains that contain porous old cement paste matrix on their surface. In this research, the high porosity observed for recycled aggregates is reflected in the water permeability results. Thus, the water permeability of C-100-100 concrete is 31% higher than the reference (C-Ref).

The presence of an old mortar with a comparatively lower modulus of elasticity attached to recycled aggregate surface may influence the modulus of elasticity of the recycled concrete. According to literature, the decrease in elastic modules for recycled concrete may reach as high as 80% [37,38]. In this study, the reduction of elastic modulus is only 12.86% compared to the reference concrete, as it is shown in Table 8. Compared with literature values, the reduction observed here can be considered small. This may partly result from the high quality of recycled aggregates processed by C2CA technologies.

Generally, concrete made of recycled aggregates tends to show higher carbonation depth compared to the reference concrete made of natural aggregates. High water absorption and increased porosity of recycled concrete are the major factors that contribute to their low carbonation resistance. Nevertheless, carbonation depth can be improved with the use of superplasticizers [21]. Fig. 5 shows the carbonation depth of the reference (C-Ref) and recycled concrete (C-100–100) at 7, 28 and 70 days of exposure. It is evident from the figure that the carbonation depth increases with the time of curing and the amount of recycled materials.

According to Silva et al. [39], the use of 100% RCA alone may increase carbonation depths as much twice in depth as that of concrete made from natural aggregates. The depth increases further when RFA are incorporated. In this study, recycled concrete made of 100% RCA and 100% RFA exhibit carbonation depths only 1.36 times higher than the reference concrete at 70 days of exposure.

4.3.2. The influence of recycled ultrafine particles

In this study, concrete made of recycled coarse and fine aggregates (C-100-100) has already displayed a promising property, yet, it is further optimized by incorporating recycled concrete ultrafine products and glass powder. RCU product has been added at 5% and 10%, whereas RGU has been added at 3% (by wt.). The addition of these ultrafine products is either as cement replacement or limestone replacement (as an additive). Fig. 6 shows the development of compressive strength for concrete samples made of recycled coarse, fine and ultrafine products. As shown in the figure, all samples show a gradual increase in compressive strength. It is clear that substituting cement with RCU or RGU displayed 12.8% decrease in compressive strength compared to the parent concrete (C-100-100). This phenomenon could be due to the presence of glass powder in the system. As Jawed and Skalny [40] reported, the presence of alkaline ions in cement decreases the solubility of Ca^{2+} ions to form hydrated phases, inhibiting or delaying the pozzolanic reaction at older ages (90 days and more). Furthermore, Moreno-Juez et al. [26] have observed a decrease in mechanical properties when more than 5% of RCU are used, and recommends not to exceed 5% replacement. Nevertheless, substituting the limestone with RCU and RGU at 5% and 3%, respectively, show almost similar compressive strength as the parent concrete (C-100-100). This suggests the use of both ultrafine products as an additive is a feasible recommendation according to this particular study. Although it is difficult to examine which ultrafine causes most of the weakness, the aforementioned effect of the RGU is most likely for the negative influence on the hydration progress.

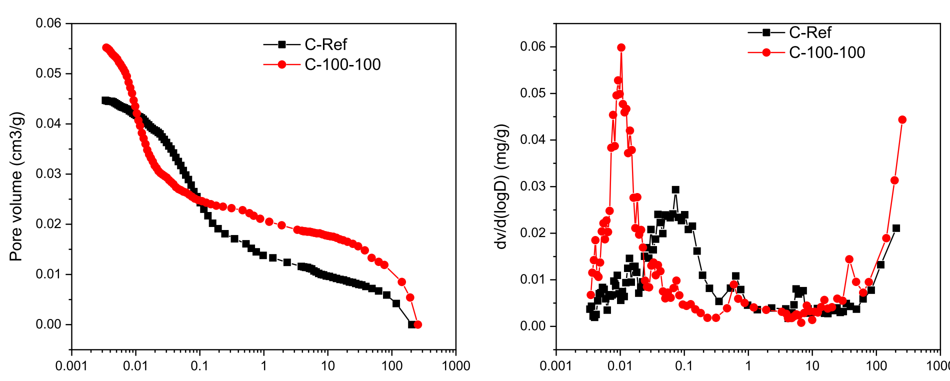

Fig. 4. Comparison of pore volume and pore size distribution of recycled concrete (C-100-100) and reference concrete (C-Ref).

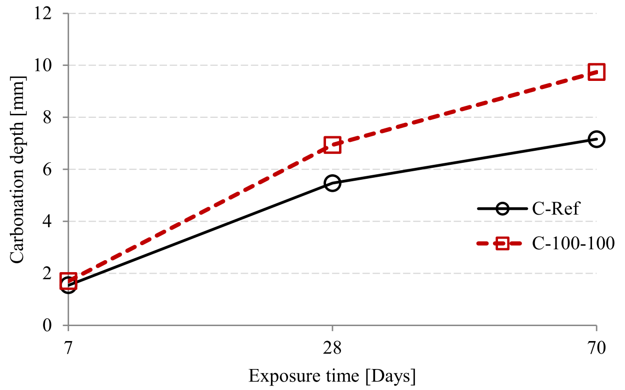

Fig. 5. Carbonation depth for recycled concrete (C-100-100) and reference concrete (C-Ref).

