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Mechanical and GWP assessment of concrete using Blast Furnace Slag, Silica Fume and recycled aggregate

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A B S T R A C T

Demolition waste and cement production is responsible for 36 % of total waste produced on earth and 8 % of the worlds CO_2 emissions, respectively. Due to limited research on concrete mixes containing ternary cementitious mixes (Ground Granulated Blast-furnace Slag (GGBS) and Silica Fume (SF)) and demolition waste, the paper reviewed the mechanical properties of concrete, and structural performance of reinforced beams. Thereafter, life cycle analysis (LCA) was investigated to understand the true environmental impact, focusing on Global Warming Potential (GWP). Results show that recycled concrete aggregates (RCA) had no significant negative impact on the compressive strength, tensile strength, and modulus of rupture of concrete. The inclusion of GGBS and SF in mixes containing RCA eliminated any negative impact and for all mixes produced greater strengths in comparison to the control mix, due to the secondary reaction of Ca $(OH)_2$ and pore refinement. The flexural behaviour of the concrete beams with 0 %, 25 %, 50 % and 100 % RCA, 25 % GGBS and 5 % SF is similar. LCA results showed that replacing NA with 25 %, 50 % or 100 % RCA has no significant impact on the GWP emissions. This is because of the similar emissions associated with manufacturing and processing of recycled and natural aggregates. However, replacing cement with 5 % SF and 25 % GGBS improves the GWP environmental response of concrete significantly. Additionally, natural aggregates have a higher GWP contribution than that of recycled concrete aggregates by almost 80 % since the process of NA required quarry operation and transportation while the RCA are produced on site from an existing building waste.

1. Introduction

Cement is the source of around 8 % of the world's CO_2 emissions [1], mainly due to the energy that is required to produce clinker from the raw materials. Construction and demolition waste (CDW) accounts for approximately 36 % of total waste produced on earth, with the countries in the European Union reaching up to 850 million tons of waste each year [2]. With the consumption of Ordinary Portland Cement (OPC) set to rise to 5.2 billion tonnes by 2050, each ton of (OPC) roughly emitting 850 kg of CO_2 and CDW providing a sustainable alternative due to reduced reliance on Natural Aggregates (NA) and a reduction in waste sent to landfill, the use of Supplementary Cementitious Materials (SCMs) and Recycled Concrete Aggregates (RCA) requires greater implementation to produce a sustainable construction industry.

Ground Granulated Blast Furnace Slag (GGBS) and Silica Fume (SF) are by-product pozzolanic SCMs. They react with calcium

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hydroxide from the initial hydration of OPC to produce calcium silicate and aluminate hydrates that can supplement and, in some cases, enhance the strength of concrete when OPC is replaced by %wt [3]. GGBS is a by-product from the iron industry. Studies have shown that using GGBS as a SCM can provide greater compressive strength [4–6] flexural strength [7,8] and splitting tensile strength [8,9] when compared to a control mix (100 % OPC). Most studies reported a decrease in early age strength than that of the control mix, the strength at 28 days and onwards however, was higher. The increase in strength after 28days was primarily due to the Ca $(OH)_2$ from the initial hydration of OPC, reacting with the SiO_2 in GGBS to produce more Calcium-Silicate-Hydrate gels (C-S-H). SF has been shown to improve the strength properties of concrete due its high SiO_2 content and fineness [10–12] and is a by-product of induction arc furnaces in the silicon metal and ferrosilicon alloy industries [3]. The three roles that describe the mechanism of SF in concrete are pore size refinement/matrix densification, secondary hydration of Ca $(OH)_2$ and SiO_2 and cement paste-aggregate interfacial refinement [10].

Traditionally the use of SCMs have been as a binary blend (OPC+SCM), however, ternary blends (OPC + 2 SCMs) have shown to provide enhanced mechanical properties and a greater reduction in OPC usage when compared to binary blends. Vance et al. [13] concluded that ternary blend of metakaolin and limestone powder resulted in compressive strengths that were higher than either of the corresponding binary blends, even at a higher overall cement replacement level.Tavasoli et al. [14] reported that as SF was added to a mix consisting of 50 % OPC and 50 % GGBS, the compressive strength was enhanced, and resulted in a mix containing only 35 % OPC producing greater strengths than the control at 91 days. It is assumed that ternary blends of SF and GGBS can provide enhanced strengths at lower levels of OPC due to SF and GGBS producing excess C-S-H through the secondary reaction of SiO_2 and Ca $(OH)_2$, the fineness of SF and GGBS allowing for greater matrix densification and reactivity, as well as SiO_2 in SF reacting with the CaO in the GGBS resulting in excess C-S-H [3].

RCA that comes from construction and demolition waste provide an alternative solution to improve the sustainability of concrete. In 2016, construction and demolition waste accounted for nearly 36 % of the total solid waste in the EU [15], and with urbanisation ever increasing, it is likely that this figure will continue to grow. Currently the disadvantages with the incorporation of RCA is that they produce higher water absorption rates, greater porosity, greater shrinkage, and lower relative density than natural aggregates [16,17]. RCA have also been shown to have a negative impact on the mechanical properties of concrete. Pedro et al. [18] reported that the incorporation of RCA reduced the compressive strength of the concrete when compared to NA and losses obtained could be justified by the mortar fraction in the RCA. Singh et al. [19] stated that the issues which revolve around the utilisation of RCA in concrete, is the presence of adhered mortar which results in an increase in the number of finer particles, the formation of additional interfacial transition zones and RCA contaminated with chlorides, sulphates, etc.

Existing research has also focused on the combination of RCA and GGBS [20,21] and RCA and SF [20–22]. Studies concluded that SCMs can increase the compressive strength of RAC by 2–19 %, depending upon the type of SCM and age of curing [21] and at all ages tested, the compressive strength of the natural and recycled aggregate concrete made with 10 % SF are higher than the other corresponding concrete mixtures [20]. It is assumed that SCMs offset the reduction that is caused with the use of RCA due to the following mechanisms. Firstly, part of the mineral admixtures could penetrate the pores of RCA, which would subsequently improve the interfacial transition zone (ITZ) bonding between the paste and the aggregates and secondly, cracks originally present in the aggregates would be filled by hydration products due the reaction of OPC and water, as well as through secondary hydration products produced with the use of SCMs [20].

Although there are studies that have looked at the impact on the mechanical properties of binary cementitious blends with the addition of RCA, there is very limited research on the impact of ternary blends and RCA on the mechanical properties of concrete with a comparative life cycle analysis (LCA). Therefore, the paper aims to review the impact on key mechanical properties of concrete, and structural performance of reinforced beams, including the load-deflection responses, ultimate moment capacities, and cracking behaviour and patterns of concrete with a ternary cementitious mix and RCA. Thereafter, a thorough LCA will be investigated to understand the true environmental impact.

2. Experimental program

The experimental program is broken down into two stages. Firstly, sixteen concrete mixes with 0 %, 25 %, 50 %, and 100 % RCA replacement ratio, and 0 wt%, 5 wt%, 10 wt% and 15 wt% SF cement replacement were prepared. For all mixes, excluding the control mix, 25 % of OPC was replaced further with 25 wt% GGBS. The aim of this stage is to determine the compressive strength of mixes containing RCA, GGBS and SF and to investigate the quality of concrete using Ultrasonic Pulse Velocity (UPV) Test. In the second stage, four full scale steel reinforced concrete (RC) beams made from 25 %, 50 % and 100 % RCA replacement ratio, with 25 % of GGBS and 5 % of SF were tested until failure. A further control RC beam casted from natural aggregates and without SCMs was also examined, for comparison.

2.1. Material properties

2.1.1. Recycled concrete aggregates

The recycled concrete aggregates used in this study were prepared from demolition waste collected from an old concrete building (over 60 years old). This old concrete is considered a representative concrete of many buildings in the UK since most of the construction in this period will be demolished in future to give space for new buildings. The demolition concrete was pre crushed on site with a long reach 360 excavator to 250 mm maximum size and supplied to a TEREX J-1170 mobile jaw crusher for further crushing. The jaw crusher utilised powerful magnets to collect ferrous metals such as reinforcement bars. The demolition concrete waste was further

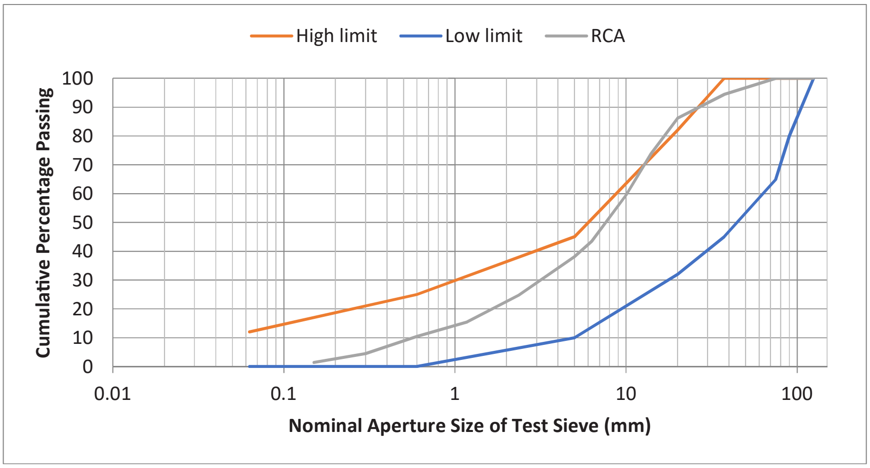


Fig. 1. Particle size distribution.

