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Low Carbon Recycled Aggregate Concrete: Roles of Slag and Silica Fume

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Abstract: Recycled coarse aggregate from construction demolition waste offers a promising and sustainable solution to overcome challenges facing the construction industry, in relation to the increasing landfill areas, decreasing natural aggregate reserves, and increasing environmental impact of concrete production. Previous studies have shown that recycled aggregate concretes (RAC) are, however, more susceptible to deterioration. This paper presents an experimental investigation to improve the performance of concretes manufactured with locally produced recycled coarse aggregate in the UAE. More specifically, it aims to investigate the potential of incorporating ground granulated blast-furnace slag (GGBS) and silica fume (SF) in RACs, and their influence on key engineering properties of concrete. It is shown that partial replacement of Portland cement with GGBS and SF is effective to reduce the resistance of RAC to chloride ion penetration (hence durability), and lower the drying shrinkage and CO_2 emissions, with minimal influence on the long-term mechanical properties. A reduction of approximately 40% in CO_2 emissions was found in a concrete mix with combined replacement of recycled and waste materials.

Keywords: Recycled coarse aggregate; GGBS, Silica fume; Durability; CO_2 emission.

1. Introduction

Over the past 15 years, much of the research in sustainable construction has focused on three main topics: reducing, reusing and recycling, commonly known as the '3Rs' principle [1]. Construction and demolition waste form the largest component of the waste stream that account for 25-30% of the total waste generation [2]. Of these, concrete constitutes a major share of the amount of construction waste produced globally. This is due to the fact that concrete is the most used construction material worldwide due to its versatility [3]. The production of concrete has, however, a negative impact on the environment, and the increasing pace of construction has even made the situation worse. According to Environment and Climate Change Canada [4], for example, in 2016 alone, cement and concrete product manufacturing contributed 13% (10 Mt CO_2 eq.) of the total CO_2 emission generated by the manufacturing sector in Canada. This problem is not exclusive to Canada, and is of major concern in many countries around the world, including the UAE. In 2018, the UAE was even identified as one of the world's largest per capita CO_2 emitters because of its relatively low population [5]. To address this issue, the UAE Government has introduced several environmental policies over the past few years. As an example, Estidama in Abu Dhabi has published a green building code with a rating system known as the Pearl Building rating system (PBRS). Under this new regulation, a new building must meet, at least, one sustainable level (out of five) to obtain construction approval.

The use of recycled aggregates has attracted increasing interest from the construction industry since the past few decades as a result of rapidly depleting natural aggregate resources. With almost 20 billion tons of concrete being produced worldwide every year [7], this has put an enormous amount of pressure on the production of raw natural aggregates, provided that aggregate accounts for 70% of the concrete volume. The situation is exacerbated by the over-burdened landfill sites as a result of increasing amount of demolition of buildings, bridges and other types of reinforced concrete structures [7]. It is not surprising, therefore, that the use of recycled aggregates has recently received widespread interest, as it offers favorable and promising means of reducing landfills, saving natural resources and reducing environmental impact [8]. Over the past few decades, many research studies have focused on investigating the properties and performance of recycled aggregate concretes (RAC). According to Xie *et al*. [8], the main parameter that influences the performance of RAC is the water-to-binder ratio. They found that the compressive strength of RAC generally decreases with increasing w/c ratio and replacement level of recycled aggregate. They also found that the Interfacial Transition Zone (ITZ) of the residual mortar which are present on the surface of RCA plays an important role on the short- and long-term properties of RAC [9]. Other key influencing factors include the amount of residual mortar lumps, the grading of recycled aggregates, and various aspects related to the production of RCA such as the crushing and treatment methods, which may discredit the potential and benefits of reusing aggregates in concrete [7].

Apart from aggregate replacement, there are also some potentials of replacing Portland cement with supplementary cementitious materials (SCM), using the by-products of traditional industrial processes such as ground granulated blast-furnace slag (GGBS) and silica fume (SF). Improvements in mechanical and durability properties have been well documented and are attributed to the pozzolanic reaction with the products of hydration, which leads to long-term pore refinement [10]. Kou and Poon [11] reported that the use of SCM has the potential to improve various properties of RAC such as drying shrinkage, creep, chloride penetration resistance and carbonation, which is in agreement with Saini and Goel findings [12].