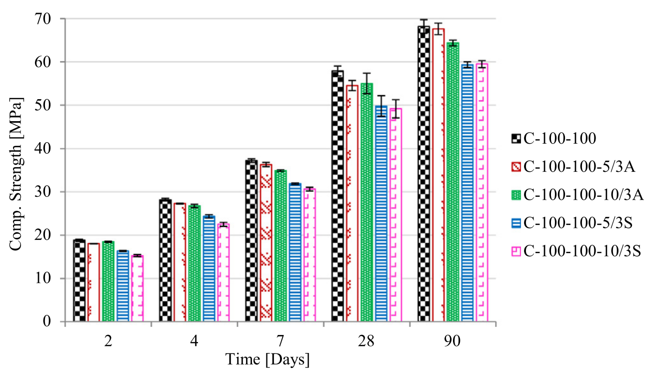

Fig. 6. Compressive strength of recycled concrete made of coarse, fine and ultrafine particles retrieved from CDW.

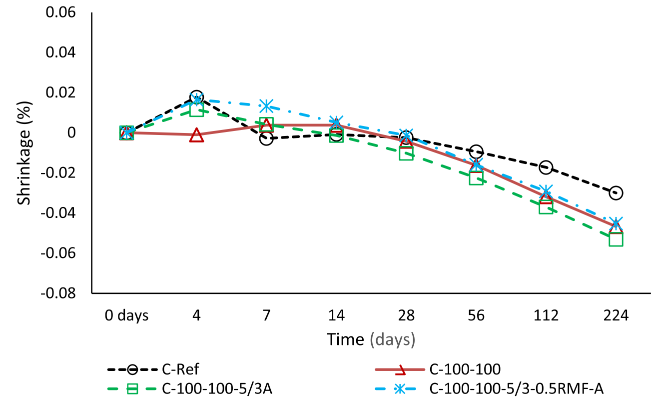

Fig. 7. Shrinkage of recycled concrete made of coarse, fine and ultrafine particles retrieved from CDW (negative values imply shrinkage and positive values for expansion).

Shrinkage of concrete is often a reason for cracking, providing easy access for oxygen, moisture, chlorides and other aggressive chemicals into the matrix, and can therefore impact the long-term durability of concrete. Drying shrinkage occurs by several factors, among which the ingredients of the mix and their proportion, design, and construction practices and environmental influences are the foremost. However, the effect of water and coarse aggregate content is profound. As the amount of coarse aggregate content increases, the total water and paste contents of the concrete mixture reduces, causing lower drying shrinkage. Drying shrinkage occurs when the adsorbed water is lost from the hydrated cement paste. Thus, it can be minimized by keeping the total water content as low as is practically possible. When admixtures are used, the volume of fine pores in the hydration product increases, resulting an increase in the drying shrinkage.

Shrinkage may induce cracking that can severely decrease the life of the concrete. According to the literature, concrete made of recycled aggregates exhibits higher drying shrinkage than the reference concrete [41,42]. It is mainly associated with volume changes attributed to the drying of concrete over a period of curing. Drying shrinkage is due to the stress developed owing to the loss of water as the concrete matures. The stress developed pulls the cement paste closer and cause a reduction in volume. According to the Laplace equation, the stress (capillary pressure) is inversely related to the diameter of the pore ($s = 2\delta/r$). Fig. 7 displays the shrinkage of recycled concrete at different curing ages, where the negative values indicate shrinkage. The fact that recycled concretes show smaller pore diameters relative to the reference aggregates is manifested by the higher shrinkage noticed for recycled concrete (C-100-100). When both coarse and fine natural aggregates are fully replaced, drying shrinkage of the recycled concrete becomes 56% higher than the corresponding control concrete made of natural aggregates (C-Ref). The presence of an old cement paste matrix on the aggregate surface may cause higher shrinkage due to reducing the restraining effect of aggregates on shrinkage. When recycled ultrafines are used as an additive in the mix design, the drying shrinkage becomes a lot higher (77% higher than C-Ref). When RMF are used along with RCU, drying shrinkage decreases compared to C-100-100-5/3A but still higher than the reference concrete.