Table 1
Particle density and water absorption rate for the used aggregates.

	NA	Sand	RCA
Saturated surface dry density SSD (kg/m^3)	2413	2416	2282
Water absorption rate%	1.7	4.44	5.5

sieved using 20 mm and 5 mm sieves to ensure that the particle size of RCA is no more than 20 mm and no less than 5 mm and therefore, providing a suitable replacement for NA. Natural coarse aggregate with a maximum size of 10 mm and Thames River fine aggregate with a maximum size of 5 mm were used in the concrete mix. The particle size distribution curve for RCA is shown in the Fig. 1 and compared to the particle distribution of upper and lower limits according to BS EN 12620. It can be noted that the RCA curve is close to the upper BS limit. The particle density and the water absorption rate of NA, natural sand and RCA were identified using BS 812, as shown in the Table 1. As anticipated, the RCA showed a lower saturated surface dry density SSD and a considerably higher absorption ratio compared to the NA. Fig. 2 illustrates the RCA and NA used in this study.

2.1.2. *Ground Granulated Furnace Slag (GGBS) and Silica Fume (SF)*

GGBS was supplied by Francis Flower and has a specific surface of 490–540 m^2/kg, vitreous content of 90–100 % and pH > 10. The SF was supplied by Elkem Microsilica and has a specific surface area of 1500–3500 m^2/g. Based on the supplier's information and literature; Table 2 shows the chemical compositions of the cements mix material.

2.2. *Concrete Mix Design*

Sixteen concrete mixes were prepared using RCA, GGBS and SF to investigate the impact on concrete strength and quality. Table 3 provides the mix design in kg/m^3. For mixes, the first letter indicates the natural aggregates NA or the recycled concrete aggregates RCA with replacement ratio (i.e. 25RCA, 50RCA and 100RCA), the next number (0 or 25) refers to GGBS replacement ratio and the final number (again, 0, 5, 10 and 15) describes the SF replacement ratio. All concrete mixes were made with a water-to-cement ratio of 0.54. To avoid the discrepancies caused by the moisture content of the aggregates, RCA was oven dried for 24 h and both NA and sand were air dried inside the laboratory for 7 days. A C30/37 concrete mix with a target slump of 200 mm was designed using the BRE Concrete Mix Design [23]. The obtained SSD of the aggregates was used in the concrete mix design, in which the total volume of RCA plus NA in one cubic metre of concrete was kept at a constant for all concrete mixes. Additional water was added to the free water to account for the SSD state of the dried RCA.

To ensure the RCA had the sufficient time to absorb the water to achieve the SSD state, aggregates were mixed for two minutes then half of the water was added and mixed for 3–4 min, thereafter, the mix was left for 30 min. OPC, GGBS and SF were added slowly to the mixer to ensure that no dry balls developed, while the remaining water was slowly added and mixed for 3–4 min to ensure a uniform mix. Five standard 100 × 100 × 100 mm cubes for 28-day tests were prepared for the compressive and UPV tests. The moulds were removed on the following day and the concrete samples were stored in a curing tank at 20 °C.

2.3. *Beam tests*

In the second stage of this study, five reinforced concrete beams having various RCA replacement ratios and 25 % and 5 % GGBS

Fig. 2. RCA (left) and NA (right).

Table 2
Typical oxide composition (reported as oxide wt%) of cement mix materials.

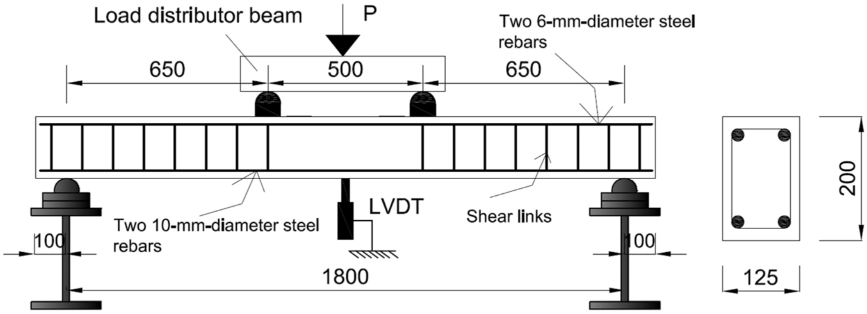
Chemical composition	GGBS (%)	SF (%)	OPC (%)
SiO_2	36	> 85	20.62
Al_2O_3	12.5		4.81
CaO	40	< 1	63.48
MgO	7.74		1.07
Fe_2O_3	0.5		2.71
Na_2O			0.21
K_2O			0.52
SO_3	0.1	< 2	3.10
P_2O_5			
TiO_2	0.9		
MnO	0.5		

and SF, respectively, were cast and tested. Beams were B-NA-0-0, B-NA-25-5, B-25RCA-25-5, B-50RCA-25-5 and B-100RCA-25-5. Fig. 3 provides the schematic views of the beam specimen configuration, including the reinforcement and geometrical details of the beam specimen and beam moulds displaying the reinforcement arrangements. In addition to the RC beams, five standard 100 × 100 × 100 mm cubes, three Ø150 × 300 mm cylinders and three 100 × 100 × 500 mm prismatic beams were cast from each batch to define the compressive strength (f_c), splitting tensile strength (f_t) and modulus of rupture (f_r) on the day of testing the beam.

All beams had a clear span of 1800 mm, with an overall length, width and depth of 2000 mm, 125 mm, and 200 mm, respectively. Two 10 mm diameter steel bars were used as the main longitudinal bottom reinforcement, whereas the top reinforcement in the compression region was steel with 6 mm bar diameter. The concrete clear cover was 20 mm. In all specimens, 8 mm shear stirrups were included at intervals of 100 mm in the shear region, to have a flexural failure at midspan of each beam, as seen in the Fig. 3(a).

Table 3
Concrete mixes.

Mix label	Cement	GGBS (0 % or 25 %)	SF (0–15 %)	Free Water	Additional Water for RCA SSD	Sand	NA	RCA
NA-0-0	463	0	0	250	0	631	836	0
NA-25-5	324	116	23	250	0	631	836	0
NA-25-10	300.7	116	46.3	250	0	631	836	0
NA-25-15	277.5	116	69.5	250	0	631	836	0
25RCA-0-0	463	0	0	250	10.9	631	627	198
25RCA-25-5	324	116	23	250	10.9	631	627	198
25RCA-25-10	300.7	116	46.3	250	10.9	631	627	198
25RCA-25-15	277.5	116	69.5	250	10.9	631	627	198
50RCA-0-0	463	0	0	250	21.7	631	418	395
50RCA-25-5	324	116	23	250	21.7	631	418	395
50RCA-25-10	300.7	116	46.3	250	21.7	631	418	395
50RCA-25-15	277.5	116	69.5	250	21.7	631	418	395
100RCA-0-0	463	0	0	250	43.5	631	0	791
100RCA-25-5	324	116	23	250	43.5	631	0	791
100RCA-25-10	300.7	116	46.3	250	43.5	631	0	791
100RCA-25-15	277.5	116	69.5	250	43.5	631	0	791



(a)

(b)

Fig. 3. Schematic views of the beam specimen configuration including (a) the reinforcement and geometrical details of the beam specimen (all dimensions in mm) and (b) beam moulds showing the reinforcement arrangements.

2.4. Instrumentation and testing procedure

To examine the quality of concrete, a UPV test was conducted on each hardened concrete cube before the compression test by direct transmission method in BS EN 12504-4 [24]. The time taken T (μs) by the pulse to travel from the transmitting transducer to the receiving transducer through the length of the specimen (L = 100 mm) was recorded to calculate the wave pulse velocity V (km/s) by dividing the pulse distance by transit time.

All beams were loaded under a four-point set-up to failure by using a hydraulic testing machine with a 250 kN capacity. The test was conducted under displacement control mode with a loading rate of 1 mm/min. A linear variable differential transducer (LVDT) was used to measure the deflection at the midspan of the beam. An automatic-data acquisition system connected to a personal computer was used to monitor loading and deflections. The crack propagation was monitored during the testing.