It is worth noting that greenhouse gases (GHG) caused by human activities increase the risk of global warming. This includes various activities related to the manufacturing of Portland cement and transport of raw materials involved in the production of concrete. Currently, the worldwide cement production accounts for 7% of the global CO_2 emission with transportation of materials contributing as the second main source of CO_2 emission [14]. Furthermore, the global cement production is estimated to reach around 4.4 billion by 2050, which poses significant challenges to environmental governance to find ways of "decarbonizing" the concrete production (including reducing cement consumption) in the construction industry [14].

In this study, an experimental program was undertaken to investigate the performance of concretes produced with a locally produced RCA in the UAE, along with the use of GGBS and SF. For this purpose, the three concrete mixtures were tested and discussed in terms of their mechanical and durability properties, and CO_2 emission.

2. Experimental program

2.1. Materials

The majority of the materials used within the experimental program was sourced locally from different parts of the UAE (see Figure 1). This includes CEM I 42.5N Portland cement to BS EN 197-1:2000 [15], coarse aggregate (<20 mm and <10 mm), fine aggregate (<5 mm) and dune sand; all of which were supplied from Ras Al-Khaimah (RAK) region. Two other materials, GGBS to BS EN 15167-1 2006 [16] and SF to BS EN 13263-1 [17], were supplied from outside the UAE (imported from China). A polycarboxylate superplasticizer (PC400) was added in all concrete mixes at an amount of 0.8 liters per 100 kg of cementitious materials to ensure adequate workability.

Figure 1. Concrete mix components.

2.2. *Recycled coarse aggregate*

The recycled coarse aggregate (RCA) used in this work was generated from construction demolition and had a relatively uniform size, generally in the range 10-14 mm (see Figure 2). The RCA was supplied by a recycling company in Sharjah Bee'ah, which was established to promote sustainable construction in the UAE, through the utilization of renewable energy resources. Every year, the company contributes up to 500,000 tons of recycled aggregate to the local market, with the aggregate produced primarily from concrete construction waste [18]. The physical and mechanical properties of all aggregates used in the test program are presented in Table 1, together with recommended values from various codes of practice. It can be observed that the measured values satisfy the specified minimum requirements indicating that the locally produced RCA can be used in concrete as normal aggregate.

Figure 2. Photograph of recycled coarse aggregates used in the project.

Table 1. Physical and mechanical properties of normal and recycled coarse aggregates.

Test descriptions			**20 mm NCA**	**10 mm NCA**	**10-14 mm RCA**	**RCA Limits**	**Standard**
Specific Gravity-oven dry			2.67	2.67	2.36	≥ 2.1	RILEM [19]
Specific Gravity-SSD			2.68	2.68	2.48		
Apparent Specific Gravity			2.70	2.71	2.69		
Water absorption		%	0.5	0.5	5.1	≤ 7%	RILEM [19]
Bulk density	Compacted	kg/m³	1,500	1,490	1,350	≥ 2,000	JIS A 5021 [20]
	Uncompacted	kg/m³	1,400	1,380	1,250		
Flakiness index		%	9	22	19	35%	EHE-08 [21]
Elongation index		%	24	23	15	35%	EHE-08 [21]
Acid soluble sulphate		%	0.03	0.04	0.21	0.80%	RILEM [19]
Acid soluble chloride		%	0.01	0.01	0.02	0.05%	CUR 1994 [22]
LA abrasion value		%	28	24	28	40	RILEM [19]

Aggregate crushing Value	%	26	23	23	45	WBTC [23]
Ten percent fines value	kN	160	180	190	≥80	RILEM [19]
Moisture content	%	0.1	0.1	1.5	-	
Soundness by MgSo$_4$	%	1.1	2	6	10	RILEM [19]

2.3. Concrete mix design

Three concrete mixes designed to ACI 211[26] were tested: (i) M1 mix incorporating normal aggregate, serving as the control mix (labelled as CON); (ii) M2 mix incorporating recycled aggregate (labelled as 100% RCA); and (iii) M3 mix incorporating recycled aggregate and supplementary cementitious materials (ground granulated blast-furnace slag (GGBS) and silica fume (SF); labelled as 100% RCA+50%GGBS+10%SF). The replacement level followed the optimum range in previous studies [12,24,25]. A summary of the concrete mixes used within the experimental program is presented in Table 2. In all mixes, the water-to-cement ratio was taken as 0.33. The water content in each mix was adjusted to account for water absorption of the RCA.

Table 2. Summary of concrete mixes.