4.3.3. The influence of recycled mineral fibres

The high aspect ratio and the composition of mineral fibres make them a potential candidate to reinforce concrete structures. The incorporation of mineral fibres into concrete is intended to improve the characteristic weakness of concrete to tensile or flexural loads. According to Ramirez et al. [28,43], the addition of 50% mineral fibres into a mortar has resulted in 12% increase in flexural and tensile strength compared to unreinforced mortar reference samples, but the compressive strength suffers 3–10% decrease. Piñeiro et al. [44] also applied recycled mineral wool in gypsum composites and found difficulties in the workability aspects. Otherwise, its distribution within the matrix was noticed uniform and an increase in flexural strength was observed. In this study, the objective of using mineral fibres is intended to improve the resistance to tensile loads while saving mineral resources at the same time. The fact that the addition of such fibres greatly influences the workability of the concrete mix, its amount has been limited to 0.5% of cement (by wt.). In this particular study, RMF has been used in the concrete either as cement replacement (S) or as an additive replacing limestone (A). Fig. 8 shows the trend in compressive strength of concrete samples made of RCA, RFA, RCU, RGU and RMF. When recycled RMFs are used in concrete (as cement replacement or as an additive), the compressive strength of the concrete decreases. The sample made by addition of 0.5% RMF as an additive (C-100-100-5/3A-0.5RMF-A) displays 5.8% decrease in compressive strength compared to the sample made of recycled aggregates and ultrafines without RMF (C-100-100-5/3A). Such observation is not different from literature where the use of such fibers in cement mortar was found to cause a minor increase in porosity, and slight decreases in density, which could result in a slight decrease in compressive strength [43,44].

On the other hand, the tensile strength and the flexural strength of the sample made of RMF has increased compared to the concrete sample made without mineral fibres (C-100-100-5/3A). As shown in Fig. 9, the flexural strength of the sample made with RMF

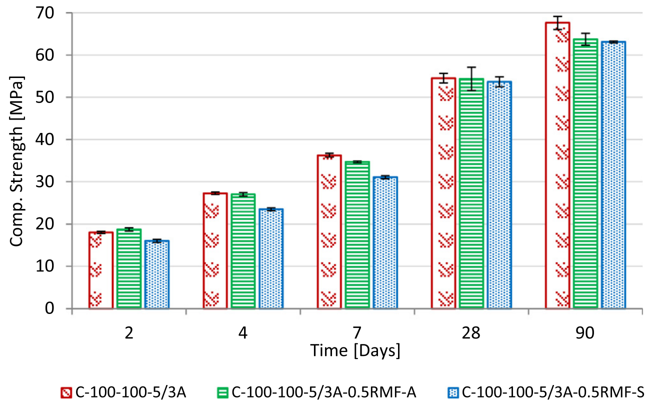

Fig. 8. Compressive strength of recycled concrete made of coarse, fine, and ultrafine particles with minor inclusion of mineral fibres retrieved from CDW.

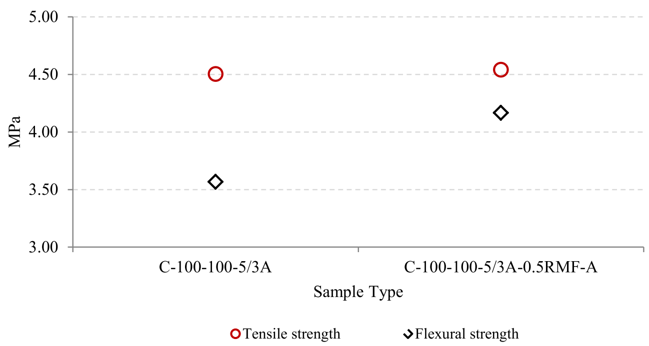

Fig. 9. Impact of mineral fibres on the tensile strength and flexural strength of recycled concrete at 28 days.

(100-100-5/3A-0.5RMF-A) increases by 16.7% compared to C-100-100-5/3A, yet the tensile strength remains similar at the 28th day of curing. The increase in tensile strength is rather visible at 90 days. This may mean that recycled mineral fibres effectively strengthen the cement matrix by increasing its resistance to cracking caused by tensile stress before they are broken or pulled out of the cement matrix. As shown in Fig. 10, the concrete sample (100-100-5/3A-0.5RMF-A) displays 6.2% increase in tensile strength at 90 days compared to 100-100-5/3A. The amount of increase at such small dosing (0.5% of cement + SCM) suggests their potential as additives in a concrete mix.

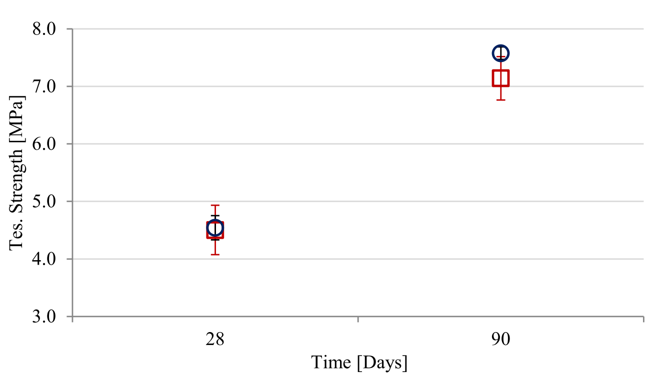

Fig. 10. The impact of mineral fibres on the tensile strength recycled concrete with time.