3. Life cycle analysis (LCA)

3.1. Goal and scope definition

The LCA is conducted to investigate the environmental benefits of using recycled concrete aggregate and cement replacement binders in concrete mixes used for structural frames in buildings and infrastructures, focusing on global warming potential measured in kg CO2 eq. This study analyses the mixes adopted in the experimental programme with the view that each of the 16 mixes is used to cast beams as part of a concrete building structural frame. The construction site considered for this research is assumed to be on the outskirts of an urban setting in the UK to facilitate the installation of onsite batching facilities for concrete production and recycled aggregate waste processing. An existing building to be demolished is assumed to be located on the site where the new building will be erected. In the scenario where a percentage of the aggregates in the concrete mixes adopted for the new concrete beams uses recycled aggregates, these are sourced from the existing building.

3.2. Assumptions

3.2.1. System boundary

Two main system boundaries were considered: one includes processes associated with the production of recycled aggregate and its adoption within the concrete mix (Fig. 4); the other considers natural aggregate only in the concrete mix (Fig. 5). For both systems a variable percentage of GGBS and SF is added to the concrete mix and the resulting functional unit CO2 emissions, calculated as kgCO2eq are compared with one another. The system boundaries for this study include all processes related to the sourcing and production of materials and construction of the beam but exclude impacts associated with its use and maintenance, as this is expected to be the same for all the mixtures considered [25]. Furthermore, this LCA follows a comparative 'cradle-to-laid' approach, also referred to as "cradle-to-end of construction" [26,27]. This approach is appropriate as all mixes considered within this research maintain a similar performance following their production so that the energy required to demolish the resulting structures would be equivalent.

3.2.2. Recycled aggregate

A 'cut-off' allocation approach is considered for the recycled concrete aggregate (RCA) environmental impact assessment, with the environmental burdens related to the building demolition not included in the system boundaries for this study [28]. The pertinence of following a cradle-to-end of construction approach for this LCA is detailed in Fig. 6, where those processes that would have similar performance for all mixes have been highlighted. For example, the existing building demolition required to make space on-site for the new building must be demolished in both the scenarios with or without RCA in the mix. Therefore, in a comparative study, this factor would not influence the study's outcome. Similarly, once the beams in the new building have been cast, the building maintenance won't be affected by the type of mix adopted for the structural frame.

Marinković et al. [38] supported the use of a no allocation method with a cut-off rule in evaluating the environmental impact of recycled aggregate concrete as proposed in this research. They compared the impact assessment results of three allocation methods - no allocation, mass allocation, and economic allocation - and found that the choice of allocation method had little impact on the overall assessment. This is because the impact of cement production, which is much larger than that of recycled aggregate production, dominates the overall impact assessment.

3.2.3. Silica Fume (SF) and Ground Granulated Blast Furnace Slag (GGBS)

Similarly, in the evaluation of the impact of resulting concrete mix with SF, a no allocation method was employed. Bajpai et al. [39] arrived at the same conclusion by noting that the by-products of silicon alloy plants, which SF is derived from, do not require separate manufacturing processes. As SF is considered a waste product, it is commonly believed to have no significant impact on the environment when used in concrete production. Additionally, as SF is a recovered material, the environmental impacts attributed to it are typically limited to the treatment and transportation necessary for its use as an input material in concrete production.

Furthermore, GGBS and SF are both by-products and only the processing and transport emissions related to these two materials are allocated for this assessment with any other emission due to steel and electricity production seen as not relevant or impactful [40].

3.2.4. Transport

A default distance of 100 km between the quarries and the site was assumed for the natural aggregate [29]. For the Recycled aggregate, this distance is dramatically reduced to a nominal 5 km to account for the use of onsite concrete batching and mixing plants. Furthermore, an average of 300 km and 50 km for GGBS and cement, respectively transport to the site has been assumed for this study [29].

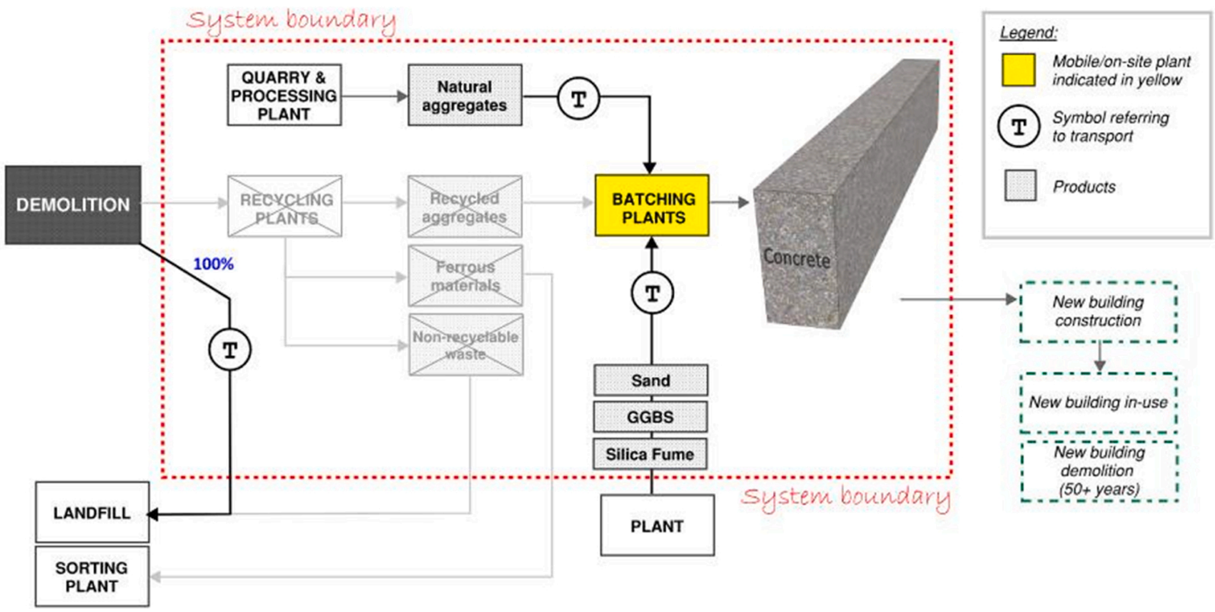


Fig. 4. System boundary and process for recycled aggregate concrete mixes.

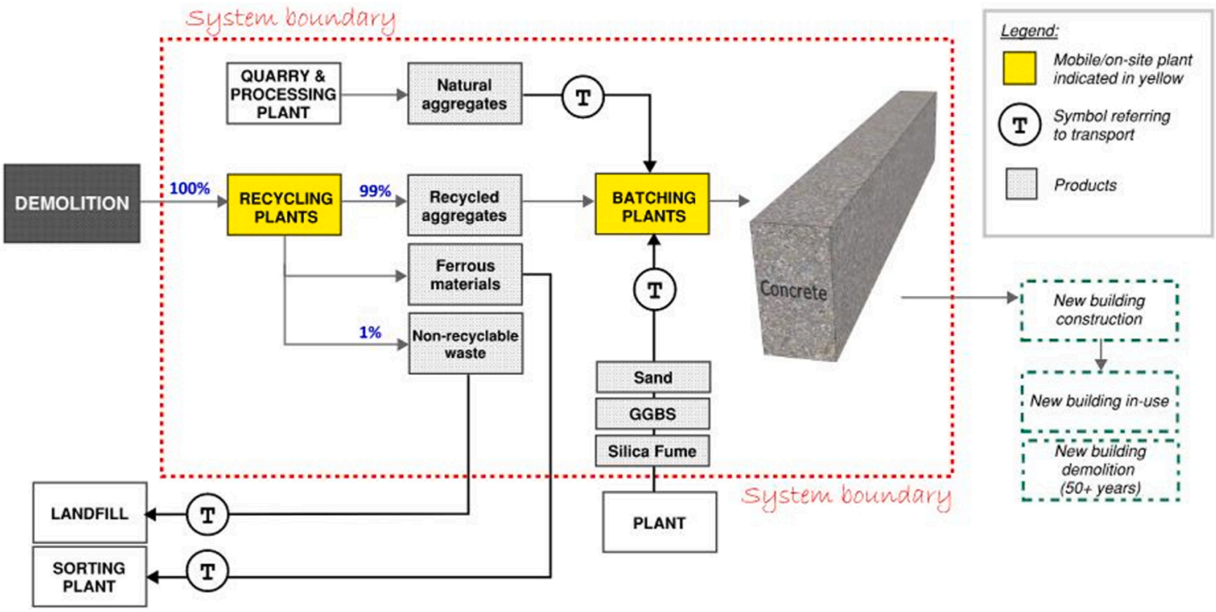


Fig. 5. System boundary and process for natural aggregate concrete mixes.

Material \ Process	Building Demolition	Quarry Operations	Transport	Production	Building Construction	End of Life
RCA	●	X	X	X	●	●
NA	●	X	X	X	●	●
CEMENT	●	X	X	X	●	●
SAND	●	●	●	●	●	●
GGBS	●	X	X	X	●	●
SILICA FUME	●	X	X	X	●	●

● Denotes those processes that are predicted to display similar environmental performance for the material noted.