Mix ID	**Mass of Constituents (kg/m^3)**									**Super-plasticiser (% by mass of OPC)**
	OPC	**Water**	**SCM**		**NCA**	**NCA**	**RCA**	**Sand**	**Dune**	
			GGBS	**SF**	**10 mm**	**20 mm**	**10-14 mm**	**5 mm**	**sand**	
M1	400	132	-	-	553	368	-	718	308	0.8
M2	400	132	-	-	-	-	735	846	362	0.8
M3	160	132	200	40	-	-	735	846	362	0.8

3. Tests on hardened concrete

In this study, various tests were performed to obtain the fundamental mechanical and durability properties of the ordinary and recycled aggregate concretes (see Figure 3). This includes:

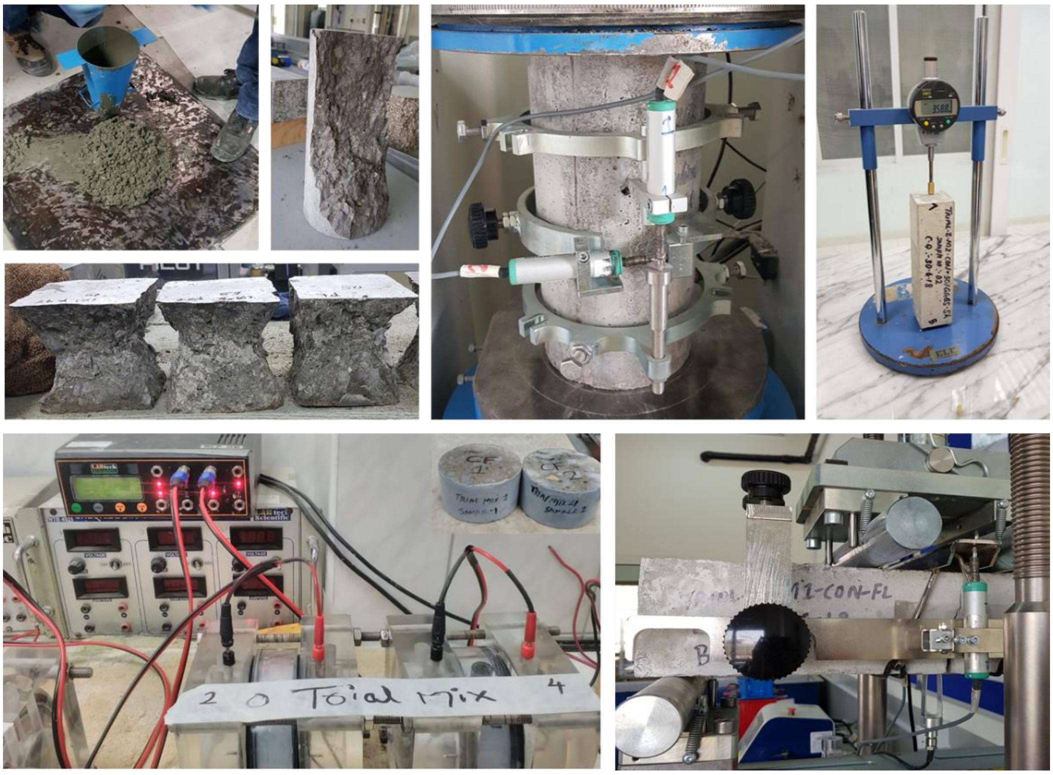

Figure 3. A collection of photos displaying the various tests undertaken on hardened concrete.

- Water absorption tests in accordance with BS 1881-122: 2011 [27] at 28 days of age;
- Compressive strength tests in accordance with BS 1881 Part 116 [28], performed on 150 mm cubes at 90 days of age. On the same day, concrete strengths and elastic moduli were also measured from 150 × 300 mm cylinders, in accordance with ASTM C39 [29] and ASTM C469 [30];
- Flexural tests in accordance with ASTM C78 [31] and 4-point load method on prism samples with dimensions of 100 × 100 × 500 mm;
- Rapid chloride penetration test (RCPT) in accordance with ASTM C1202-17a [32], on concrete disc specimens with a diameter of 100 mm and a thickness of 50 mm; and
- Drying shrinkage tests in accordance with ASTM C157 [33], on prismatic samples with dimensions of 50 × 50 × 200 mm. The samples were placed in an outdoor environment with ambient temperatures of 35±10°C and relative humidity of 60±10%, which represents common curing practice in the UAE. Readings were taken at 7, 14, 21, 28, 90 and 180 days.