The microstructure of the concrete made with RMF (100-100-5/3A-0.5RMF-A) has been observed with scanning electron microscopy (SEM). As shown in Fig. 11, fibres are observed in clusters sporadically, which may suggest homogenizing fibres within the concrete matrix may not be an issue. In fact, fibres seem to be broken at the interface suggesting effective reinforcement. The surface of mineral fibres seems to be clean, which indicates no bonding was observed between the cement hydration products and the mineral fibre; thus, fibre pull-out may be experienced at a higher dosage.

The elastic modulus (E_c) of a concrete quantifies the material's ability to deform elastically and is an essential mechanical parameter used in design. The modulus of elasticity has been examined for four selected concrete samples. Fig. 12 shows a decrease in modulus of elasticity as the amount of recycled material in the mix increases. This behaviour is directly related to the concrete's compressive strength, except that the large decrease in modulus of elasticity is due to the addition of coarse and fine aggregates, whereas the large reduction in compressive strength is due to the addition of recycled ultrafines.

Several empirical relationships have been suggested by various investigators to relate the modulus of elasticity of concrete to its compressive strength (f_{cu}) [23,45–47]. In this study, two models have been used to correlate the modulus of elasticity of recycled aggregates with the compressive strength. According to Xiao et al. [45], a statistical regression analysis of the collected experimental results is used to estimate the elastic modulus (E_c) of recycled concrete. The correlation between elastic modulus (E_c) and the compressive strength (f_{cu}) of recycled concrete is given as:

$$E_c = \frac{10^5}{2.8 + \frac{40.1}{f_{cu}}}$$

Kakizaki et al. [46] also correlated the mass density of the recycled aggregate concrete with its compressive strength (f_{cu}) to come to an empirical relationship to calculate the elastic modulus (E_c) as;

$$E_c = 1.9 \times 10^5 \times \left(\frac{\rho}{2300}\right) \times \sqrt{\frac{f_{cu}}{2000}}$$

The above two empirical formulas are used to evaluate the experimentally measured elastic modulus (E_c) of recycled aggregates and further estimate the elastic modulus of samples whose (E_c) has not been experimentally measured in this study. Fig. 13 shows the relationship between E_c and f_{cu} of recycled concrete predicted by models. Based on such model, the E_c of recycled concrete is estimated. Accordingly, the experimentally measured E_c values lie in between the trend lines given by the two models, suggesting the relevance of these models in predicting the E_c. These types of empirical relationships are diverse in the literature and may not be reliable. Nonetheless, based on these two models, it can be deduced the E_c values for recycled concrete in this study varies 24 – 28 GPa, the highest being for C-100-0 and the lowest for C-100-100-5/3S.

Generally, this study has revealed the feasibility of using recycled aggregate resources and other products recovered from CDW. The use of properly sorted, processed and recycled materials are vital resources that need to be seriously considered. Although the quality of recycled aggregate depends on the quality of the original concrete [48] and the method of crushing [49], the amount of adhered mortar on the aggregate surface has a significant effect on the performance of recycled aggregates. It has been demonstrated in this study that the most sustainable concrete (C-100-100-5/3A-0.5RMF) comprising 100% RCA, 100% RFA, 5% RCU, 3% RGU and 0.5% RMF, has displayed compressive strength of 63.7 MPa, which is 11.7% lower than the reference concrete (C-Ref = 72.2 MPa), yet within the limit for structural applications. From