X Denotes those processes that are material specific and have been included within the system boundary of this LCA.

Fig. 6. Materials and processes environmental performance matrix.

For the supplementary cementitious material (SCM), Silica Fume, transport was regarded as 50 km based on a survey conducted in [41].

3.2.5. Functional unit

In this research, the functional unit (FU) used for the life cycle assessment (LCA) is a concrete beam made using the mixes investigated. The quantities of each component are adjusted per unit volume of the FU, which is expressed as a cubic metre of concrete. This approach ensures that the composition of the FU matches that of the tested samples, including their associated strength. To calculate the reinforcement required for the functional unit, a 300 mm deep and 200 mm wide concrete beam has been considered, assuming a span of 5 m and an imposed uniform load equivalent to the beam self-weight. As such the overall reinforcement considered for the sample beam is equivalent to the minimum requirements from the BS EN 1992 [30].

3.3. Methodology

The software SimaPro, version 9.1.1 was used for modelling the LCA of the concrete functional unit. The Life Cycle Impact Assessment (LCIA) calculation methodology used in this study is ReCiPe 2016 Midpoint Hierarchist (H) created by RIVM, Radboud University, Norwegian University of Science and Technology and PRé Sustainability. Ecoinvent database version 3.6 is mainly adopted to source LCI data for this study. The commonly used midpoint characterisation factor for climate change is the global warming potential (GWP), which measures the total increase in infra-red radiative forcing caused by a greenhouse gas (GHG). GWP is typically expressed in kg CO2-eq.

3.4. Life Cycle Inventory (LCI)

Data was collected from the literature and information from the Ecoinvent 3 Life Cycle Inventory database. The energy required to process the construction and demolition waste (CDW) from the on-site concrete frame being demolished for adoption in the new concrete mix was considered. It is assumed that a mobile processing plant was installed beforehand on site, so that enough storage was available on site to store the CDW and the processed RCA. The consumable materials required for RCA production were 1.56 l/t water consumption; and 0.02 kg/t steel consumption [31]. A 99 % of the recycled CDW was assumed to be used within the new concrete mix [31]. The study has considered Borghi et al. [31] research on processing of 1 tonne recycled aggregates from construction waste, which reported that 0.64 litres of diesel, equivalent to 24.32 MJ/t.

4. Results and discussion

4.1. UPV

The quantity of RCA plays a significant role in the quality of concrete, as indicated by UPV results in Fig. 7. Results show that the UPV for mixes with 50 % and 100 % RCA is 4.3 % and 8 % lower than that for the NA concrete, respectively. Gómez-Soberón [32] reported that the porosity of RCA is around three times higher than the porosity of the NA due to the old mortar attached on the aggregates. However, using 25 % RCA has negligible effect on the UPV results. For NA mixes, replacing the cement with GGBS reduces the UPV values. As the SF percentage increases, the UPV value increases, indicating that the quality of concrete is enhanced. For mixes with 100 % RCA, as the SF percentage increases up to 10 %, the UPV value also increases. The concrete mix with 50 % RCA and 15 % SF provides the highest UPV value when compared to all mixes tested. It can be noted that concrete mixes with NA, 25 % RCA, 50 % RCA or 100 % RCA and 10–15 % SF produce a good quality mix as the UPV values being in the range of 3.6–4.5 km/s [33].

4.2. Compressive test

Fig. 8 provides the 28-day compressive strength for all mixes tested. Results show that RCA had no significant negative impact on

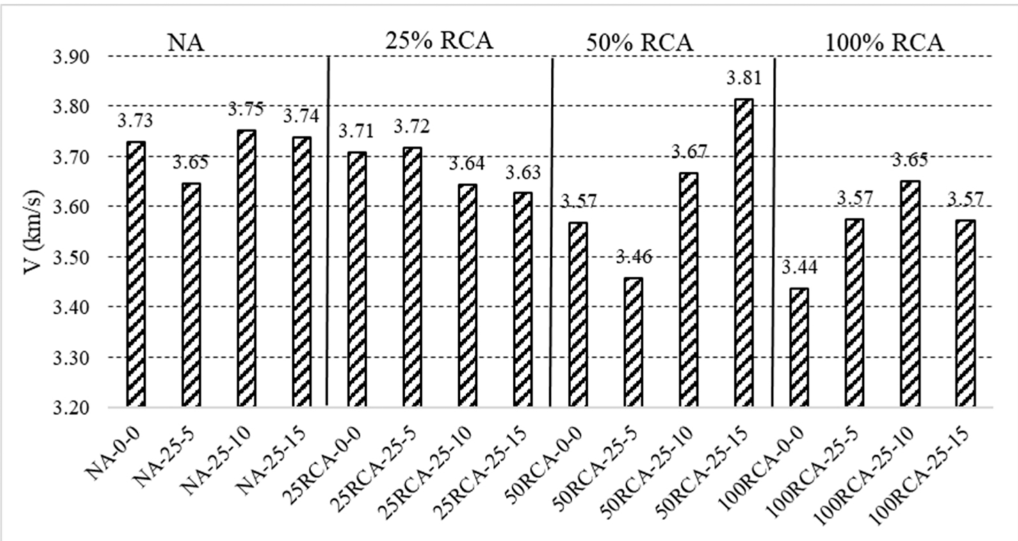


Fig. 7. UPV test results.

the compressive strength of concrete. The concrete mixes with and without RCA provided a similar compressive strength, except for those with 100 % RCA. The reduction in the compressive strength of concrete with 100 % RCA was only 13.5 % in comparisons with concrete made from NA. A similar finding was reported by Limbachiya et al. [3] and Alengaram et al. [34]. This is due to greater angularity and surface roughness of the RCA, resulting in better interlocking of aggregates and improved interfacial bond between aggregates and cement paste [35]. These two factors may help to compensate for the drop in compressive strength caused by weaker RCA. However, for concrete with 100 % RCA, the weakness of RCA is assumed to be due its angularity and surface roughness, hence, the compressive strength of produced concrete is reduced [34]. Replacing OPC with 25 % GGBS and only 5 % SF can mitigate the reduction in compressive strength of mixes from 100 % RCA. For this case, the compressive strength of the concrete 100RCA-25-5 is 11.7 % higher that for the concrete with full RCA (i.e. 100RCA-0-0).

For all concrete mixes, as the percentage of SF increased, the compressive strength of concrete increases. For example, for mixes without RCA and 25 % GGBS, adding 10 % SF increases the compressive strength of concrete by 33 % while mixes with 25 % RCA and 25 % GGBS, adding 5 % of SF increases the compressive strength of concrete by 17.5 %. Results show that the ternary mix of OPC, GGBS and SF work well in combination to offset the reduction in strength caused by RCA. It is assumed that this is due to the secondary reaction of $Ca(OH)_2$ from the initial of hydration of OPC and the SiO_2 in both the SF and GGBS resulting in the formation of Alite and Belite, the reaction of CaO and SiO_2 in GGBS and SF respectively and the fineness of SF resulting it a greater matrix densification.

4.3. Reinforced beams

Based on the results of the UPV and compressive strength, it can be concluded that adding 5 % SF and 25 % GGBS in RCA can enhance the concrete strength and improve the quality of concrete to the level comparable with the control mix. Hence, five beams (B-NA-0-0, B-NA-25-5, B-25RCA-25-5 B-50RCA-25-5, B-100RCA-25-5) were cast and tested to investigate the load-deflection responses, ultimate moment capacities, and cracking behaviour and patterns. Furthermore, the impact of ternary blends and RCA on the mechanical properties of produced concrete is analysed.

4.3.1. Mechanical properties of concrete

It can be noted form the Table 4 that replacing NA with 25 % and 50 % RCA has no significant negative impact on the compressive strength, tensile strength, and modulus of rupture of concrete. This is because the RCA aggregate surface roughness and angularity enhance the interfacial bond and mechanical. Furthermore, GGBS and SF contributing to the formation of Alite and Belite through the secondary reaction of Ca $(OH)_2$. For mixes with 100 % RCA, the compressive strength of concrete reduces by 9.8 % while the tensile strength and modulus of rupture of concrete reduce by 17 % and 21 %, respectively, in comparison to B-NA, 25, 5 mix. In comparisons to control mix (i.e. B-NA, 0, 0), the compressive strength, tensile strength and modulus of rupture reduce by 9.3 %, 12.3 % and 20.5 %, respectively. It seems that the RCA aggregates high roughness ratio and angularity enhancement contribution as well as the effect of SF cannot compensate the reduction in the concrete strength due to RCA weakness.