4. Results and discussion

4.1. Mechanical properties

Table 3 presents the results of all tests described in Section 3. Regarding the 90-day cube compressive strength, it is evident that the addition of RCA results in a reduction in compressive strength, with Mix M2 displaying 13% lower strength than the regular concrete mix (Mix M1). The lower strength was expected, and this could be attributed to the presence of old mortars which had adhered to the surface of RCA. This 'old' mortar could be quite porous and might have pre-existing cracks due to the crushing process involved in the production of the recycled aggregate. Accordingly, RCA tends to have a weaker bond with the surrounding cement matrix than normal aggregate. This could be associated with the more porous nature of interfacial transition zone (ITZ) in concrete incorporating RCA [35], when compared to the ITZ in concrete produced with normal aggregate. No significant improvement in strength was observed for Mix M3 and this could be due to the fact that although the long-term pozzolanic reaction of GGBS and SF was found beneficial to improve the ITZ [10], this was limited to the new ITZ between the cement matrix and RCA surface only [36] (i.e., it did not influence the pre-existing ITZ between the old mortar and natural aggregates). The results of the cylinder tests follow the same trend as those for the cubes, with Mixes M2 and M3 displaying a 13% and 25% reduction in compressive strength, respectively. Similarly, the incorporation of RCA was found to decrease the flexural tensile strength, although to a less extent [37]. Mix M2 displayed an 8% lower (tensile) strength than Mix M1, while Mix M3 exhibited a 15% reduction. No improvement in flexural strength was observed through the incorporation of GGBS and SF in Mix M3, as this could be masked by the lower matrix strength. The same trends were observed in other studies [38, 39].

Table 3. Properties of concrete measured at 90 days of age ($^{\#}$ tests were undertaken at 28 days of age).

Mix ID	Density	Cube Compressive Strength	Cylinder Compressive Strength	Flexural Tensile Strength	Elastic Modulus	Water Absorption$^{\#}$
	kg/m^3	MPa	MPa	MPa	MPa	%
M1	2,480	72	67	4.30	43,260	1.5
M2	2,410	63	58	3.96	28,849	2.2
M3	2,294	60	50	3.66	28,041	2.2

Regarding the results of elastic modulus tests, it was found that the incorporation of RCA decreases the elastic modulus of the concrete by 33%, from approximately 43 GPa to 29 GPa. This is higher than the average reduction of 16% reported for 100% RCA replacement in [10], but within the range 6-45% reported by Batikha *et al*. [37].

With regard to the results of water absorption tests, an increase in water absorption by 46% was found in the concrete with 100% RCA (Mix M2), when compared to the regular concrete with normal aggregate (Mix M1). The use of GGBS and SF in the RCA concrete (Mix M3) did not improve the water absorption properties, possibly being masked by the high-water absorption of the RCA (5.1%, which is ten times higher than that of the normal coarse aggregate). This finding is in general agreement with Çakır [34] who found higher water absorptions in RAC with 10% SF, and in another RAC mix with 60% GGBS.

4.2. Durability properties

The results of the Rapid Chloride penetration tests (RCPT), which were undertaken at 7, 28 and 90 days, are presented in Figure 4. It is evident over the first 90 days of curing, Mix M2 displays higher charge passed values than Mix M1, which is in agreement with previous studies [40]. Furthermore, in all three mixes, chloride ion penetrability is noticed to decrease with curing time, as would be expected [41]. By comparing the results of Mixes M2 and M3, it is interesting to note that when GGBS (50%) and SF (10%) are added into the mix, the chloride ion penetrability of the concrete at 90 days of curing decreases significantly, from being classified as "Moderate" (as per ASTM C1202) to "Very Low". This clearly highlights the benefits of the supplementary cementitious materials in improving the resistance of concrete to chloride ingress (hence durability of the concrete in chloride-rich environments).