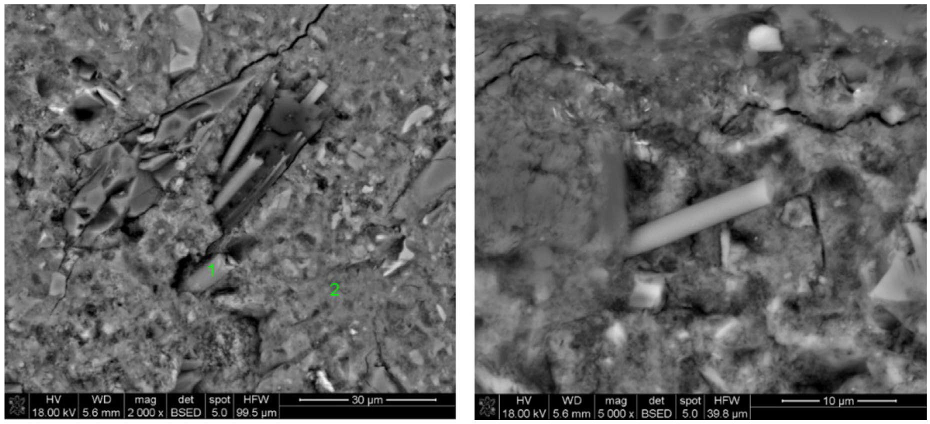

Fig. 11. SEM micrograph of 100-100-5/3A-0.5RMF-A at fibre locations

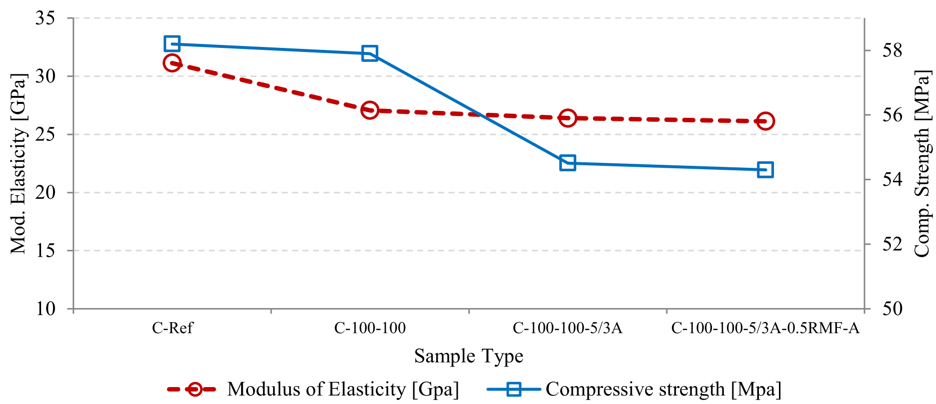

Fig. 12. The trend in modulus of elasticity for different representative recycled concrete samples.

the perspective of material usage, the most sustainable concrete recipe saves 75% of natural aggregates that would have been used in normal concrete design. We believe, it is time for recycled aggregated to get the attention they deserve in the near future. The added value of using most of recycled concrete products as a replacement of natural components in a concrete mix could be seen from different perspectives: firstly, it does not adversely affect the behaviour of recycled concrete, in fact some mechanical properties are improved; secondly, it has got environmental benefits (saves emission of CO_2), and thirdly, resources are efficiently utilized in a more circular manner bringing about a reduction in quarrying for natural resources and limiting landfilling.

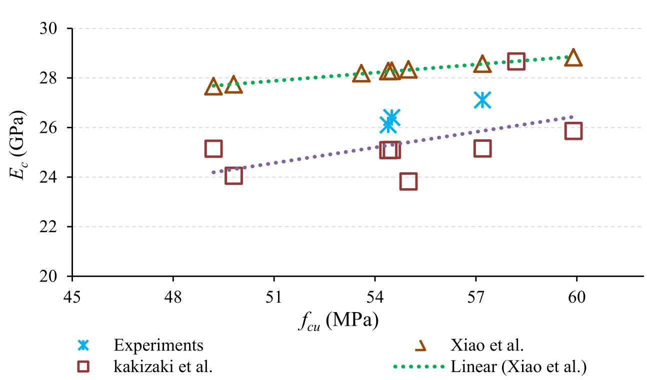

Fig. 13. Relationship between the elastic modulus, E_c, the compressive strength, f_{cu} of RAC and experimental values.

5. Conclusion

This study presents the feasibility of using coarse and fine recycled aggregates in a concrete mix for structural purposes and examines the possibility of using other recycled products retrieved from C&D activities such as cement-rich hydrated powder, recycled glass powder, and recycled mineral fibres. The study revealed the possibility of designing the most green and sustainable concrete that contains more than 75% (by weight) recycled components retrieved from C&D activities. Furthermore, it demonstrates the viability of the full use of recycled concrete aggregates valued through the novel technology ADR + HAS in new eco-designed concretes that strongly improve consumer confidence and raise awareness to promote the use of recycled aggregates in high value-added applications. This study allows a breakthrough in the reduction of natural resources extraction, the elimination of potentially valuable CDW and is in line with the objectives of sustainability and climate change established by the European Commission in "The European Green Deal [50]" and the "Circular Economy Action Plan [51]". Based on the results achieved in this study, the following major conclusions are drawn:

- It is possible to fully replace natural coarse and fine aggregates with recycled coarse and fine aggregates without compromising the mechanical properties of the concrete. The use of the novel technology (ADR + HAS) allows to improve the performance of recycled aggregates and, therefore, the behaviour of recycled concrete with a total substitution of both coarse and fine aggregates. This gives the opportunity of shifting the construction sector into completely circular practice.