4.3.2. Load-deflection response

Fig. 9 shows the applied load versus the midspan deflection curves for all tested beams. Table 4 shows the first cracking load, the ultimate load and the deflection corresponding to the ultimate load for each beam. The cracking load is defined as the value of the load at the end of the initial linear zone in the load-deflection response, while the ultimate load is the maximum load of the load-deflection

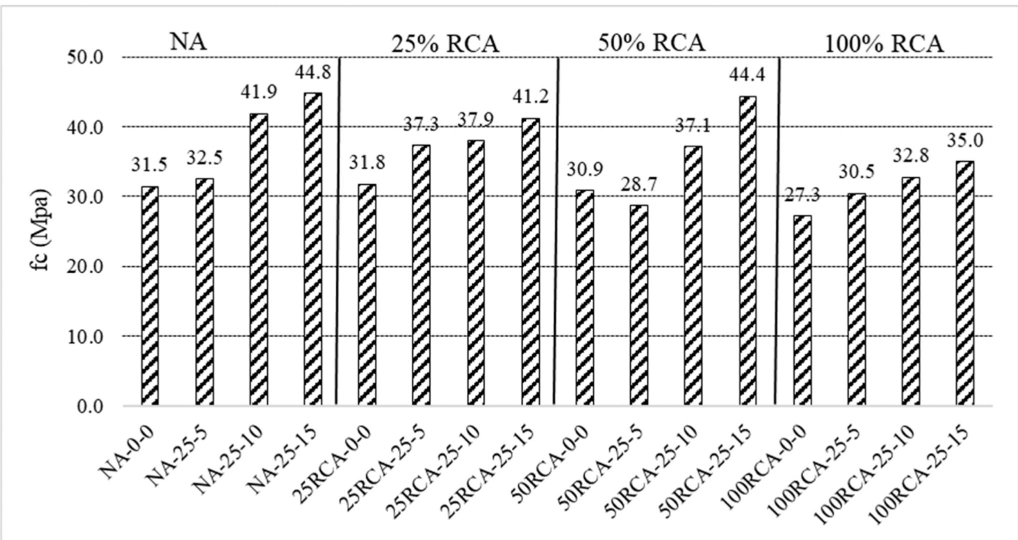


Fig. 8. Compressive strength test results.

Table 4
RC beam results.

Beam	f_c (N/mm^2)	f_t (N/mm^2)	f_r (N/mm^2)	P_{cr} (kN)	P_u (kN)	δ_u (mm)
B-NA-0-0	36.8	2.84	4.55	10	45	9.3
B-NA-25-5	37.0	3.00	4.59	9	43	9.9
B-25RCA-25-5	35.0	2.84	4.62	7.16	42.5	10.4
B-50RCA-25-5	38.1	2.89	4.61	10.2	41.1	10.1
B-100RCA-25-5	33.4	2.49	3.62	9.7	42.7	10.6

curve. The test results showed that the cracking load of the beams B-25RCA-25-5 was lower than that of the control beam while the other beams exhibited a comparable cracking load with the control beam. The beams B-NA- 25-25 and B-25RCA-25-5 displayed similar initial stiffness to the control beam while the beams B-50RCA-25-5 and B-100RCA-25-5 showed slightly lower initial stiffness. After the cracking load, each beam exhibits linear behaviour until the stress in the steel reaches its yield stress, followed by a short yield plateau and slight increase in the loading capacity due to the steel hardening. Furthermore, the effect of the RCA content, GGBS and SF on the ultimate load was not significant.

Beams B-NA-0-0 and B-NA-25-5 have a similar cracking load, however, the slope of the load-deflection curves after the cracking load of the beam B-NA-25-5 was slightly less than that of the beam B-NA-25-5. The beams with 25 % and 50 % RCA content exhibited minor changes in the slope in comparison to the beam B-NA-25-5. The beam with 100 % RCA showed the lowest bending stiffness in comparison to all tested beams. This could be attributed to the 100 % RCA beams having the lowest elastic modulus and the bonding between the rebars and the concrete being impacted by the high content of RCA.

4.3.3. Ultimate moment capacity

The experimental ultimate bending moment ($M_{u,exp}$) together with predictions of Eurocode 2 ($M_{u,pre}$) are presented in Table 5. It is observed that the ultimate moment capacity of the beam is slightly influenced by inclusion of RCA, and ternary cementitious (GGBS and SF). For instance, the control beam B-NA-0-0 has 4.4 % higher ultimate moment capacity than the beam with ternary cementitious (B-NA-25-5). This could be due to the presence on unreacted GGBS within the cement paste. The experimental bending capacity of the beams B-25RCA-25-5; B-50RCA-25-5; and B-100RCA-25-5 is slightly lower than this for the control beam by 5.6 %, 8.6 % and 5.1 %, respectively. This again could be due to unreacted GGBS within the cement paste and inclusion of the RCA that affect the mechanical properties of concrete mixture. However, studies have shown that mixes with GGBS tend to gain strength at a quicker rate past the 28 days in comparison to the control and therefore potentially surpass that of the control mix at a later age [36]. Hence, 30 % replacement of cement and 100 % RCA have no significant effect on the flexural capacity of the beam.

The ultimate moment capacity for singly reinforced concrete members using Eurocode 2 can be calculated using the Eq. (1):

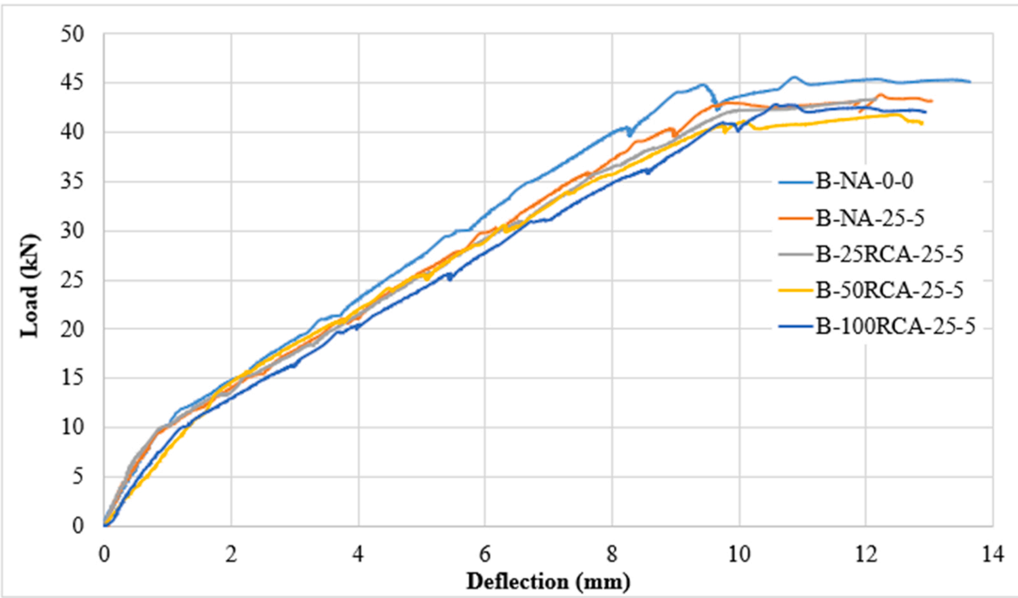


Fig. 9. Load-deflection relationship.

Table 5
Ultimate moments; experimental and theoretical.

Beam	P_u (kN)	δ_u (mm)	$M_{u,exp}$	$M_{u,pre}$	$M_{u,pre}/M_{u,exp}$
B-NA-0-0	45	9.3	14.63	12.70	0.87
B-NA-25-5	43	9.9	13.98	12.70	0.91
B-25RCA-25-5	42.5	10.42	13.81	12.64	0.92
B-50RCA-25-5	41.1	10.12	13.36	12.73	0.95
B-100RCA-25-5	42.7	10.65	13.88	13.77	0.99
Average					0.93
COV (%)					5.08

$$M_{u,pre} = f_y A_s \left(d - \frac{\lambda x}{2} \right) \quad \lambda x = \frac{A_s f_y}{\eta \quad \alpha_{cc} f_c b} \tag{1}$$

In these expressions, the partial material factors are taken as unity and η is taken as 1, for $f_c \leq 50$MPa, in accordance with Eurocode 2. α_{cc} is taken as 0.85 as recommended by the UK National Annex to Eurocode 2, d is the effective depth from the top of a reinforced concrete beam to the centroid of the tensile reinforcement, b is the width of the cross-section, As is the reinforcement area in mm^2, and f_y is the yield stress of the used steel, and is equal to 525 Mpa.

It can be noted from the results presented in Table 5 that Eurocode 2 provides a slightly conservative estimation of the ultimate moment capacity for all beams, with the average predicted-to-experimental ultimate moment being 0.93. It can be concluded that the Eurocode 2 design provision can be used for flexural design of RC beams made of RCA, and ternary cementitious GGBS and SF.