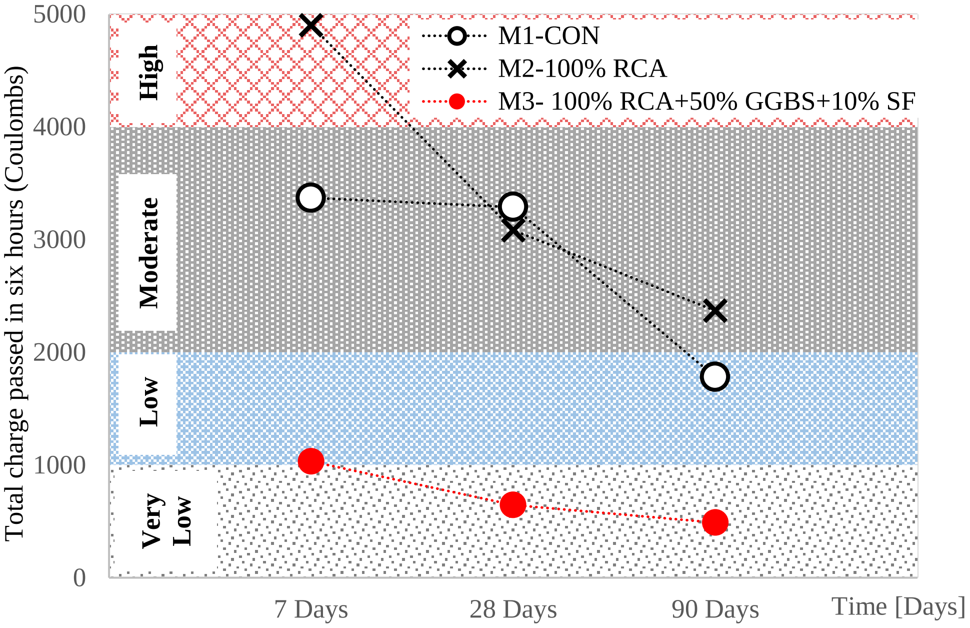

Figure 4. RCPT results for all concrete mixes.

The results of the drying shrinkage measurements at different stages of curing (up to 180 days) are presented in Figure 5. It is apparent that at 90 days, the drying shrinkage of Mix M2 is about 34% higher than that of Mix M1, which is in general agreement with previous study [42]. According to [10], 100% RCA replacement generally increases the shrinkage of concrete by 20-50%. It is interesting to note that the drying shrinkage of Mix M3 with 50%GGBS+10%SF is only half that of Mix M1 at 28 days; the difference between the two values, however, decreases with increasing curing time.

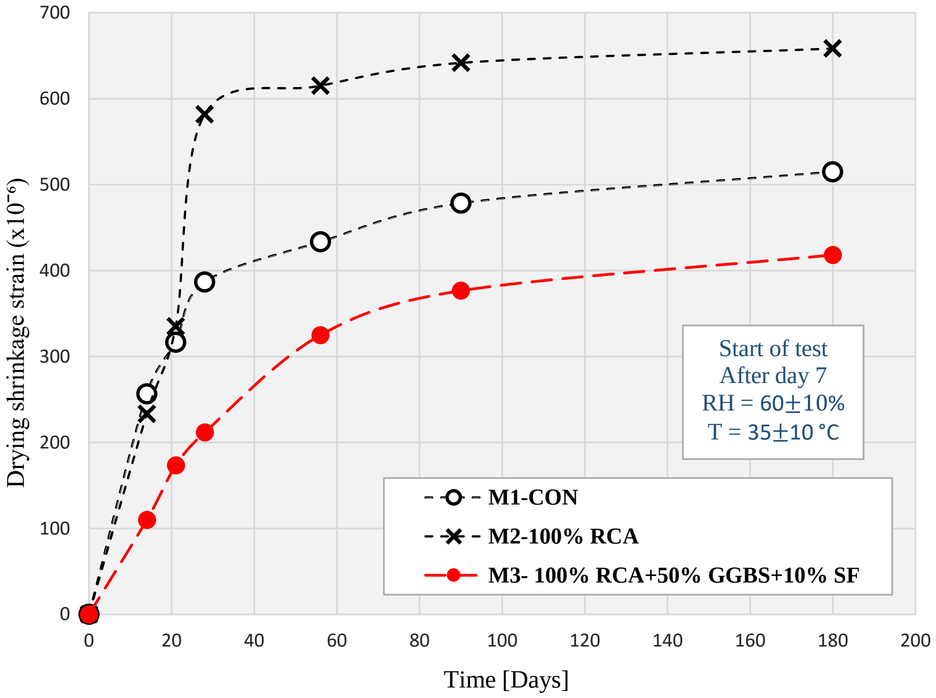

Figure 5. Drying shrinkage measured from all concrete mixes.