- The addition of cement paste rich recycled powder is limited to only 5%. Further addition of glass powder from CDW somewhat deteriorates the mechanical strength of recycled concrete. This may be due to the solubility of Ca^{2+} ions that inhibit the pozzolanic reaction at early ages. Further studies should be performed to understand the behaviour of the glass powder at advanced ages.
- Incorporation of mineral fibres may have some benefits on the tensile strength and modulus of elasticity of recycled concrete, however, their amount at lower percentages of addition affects the workability of recycled concrete. The use of such fibres at higher ratios may complicate the workability and durability of recycled concrete.
- As the amount of recycled aggregates and products used in the concrete mix increases, the density decreases. This can be taken as an advantage in designing lightweight buildings and thermal insulation cement-based products while maintaining mechanical performance.

CRediT authorship contribution statement

Abraham T. Gebremariam: Conceptualization, Investigation, Formal analysis, Methodology, Data curation, Writing - original draft, Writing - review & editing. **Ali Vahidi:** Investigation, Methodology, Data curation, Reviewing & editing. **Francesco Di Maio:** Conceptualization, Funding acquisition, Methodology, Project administration, Reviewing & editing. **J. Moreno-Juez:** Conceptualization, Data curation, Methodology, Investigation, Writing - review & editing. **I. Vegas-Ramiro:** Conceptualization, Funding acquisition, Project administration, Reviewing & editing. **Artur Łagosz:** Data curation, Methodology, Investigation, Reviewing & editing. **Radosław Mróz:** Data curation, Methodology, Investigation, Writing - review & editing. **Peter Rem:** Conceptualization, Methodology, Visualization, Reviewing & editing.

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.