4.3.4. Cracking behaviour

Fig. 10 shows a view of the crack patterns at failure for the beams B-NA-0-0; B-50RCA-25-5; and 100RCA-25-5. These beams were selected for illustrative purposes and similar comparisons have been found for all of the other beams in this study. The crack patterns and propagation are similar all beams. At the beginning of the test until the cracking load, cracks did not appear. After the cracking load, a first crack initiated at on the bottom of the beam in the constant-moment region (i.e. the region between the middle of the beam and the application of the point load). As the load increased after the initial cracking, additional flexural cracks formed and propagate

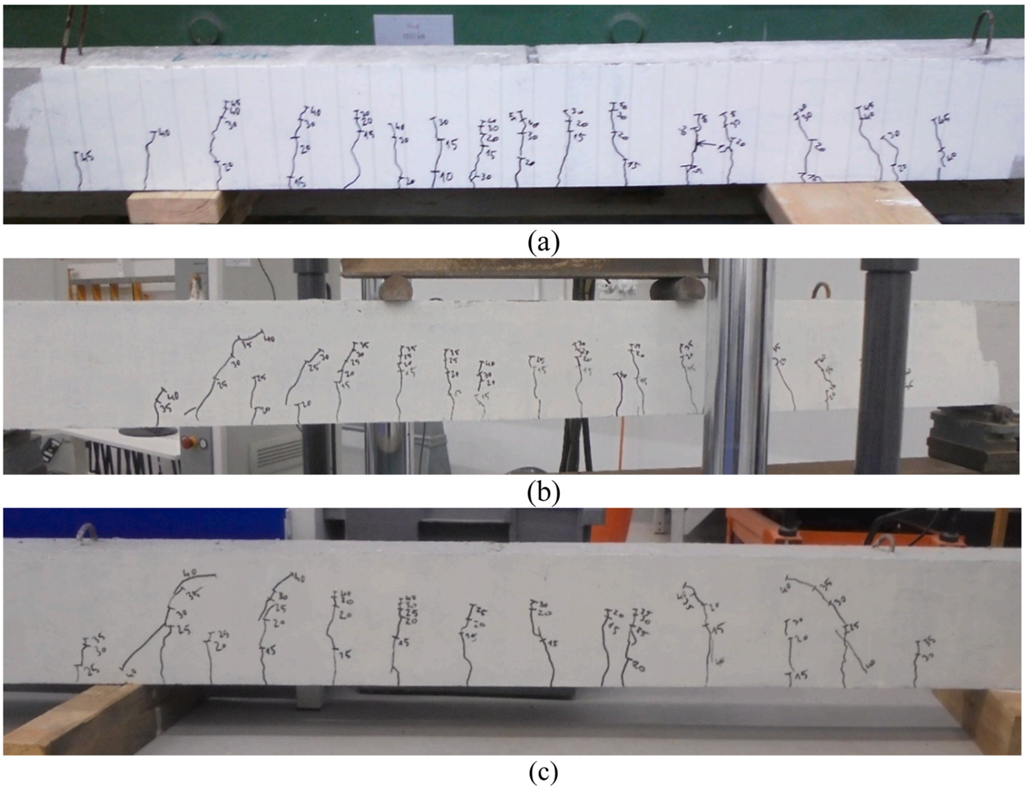


Fig. 10. Final crack patterns for the beam (a) B-NA-0-0; (b) B-50RCA-25-5; and (c) 100RCA-25-5.

vertically upwards towards the compression zone. As the load further increased, a few cracks were formed in the shear region (i.e. the region between the support and the application of the point load) and propagated diagonally towards the application of the point load. At the ultimate load, all steel RC beams fail by steel yielding, indicating flexural failure.

4.4. Life cycle analysis

Fig. 11 provides the Global Warming Potential (GWP) for all the mixes that have been tested in this experimental programme. Results show that for all concrete mixes the GWP decreases when the cement is replaced with GGBS and SF. For examples, the mix NA-25-5 has 20 % lower GWP than that for the benchmark sample NA-0-0. Furthermore, as the percentage of SF is increased in the mixes the GWP decrease. For example, the mixes NA-25-10 and NA-25-15 % have 72 % and 68 % lower GWP than that for the benchmark sample NA-0-0. It worth pointing out that replacing cement with SF does not provide significant reduction in the GWP as the replacement ratio is low. For example, when comparing NA-25-5 samples to the samples utilising 10 % (NA-25-10) and 15 % of SF (NA-25–15), the improvement in GWP emissions is limited to 8 % and 4 % respectively. However, the use of SF is beneficial to concrete with RCA as it eliminates the strength loss that is noted with the incorporation of RA.

In contrast, the GWP reduction by including 100 % RCA alone in the mix 100RCA-0-0 is limited to 5 % when compared to the benchmark mix NA-0-0. This is because of the similar emissions associated with manufacturing and processing of recycled and natural aggregates [37]. To further understand the GWP contribution for mixes with and without RCA, it can be seen from Fig. 12 that the GWP contribution of each process is similar between mixes with or without RCA with an average 85 % of GWP value due to the cement manufacturing and processing alone. Consequently, the improvement that is generated by adopting RCA in the mix does not sufficiently impact the overall GWP performance of the concrete mixes since cement contribute to the highest GWP. Further details into the GWP for processing RCA and NA only can be found in the Fig. 13. It can be noted that natural aggregates have higher GWP contribution that recycled concrete aggregates by almost 80 % since the process of NA required quarry operation and transportation while the RCA are produced on site from an existing building waste. The GWP contribution for the concrete ingredients that make the concrete mixes NA-0-0 and 100RCA-25-5, including associated processes and transportation, is illustrated in Fig. 14. The values were obtained as a percentage of the total GWP for each mix. It can be seen that the mix 100RCA-25-5 had lower GWP that the control mix by 33 %. The RCA contributes for only 4 % of the overall GWP of the mix 100RCA-25-5 while the natural aggregate contributes for 9 % of the overall GWP of the mix NA-0-0. Furthermore, the transportation contribution to the overall GWP accounts for 3 % and 9 % for the mixes

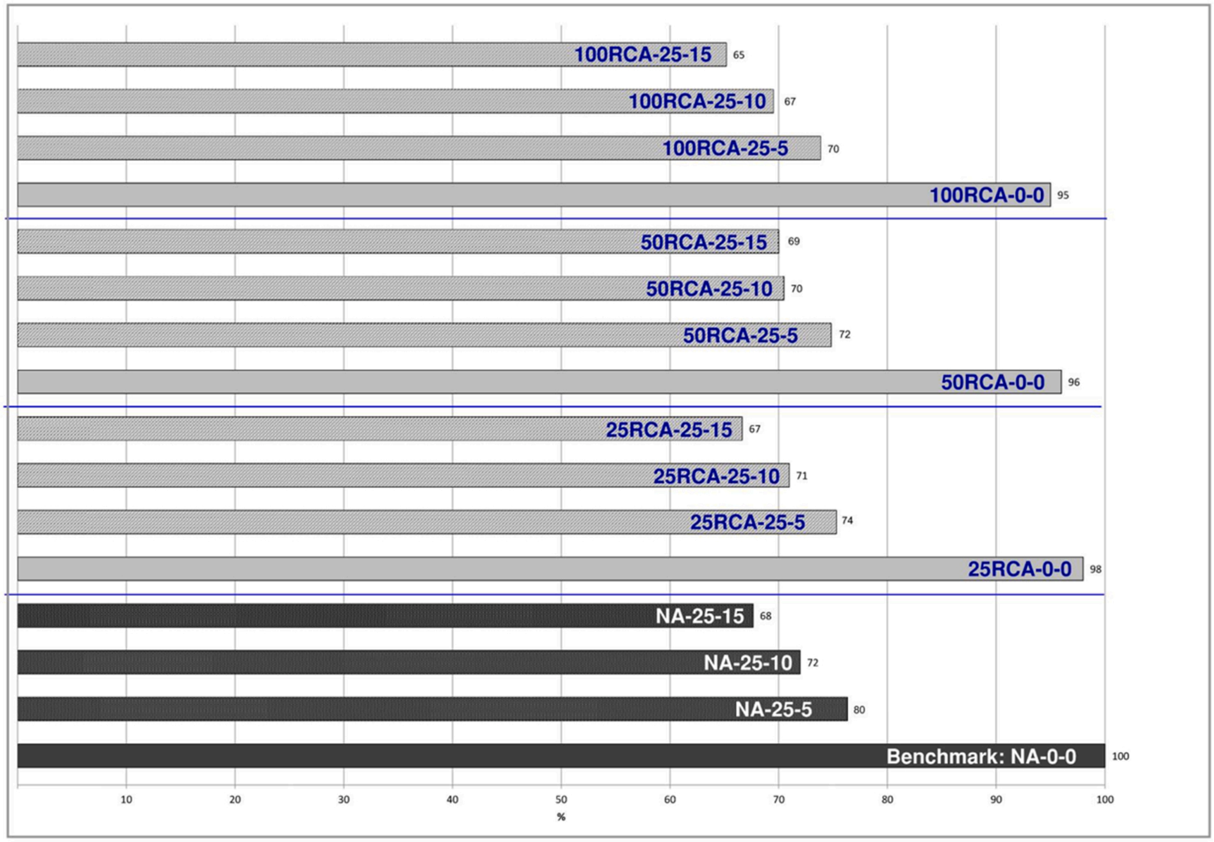


Fig. 11. Global Warming Potential overview of the Stage 1 Experimental Programme fifteen mixes (normalised values to NA-0-0).