4.2. CO_2 Emission

The Green House Gas (GHG) emission was calculated for the three concrete mixtures using the methodology proposed in [43]. In this method, the total GHG emission is expressed as the carbon dioxide equivalent (CO_{2eq}) per ton of materials, considering not only CO_2 but also other unfavorable gases such as CH_4, NO_x, SO_x, which are normally emitted during the excavation and transportation activities. In this study, the GHG estimation has been done based on the total greenhouse gas emission ($kgCO_{2eq}$) per ton of concrete materials used in this study. As illustrated in Table 4, a number of assumptions were taken into account in estimating the CO_{2eq} emission, including the phases in cement production and the production of both coarse and fine aggregates. Moreover, transportation distance in the GHG calculation was taken as 400 km, considering the greatest possible distance in the UAE as a worst-case scenario. It is worth noting that the construction recycling in Bee'ah Tadweer follows the least energy consumption for processing recycled aggregate. It implements the common method of mechanical separation between the primary and secondary phases along with the primary and secondary crushing and washing activities. This mechanical treatment (without any heating treatment by furnace or kiln) is estimated to lie in the region of 21.7 kg CO_{2eq} / t_{RCA} [37].

Table 4 presents the total emission (in kg CO_{2eq} / t) for each concrete constituent, considering the distance required for transporting the materials across the UAE (based on the above assumptions). By mapping Table 4 onto Table 2, the calculated kg CO_{2eq} per 1 m^3 for each concrete mixture could be determined and the results of which are presented in Figure 6.

Table 4. Calculated total emission kg CO_{2eq} per 1 tonne of concrete considering transportation of materials across the UAE.

Material	**Emission factor kg CO_{2eq} per 1 tonne of material**		**References**
	without transportation	**with transportation in UAE**	
OPC	709	745	[44]
GGBS	25	120.8	[45]
SF	0.007	95.8	[46]
Coarse aggregate	45.9	81.9	[47]
Fine aggregate	13.9	49.9	[47]
RCA	21.7	57.7	[48]

With reference to Figure 6, it is evident that CO_{2eq} emission for Mix M2 is only 6% lower than that of Mix M1 which would indicate that the use of RCA would result in a marginal reduction in carbon emission. The addition of GGBS (50%) and SF (10%) into the binder of Mix M3 results in a concrete mix with 41% less CO_{2eq} emission than the control mix (M1), which is promising.

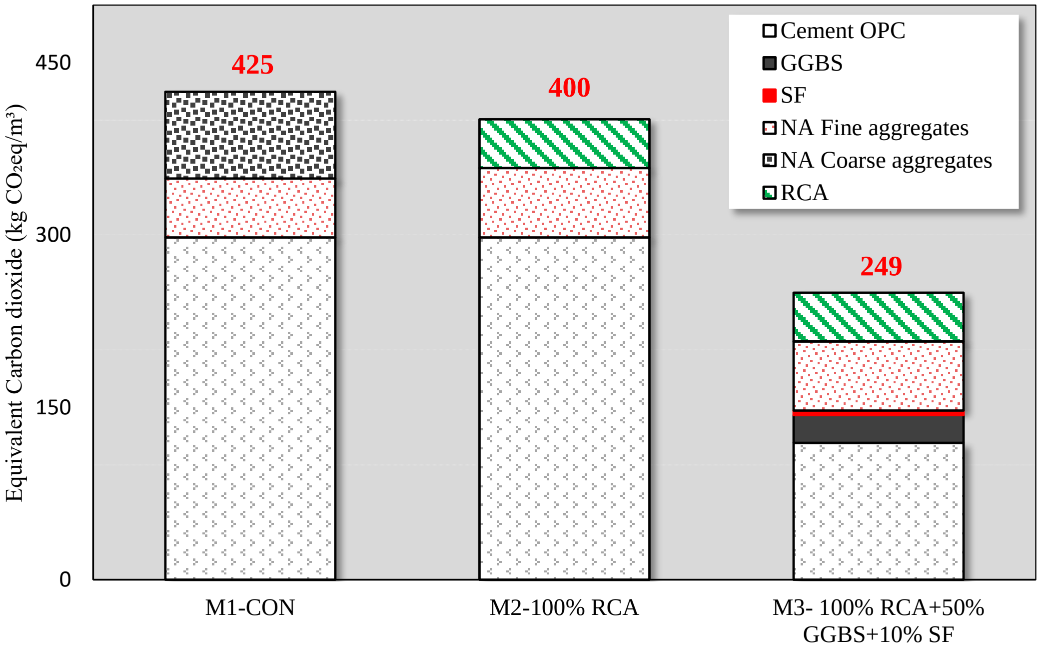

Figure 6. Equivalent Carbon dioxide (kg CO_{2eq}/m^3) for concrete mixtures.