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References

[1] European Commission, Sustainable products in a Circular Economy, Brussels, 2019. Accessed on Feb, 2020.
[2] L.C.M. Eberhardt, M. Birkved, H. Birgisdottir, Building design and construction strategies for a circular economy, Archit. Eng. Des. Manag. (2020) 1–21, https://doi.org/10.1080/17452007.2020.1781588.
[3] M. Wahlström, J. Bergmans, T. Teittinen, J. Bachér, A. Smeets, A. Paduart, Construction and Demolition Waste: Challenges and opportunities in a circular economy, Boeretang, Belgium, 2020. https://www.eea.europa.eu/themes/waste/waste-management/construction-and-demolition-waste-challenges, Accessed on March 2020.
[4] T.C. Hansen, Recycling of Demolished Concrete and Masonry, CRC Press LLC, London, 1992. https://doi.org/https://doi.org/10.1201/9781482267075.
[5] Y. Menard, K. Bru, S. Touze, A. Lemoign, J.E. Poirier, G. Ruffie, F. Bonnaudin, F. Von Der Weid, Innovative process routes for a high-quality concrete recycling, Waste Manag. 33 (2013) 1561–1565, https://doi.org/10.1016/j.wasman.2013.02.006.
[6] K. Bru, S. Touzé, F. Bourgeois, N. Lippiatt, Y. Ménard, Assessment of a microwave-assisted recycling process for the recovery of high-quality aggregates from concrete waste, Int. J. Miner. Process. 126 (2014) 90–98, https://doi.org/10.1016/j.minpro.2013.11.009.
[7] K. Kalinowska-Wichrowska, E. Pawluczuk, M. Bołtryk, Waste-free technology for recycling concrete rubble, Constr. Build. Mater. 234 (2020), https://doi.org/10.1016/j.conbuildmat.2019.117407 117407.
[8] H. Shima, H. Tateyashiki, R. Matsuhashi, Y. Yoshida, An advanced concrete recycling technology and its applicability assessment through input-output analysis, J. Adv. Concr. Technol. 3 (2005) 53–67, https://doi.org/10.3151/jact.3.53.
[9] M.V.A. Florea, Z. Ning, H.J.H. Brouwers, Smart crushing of concrete and activation of liberated concrete fines, Eindhoven, 2013. https://slimbreker.nl/downloads/SC1 Final Report.pdf, Accessed on July, 2019.
[10] A. Akbarnezhad, K.C.G. Ong, M.H. Zhang, C.T. Tam, T.W.J. Foo, Microwave-assisted beneficiation of recycled concrete aggregates, Constr. Build. Mater. 25 (2011) 3469–3479, https://doi.org/10.1016/j.conbuildmat.2011.03.038.
[11] M. Shigeishi, Separation and collection of coarse aggregate from waste concrete by electric pulsed power, AIP Conf. Proc. 1887 (2017), https://doi.org/10.1063/1.5003560.
[12] A.T. Gebremariam, F. Di Maio, A. Vahidi, P. Rem, Innovative technologies for recycling End-of-Life concrete waste in the built environment, Resour. Conserv. Recycl. 163 (2020) 104911, https://doi.org/10.1016/j.resconrec.2020.104911.
[13] W. De Vries, P.C. Rem, S.P.M. Berkhout, ADR: A new method for dry classification, in: Int. Solid Waste Assoc., 2009: pp. 1–10. https://www.iswa.org/uploads/tx_iswaknowledgebase/paper34.pdf.
[14] W. De Vries, ADR: The use of Advanced Dry Recovery in recycling fine moist granular materials, Delft University of Technology (2017), https://doi.org/10.4233/uuid:c3c8578d-fd2c-493f-b4c5-79e63bc6d70c.
[15] S. Omary, E. Ghorbel, G. Wardeh, Relationships between recycled concrete aggregates characteristics and recycled aggregates concretes properties, Constr. Build. Mater. 108 (2016) 163–174, https://doi.org/10.1016/j.conbuildmat.2016.01.042.
[16] Z. Zhao, S. Remond, D. Damidot, W. Xu, Influence of fine recycled concrete aggregates on the properties of mortars, Constr. Build. Mater. 81 (2015) 179–186, https://doi.org/10.1016/j.conbuildmat.2015.02.037.
[17] A. Nataatmadja, Y.L. Tan, Resilient response of recycled concrete road aggregates, J. Transp. Eng. 127 (2001) 450–453, https://doi.org/10.1061/(ASCE)0733-947X(2001)127:5(450).
[18] C.S. Poon, D. Chan, Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base, Constr. Build. Mater. 20 (2006) 578–585, https://doi.org/10.1016/J.conbuildmat.2005.01.045.
[19] C.S. Poon, X.C. Qiao, D. Chan, The cause and influence of self-cementing properties of fine recycled concrete aggregates on the properties of unbound sub-base, Waste Manag. 26 (2006) 1166–1172, https://doi.org/10.1016/j.wasman.2005.12.013.
[20] D. Xuan, B. Zhan, C.S. Poon, Durability of recycled aggregate concrete prepared with carbonated recycled concrete aggregates, Cem. Concr. Compos. 84 (2017) 214–221, https://doi.org/10.1016/j.cemconcomp.2017.09.015.
[21] F. Cartuxo, J. De Brito, L. Evangelista, J.R. Jiménez, E.F. Ledesma, Increased durability of concrete made with fine recycled concrete aggregates using superplasticizers, Materials (Basel). 9 (2016), https://doi.org/10.3390/ma9020098.
[22] Z. Shui, D. Xuan, H. Wan, B. Cao, Rehydration reactivity of recycled mortar from concrete waste experienced to thermal treatment, Constr. Build. Mater. 22 (2008) 1723–1729, https://doi.org/10.1016/j.conbuildmat.2007.05.012.
[23] N.K. Bui, T. Satomi, H. Takahashi, Mechanical properties of concrete containing 100% treated coarse recycled concrete aggregate, Constr. Build. Mater. 163 (2018) 496–507, https://doi.org/10.1016/j.conbuildmat.2017.12.131.
[24] A. Bordy, A. Younsi, S. Aggoun, B. Fiorio, Cement substitution by a recycled cement paste fine: role of the residual anhydrous clinker, Constr. Build. Mater. 132 (2017) 1–8, https://doi.org/10.1016/j.conbuildmat.2016.11.080.
[25] L. Oksri-Nelfia, P.Y. Mahieux, O. Amiri, P. Turcry, J. Lux, Reuse of recycled crushed concrete fines as mineral addition in cementitious materials, Mater. Struct. Constr. 49 (2016) 3239–3251, https://doi.org/10.1617/s11527-015-0716-1.
[26] J. Moreno-Juez, I.J. Vegas, A.T. Gebremariam, V. García-Cortés, F. Di Maio, Treatment of end-of-life concrete in an innovative heating-air classification system for circular cement-based products, J. Clean. Prod. 263 (2020), https://doi.org/10.1016/j.jclepro.2020.121515.
[27] D. Gastaldi, F. Canonico, L. Capelli, L. Buzzi, E. Boccaleri, S. Irico, An investigation on the recycling of hydrated cement from concrete demolition waste, Cem. Concr. Compos. 61 (2015) 29–35, https://doi.org/10.1016/j.cemconcomp.2015.04.010.
[28] C.P. Ramírez, E.A. Sánchez, M. del R. Merino, C.V. Arrebola, A.V. Barriguete, Feasibility of the use of mineral wool fibres recovered from CDW for the reinforcement of conglomerates by study of their porosity, Constr. Build. Mater. 191 (2018) 460–468. doi: 10.1016/j.conbuildmat.2018.10.026.
[29] R. Yu, Z. Shui, Efficient reuse of the recycled construction waste cementitious materials, J. Clean. Prod. 78 (2014) 202–207, https://doi.org/10.1016/j.jclepro.2014.05.003.
[30] V.W.Y. Tam, X.F. Gao, C.M. Tam, Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach, Cem. Concr. Res. 35 (2005) 1195–1203, https://doi.org/10.1016/j.cemconres.2004.10.025.
[31] K.P. Verian, W. Ashraf, Y. Cao, Properties of recycled concrete aggregate and their influence in new concrete production, Resour. Conserv. Recycl. 133 (2018) 30–49, https://doi.org/10.1016/j.resconrec.2018.02.005.