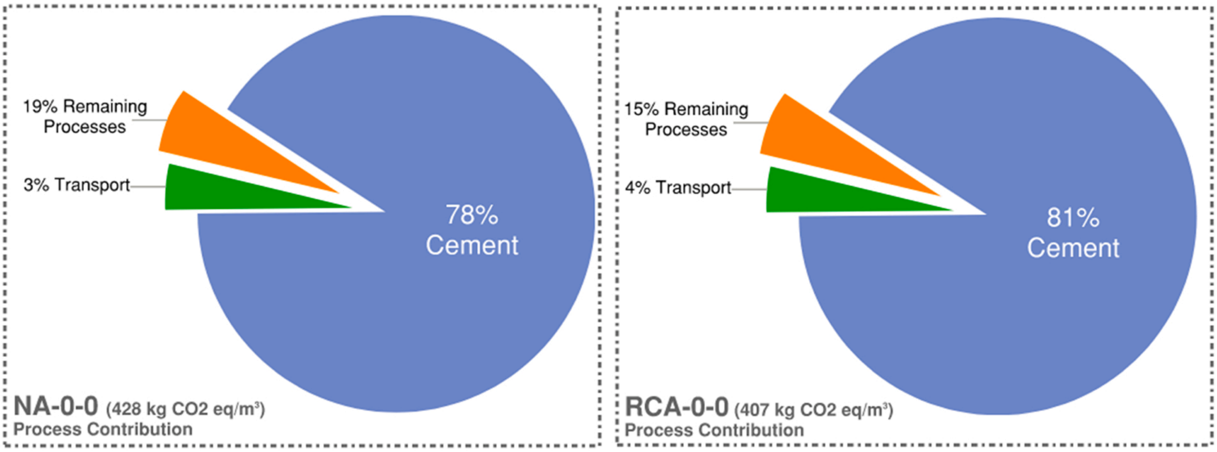


Fig. 12. Impact on GWP contribution of each process as a percentage of total GWP value.

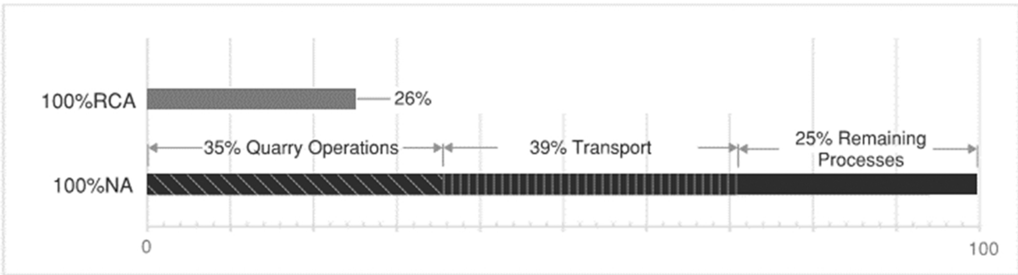


Fig. 13. Global Warming Potential overview of the operations associated with 100 % RCA and 100 % NA (normalised values to 100 % NA).

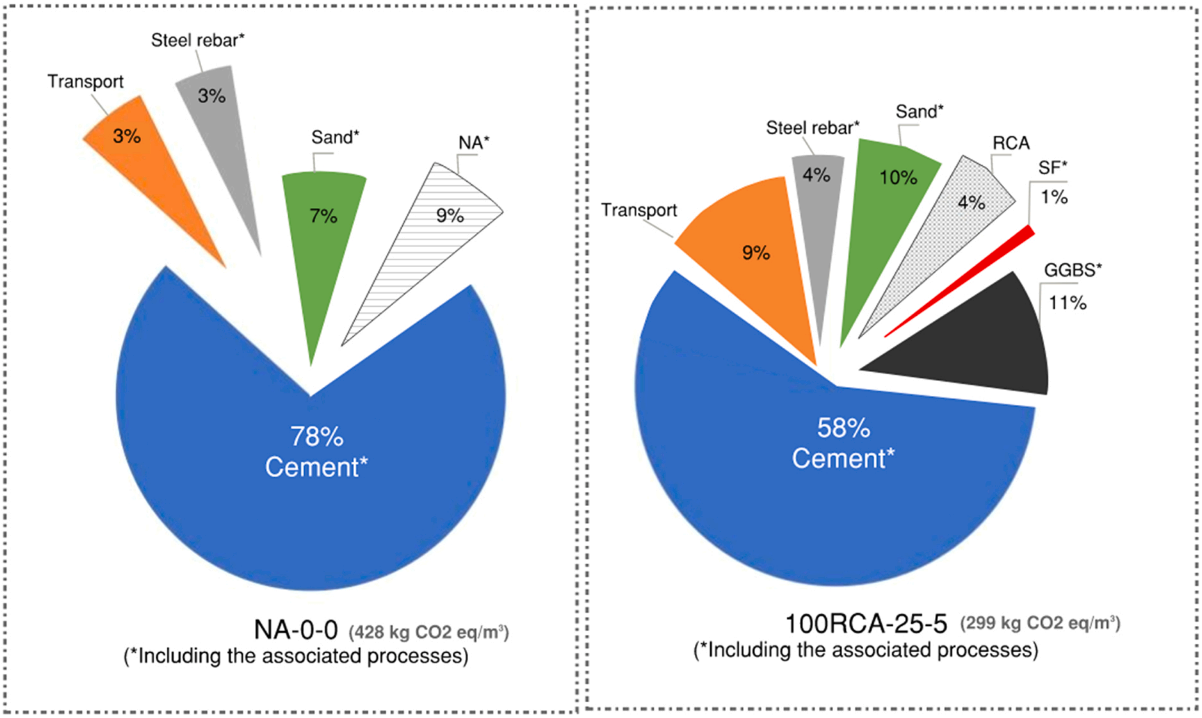


Fig. 14. Global Warming Potential overview of the concrete ingredients, including the associated processes and transportation, for NA-0-0 and 100RCA-25-5.

NA-0-0 and 100RCA-25-5, respectively. This is due to the fact that the GGBS is delivered from the distance of 300 km.

Based on the results of the LCA, it can be concluded that the concrete mixes with and without RCA provide a similar GWP performance. For example, replacing NA with 25 %, 50 % or 100 % RCA has no significant positive impact on the GWP emissions. However, adding 5 % SF and 25 % GGBS in concrete mixes improves GWP environmental response significantly, even though, based on GWP emissions alone, further increases of SF do not demonstrate a significant reduction effect. Future research studies, however, should consider impact assessment categories other than GWP when studying RCA as this would contribute in further understand the RCA environmental impact.

5. Conclusion

The paper aimed to review the impact on key mechanical properties of concrete, structural performance of reinforced beams and provide a thorough LCA to understand the true environmental impact, focusing on the GWP, of incorporating a ternary cementitious mix and RCA. In conclusion:

- Results show that RCA had no significant negative impact on the compressive strength, tensile strength, and modulus of rupture of concrete. This is assumed to be due to greater angularity and surface roughness of the RCA, resulting in better interlocking of aggregates and improved interfacial bond between aggregates and cement paste.
- At high levels of RCA replacement, the inclusion of GGBS and SF as a SCM in a ternary blend eliminated any negative impact and for all mixes produced greater strengths in comparison to the control mix. This was mainly due to the secondary reaction of Ca $(OH)_2$ and pore refinement that took place due to the chemical and physical properties of GGBS and SF
- Beams B-NA-25-25 and B-25RCA-25-5 displayed similar initial stiffness to the control beam while the beams B-50RCA-25-5 and B-100RCA-25-5 showed slightly lower initial stiffness.
- Experimental bending capacity of beams B-25RCA-25-5; B-50RCA-25-5; and B-100RCA-25-5 were slightly lower than this for the control beam and this is assumed to be due to unreacted GGBS within the cement paste and inclusion of the RCA that affect the mechanical properties of concrete mixture.
- Cradle-to-laid LCA focusing on Global Warming Potential (GWP) demonstrated that replacing NA with 25 %, 50 % or 100 % RCA has no significant impact on the GWP emissions, however, there is significant GWP impact in adopting Silica Fume and GGBS as cement replacements in a concrete mix.
- A similar optimistic conclusion could not be drawn for adopting Recycled Concrete Aggregates in lieu of natural aggregate within the concrete mix. However, this study has limited the RCA environmental assessment to GWP, while other impact categories might present a significantly better performance of RCA than natural aggregate.

CRediT authorship contribution statement

Rabee Shamass: Methodology, Conceptualization, Investigation, Writing – original draft. **Ottavia Rispoli:** Methodology, Investigation, Writing – original draft. **Vireen Limbachiya:** Methodology, Validation, Investigation, Writing – original draft. **Robert Kovacs:** Methodology, Investigation, Writing – review & 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.