Figure 7 provides a summary of all properties obtained from the tests undertaken as part of this research study for the three concrete mixes (conventional concrete, 100% RCA concrete, and 100% RCA concrete with 50%GGBS and 10% SF as a cement replacement). It can be seen that the addition of GGBS and SF in RCA concrete has the potential not only to improve the durability properties of concrete (as indicated by the lower RCPT and drying shrinkage values) but also to reduce CO_2 emission, with a 41% reduction observed from the mix presented in this paper. Comparable long-term mechanical properties to the ordinary concrete were obtained.

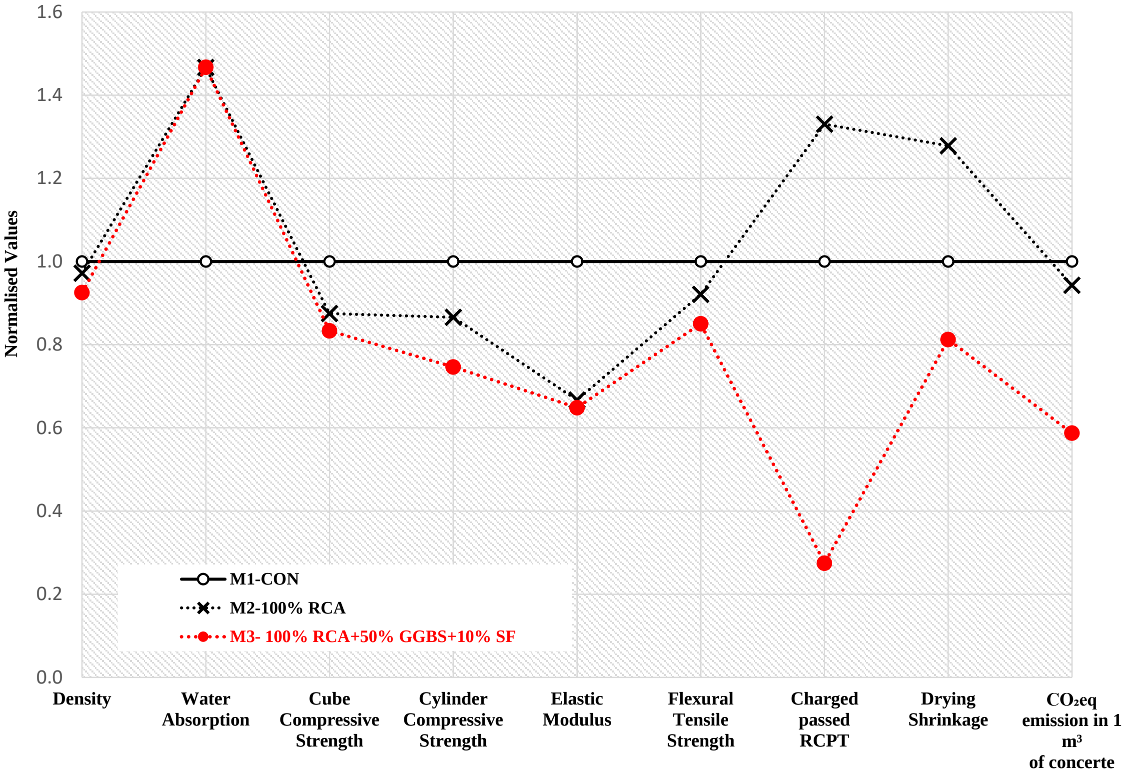

Figure 7. Properties comparison for all concrete mixtures.

5. Conclusions

Recycled aggregate and supplementary cementitious materials are untapped potentials in the UAE and their utilization can promote sustainable development in the Middle East. It is shown that the properties of concrete produced using the recycled aggregate in the UAE (produced by Bee’ah) exhibit comparable performance to those reported in previous studies, and satisfy minimum requirements specified in various international standards. The inclusion of GGBS and SF along with 100% RCA is shown to result in a 41% reduction in CO_2 emission, along with some improvements in durability aspects such as higher resistance to chloride ingress and lower drying shrinkage.

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