[32] M. Malešev, V. Radonjanin, S. Marinković, Recycled concrete as aggregate for structural concrete production, Sustainability 2 (2010) 1204–1225, https://doi.org/10.3390/su2051204.
[33] K.P. Verian, N. Whiting, J. Olek, J. Jain, M. Snyder, Using Recycled Concrete as Aggregate in Concrete Pavements to Reduce Materials Cost, (2013). doi: 10.5703/1288284315220.
[34] S. Diamond, Mercury porosimetry. An inappropriate method for the measurement of pore size distributions in cement-based materials, Cem. Concr. Res. 30 (2000) 1517–1525. doi: 10.1016/S0008-8846(00)00370-7.
[35] J.M.V. Gómez-Soberón, Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study, Cem. Concr. Res. 32 (2002) 1301–1311, https://doi.org/10.1016/S0008-8846(02)00795-0.
[36] K.S. and T. Ayano, Improvement of Concrete with Recycled Aggregate, ACI Symp. Publ. 192 (n.d.). doi: 10.14359/5803.
[37] ilker B. Topçu, N.F. Günçan, Using waste concrete as aggregate, Cem. Concr. Res. 25 (1995) 1385–1390. doi: 10.1016/0008-8846(95)00131-U.
[38] J. Xiao, J. Li, C. Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, Cem. Concr. Res. 35 (2005) 1187–1194, https://doi.org/10.1016/j.cemconres.2004.09.020.
[39] R.V. Silva, R. Neves, J. De Brito, R.K. Dhir, Carbonation behaviour of recycled aggregate concrete, Cem. Concr. Compos. 62 (2015) 22–32, https://doi.org/10.1016/j.cemconcomp.2015.04.017.
[40] I.J. and J. Skanly, Alkalies in cement: a review: II. Effects of alkalies on hydration and performance of Portland cement, Cem. Concr. Res. 9 (1978) 37–52. doi: 10.1016/0008-8846(78)90056-X.
[41] J.M. Khatib, Properties of concrete incorporating fine recycled aggregate, Cem. Concr. Res. 35 (2005) 763–769, https://doi.org/10.1016/j.cemconres.2004.06.017.
[42] V. Corinaldesi, G. Moriconi, Influence of mineral additions on the performance of 100% recycled aggregate concrete, Constr. Build. Mater. 23 (2009) 2869–2876, https://doi.org/10.1016/j.conbuildmat.2009.02.004.
[43] C. Piña Ramírez, M. del Río Merino, C. Viñas Arrebola, A. Vidales Barriguete, M. Kosior-Kazberuk, Analysis of the mechanical behaviour of the cement mortars with additives of mineral wool fibres from recycling of CDW, Constr. Build. Mater. 210 (2019) 56–62. doi: 10.1016/j.conbuildmat.2019.03.062.
[44] S.R. Piñeiro, M. Del Río Merino, C. Pérez García, New plaster composite with mineral wool fibres from CDW recycling, Adv. Mater. Sci. Eng. (2015 (2015).), https://doi.org/10.1155/2015/854192.
[45] J.Z. Xiao, J.B. Li, C. Zhang, On relationships between the mechanical properties of recycled aggregate concrete: an overview, Mater. Struct. Constr. 39 (2006) 655–664, https://doi.org/10.1617/s11527-006-9093-0.
[46] K.Y. Kakizaki M, Harada M, Soshiroda T, Kubota S, Ikeda T, Strength and elastic modulus of recycled aggregate concrete, in: Proc. 2nd Int. RILEM Symp. Demolition Reuse Concr. Mason., Tokio, Japan, 1988: pp. 565–574.
[47] A. Behnood, J. Olek, M.A. Glinicki, Predicting modulus elasticity of recycled aggregate concrete using M5′ model tree algorithm, Constr. Build. Mater. 94 (2015) 137–147, https://doi.org/10.1016/j.conbuildmat.2015.06.055.
[48] M. Bravo, J. De Brito, J. Pontes, L. Evangelista, Durability performance of concrete with recycled aggregates from construction and demolition waste plants, Constr. Build. Mater. 77 (2015) 357–369, https://doi.org/10.1016/j.conbuildmat.2014.12.103.
[49] A.K. Padmini, K. Ramamurthy, M.S. Mathews, Influence of parent concrete on the properties of recycled aggregate concrete, Constr. Build. Mater. 23 (2009) 829–836, https://doi.org/10.1016/j.conbuildmat.2008.03.006.
[50] European Commission, Communication from the Commission: The European Green Deal, Brussels,COM(2019) 640 final, 2019. https://doi.org/10.1017/CBO9781107415324.004.
[51] European Commission, A new Circular Economy Action Plan for a cleaner and more competitive Europe, Brussels, COM(2020)98, 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52019DC0640&from=EN.