Data Availability

Data will be made available on request.

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References

[1] W. Shen, L. Cao, Q. Li, W. Zhang, G. Wang, C. Li, Quantifying CO_2 emissions from China's cement industry, Renew. Sustain. Energy Rev. 50 (2015) 1004–1012.
[2] F. De Andrade Salgado, F. De Andrade Silva, Recycled aggregates from construction and demolition waste towards an application on structural concrete: a review, J. Build. Eng. 52 (2022), 104452.
[3] V. Limbachiya, E. Ganjian, P. Claisse, Strength, durability and leaching properties of concrete paving blocks incorporating GGBS and SF, Constr. Build. Mater. 113 (2016) 273–279.
[4] R. Siddique, R. Bennacer, Use of iron and steel industry by-product (GGBS) in cement paste and mortar, Resour. Conserv. Recycl. 69 (2012) 29–34.
[5] A. Oner, S. Akyuz, An experimental study on optimum usage of GGBS for the compressive strength of concrete, Cem. Concr. Compos. 29 (6) (2007) 505–514.

[6] O.A. Mohamed, O.F. Najm, Compressive strength and stability of sustainable self-consolidating concrete containing fly ash, silica fume, and GGBS, Front. Struct. Civ. Eng. 11 (4) (2017) 406–411.
[7[V.B.R. Suda, P. Srinivasa Rao, Experimental investigation on optimum usage of Micro silica and GGBS for the strength characteristics of concrete, Mater. Today: Proc. 27 (2020) 805–811.
[8] R. Siddique, Utilization (recycling) of iron and steel industry by-product (GGBS) in concrete: strength and durability properties, J. Mater. Cycles Waste Manag. 16 (3) (2014) 460–467.
[9] S.K. Rao, P. Sravana, T.C. Rao, Abrasion resistance and mechanical properties of Roller Compacted Concrete with GGBS, Constr. Build. Mater. 114 (2016) 925–933.
[10] R. Siddique, Utilization of silica fume in concrete: review of hardened properties, Resour. Conserv. Recycl. 55 (11) (2011) 923–932.
[11] R. Banar, P. Dashti, A. Zolfagharnasab, A.M. Ramezanianpour, A.A. Ramezanianpour, A comprehensive comparison between using silica fume in the forms of water slurry or blended cement in mortar/concrete, J. Build. Eng. 46 (2022), 103802.
[12] C. Fu, R. Guo, Z. Lin, H. Xia, Y. Yang, Q. Ma, Effect of nanosilica and silica fume on the mechanical properties and microstructure of lightweight engineered cementitious composites, Constr. Build. Mater. 298 (2021), 123788.
[13] K. Vance, M. Aguayo, T. Oey, G. Sant, N. Neithalath, Hydration and strength development in ternary portland cement blends containing limestone and fly ash or metakaolin, Cem. Concr. Compos. 39 (2013) 93–103.
[14] S. Tavasoli, M. Nili, B. Serpoush, Effect of GGBS on the frost resistance of self-consolidating concrete, Constr. Build. Mater. 165 (2018) 717–722.
[15] L.A. López Ruiz, X. Roca Ramón, S. Gassó Domingo, The circular economy in the construction and demolition waste sector – a review and an integrative model approach, J. Clean. Prod. 248 (2020), 119238.
[16] P. Folino, H. Xargay, Recycled aggregate concrete – mechanical behavior under uniaxial and triaxial compression, Constr. Build. Mater. 56 (2014) 21–31.
[17] Z. Tahar, T. Ngo, E.H. Kadri, A. Bouvet, F. Debieb, S. Aggoun, Effect of cement and admixture on the utilization of recycled aggregates in concrete, Constr. Build. Mater. 149 (2017) 91–102.
[18] D. Pedro, J. De Brito, L. Evangelista, Structural concrete with simultaneous incorporation of fine and coarse recycled concrete aggregates: mechanical, durability and long-term properties, Constr. Build. Mater. 154 (2017) 294–309.
[19] R. Singh, D. Nayak, A. Pandey, R. Kumar, V. Kumar, Effects of recycled fine aggregates on properties of concrete containing, J. Build. Eng., vol. 45, 2033, 103442.
[20] S. Kou, C. Poon, F. Agrela, Comparisons of natural and recycled aggregate concretes prepared with the addition of different mineral admixtures, Cem. Concr. Compos. 33 (8) (2011) 788–795.
[21] L.A. Qureshi, B. Ali, A. Ali, Combined effects of supplementary cementitious materials (silica fume, GGBS, fly ash and rice husk ash) and steel fiber on the hardened properties of recycled aggregate concrete, Constr. Build. Mater. 263 (2020), 120636.
[22] O. Cakir, O.O. Sofyanli, Influence of silica fume on mechanical and physical properties of recycled aggregate concrete, HBRC J. 11 (2) (2015) 157–166.
[23] D.C. Teychenné, R.E. Franklin, H.C. Erntroy, B.K. Marsh, Design of Normal Concrete Mixes, HM Stationery Office, London, UK, 1975.
[24] British Standards Institution, BS EN 12504-4: Testing Concrete - Determination of Ultrasonic Pulse Velocity, British Standards Institution, London, 2004.
[25] F. Colangelo, T.G. Navarro, I. Farina, A. Petrillo, Comparative LCA of concrete with recycled aggregates: a circular economy mindset in Europe, Int. J. Life Cycle Assess. 25 (9) (2020) 1790–1804.
[26] A. César, M. Pradena, Sustainable engineering: load transfer characterization for the structural design of thinner concrete pavements, Sustainability 12 (21) (2020) 9153.
[27] J. Harvey, J. Meijer, H. Ozer, I.L. Al-Qadi, A. Saboori, A. Kendall. Pavement Life Cycle Assessment Framework (No. FHWA-HIF-16-014), Federal Highway Administration, Washington, DC, USA, 2016.
[28] A. Vega, D.L, J. Santos, G. Martinez-Arguelles. Life Cycle Assessment of Hot Mix Asphalt with Recycled Concrete Aggregates for Road Pavements Construction, Informa UK Limited, 2020.
[29] M.W. Tait, W.A.I.M. Cheung, comparative cradle-to-gate life cycle assessment of three concrete mix designs, Int. J. Life Cycle Assess. 21 (6) (2016) 847–860.
[30] British Standards Institution, BS EN 1992-1-1: Eurocode 2. Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings, British Standards Institution, London, 2004.
[31] G. Borghi, S. Pantini, L. Rigamonti, Life cycle assessment of non-hazardous Construction and Demolition Waste (CDW) management in Lombardy Region (Italy), J. Clean. Prod. 184 (2018) 815–825.
[32] J.M.V. Gómez-Soberón. Porosity of Recycled Concrete with Substitution of Recycled Concrete Aggregate, Elsevier BV, 2002.
[33] R.F. Feldman, Non-destructive testing of concrete; Record identifier.Identificateur de l'enregistrement: d79248be-a237-4f1c-b2e2–51a540be1232. Canadian Building Digest; no.CBD-187, 1977.
[34] Safiuddin, U.J. Alengaram, A. Salam, M.Z. Jumaat, F.F. Jaafar, H.B. Saad, Properties of high-workability concrete with recycled concrete aggregate, Mater. Res. 14 (2) (2011) 248–255.
[35] S.W. Tabsh, A.S. Abdelfatah, Influence of recycled concrete aggregates on strength properties of concrete, Constr. Build. Mater. 23 (2) (2009) 1163–1167.
[36] Z. Wu, C. Shi, W. He, Comparative study on flexural properties of ultra-high performance concrete with supplementary cementitious materials under different curing regimes, Constr. Build. Mater. 136 (2017) 307–313.
[37] B. Bennett, P. Visintin, T. Xie, Global warming potential of recycled aggregate concrete with supplementary cementitious materials, J. Build. Eng. 52 (2022), 104394.
[38] S. Marinković, I. Josa, S. Braymand, N. Tošić, Sustainability assessment of recycled aggregate concrete structures: a critical view on the current state-of-knowledge and practice, Struct. Concr. (2023).
[39] R. Bajpai, K. Choudhary, A. Srivastava, K.S. Sangwan, M. Singh, Environmental impact assessment of fly ash and silica fume based geopolymer concrete, J. Clean. Prod. 254 (2020), 120147.
[40] M.W. Tait, W.M. Cheung, A comparative cradle-to-gate life cycle assessment of three concrete mix designs, Int. J. Life Cycle Assess. 21 (2016) 847–860.
[41] S. Fallah-Valukolaee, R. Mousavi, A. Arjomandi, M. Nematzadeh, M. Kazemi, A comparative study of mechanical properties and life cycle assessment of high-strength concrete containing silica fume and nanosilica as a partial cement replacement, in: Structures 46, Elsevier, 2022, pp. 838–851.