Using Recycled Concrete as a Replacement for Coarse Aggregate in the Production of Green Concrete

Mohamed Tarek El-Hawary[1,2(✉)], Carsten Koenke[2], Amr El-Nemr[3], and Nagy F. Hanna[3]

[1] German University in Cairo, Cairo, Egypt
elhawary.mth@gmail.com
[2] Bauhaus-Universität Weimar and MFPA Weimar, Weimar, Germany
Carsten.koenke@uni-weimar.de
[3] Civil Engineering Department, German University in Cairo, Cairo, Egypt
amr.elnemr@guc.edu.eg, nagy.hanna@gu.edu.eg

Abstract. Reducing the environmental impact and enhancing the properties of concrete is of great significance environmentally and economically. Using sustainable construction materials coming from construction wastes like recycled concrete that comes out from demolishing or renovating of existing structures could help in producing sustainable materials of good quality and low cost. The use of recycled concrete improved the concrete quality and enhanced the mechanical and microstructural properties of concrete. Tests and research done on this type of sustainable concrete proved the applicability of usage of recycled concrete aggregates as a full replacement of coarse aggregate by using different grain sizes of natural and recycled coarse aggregates. The desired concrete strength as per the concrete mix design is 35 MPa with fixed water to cement ratio of 0.48. The concrete mechanical properties increased clearly after replacing the natural coarse aggregates by recycled concrete aggregates. This research studied the concrete density, workability, temperature, compressive strength, split tensile strength, flexural strength, and microstructural analysis; which is the main focus of this paper.

Keywords: Green concrete · Recycled concrete aggregates · Sustainable construction materials · Mechanical properties · Microstructural analysis · Fresh concrete properties · Hardened concrete properties

1 Introduction

Concrete production and industry is the main concern in research nowadays, taking into account the sustainability of the environment and the economic benefits from such researches. From the environmental aspect, the ceramic wastes contribute with huge percentage -about 30% from the production of ceramic tiles comes as waste, (Raval

N. F. Hanna—Former Professor at Mataria University.

H. Shehata and S. El-Badawy (Eds.): *Sustainable Issues in Infrastructure Engineering*, SUCI, pp. 127–151, 2021.
https://doi.org/10.1007/978-3-030-62586-3_9

et al. 2013) - in the construction waste, and also the ceramic industry waste. The use of these wastes enables us to get rid of these wastes in a useful way, instead of the traditional ways that are harmful to the environment. From the economic aspect, using ceramic as replacement to the aggregate has its own benefits as it reduces the cost of concrete production and also it is a lightweight material, so it decreases the total weight of the structure. In addition to lowering the cost of concrete mix itself, this will enable the designers to decrease the foundation cost of the buildings as a result of using lighter weight concrete. Using concrete waste could save energy, reduce the manufacturing cost of concrete, and also save the environment, (Medina et al. 2012).

The replacement of aggregate in concrete can be done using several materials such as ceramic which is the used material in this research, bricks (Adams 2012), oil palms shells (Basri et al. 1999), tire rubber (Nehdi and Khan 2001), quarry wastes (Nataraja et al. 2001), building rubbles (Khalaf and DeVenny 2004), vitrified soil aggregate (Palmquist et al. 2001), sand stone (Kumar et al. 2007), basaltic pumice (Binici 2007), and electric arc furnace slag (Manso 2006). The use of all these materials has economical, and environmental benefits by reducing the cost of concrete manufacture and decreasing the landfill demand for such solid waste materials.

The use of construction wastes could be categorized into three main groups, coarse aggregate replacement for concrete mixes, fine aggregate replacement for cement mortar, and cement replacement for cement mortar. The used wastes are crushed using grinder. Usage of construction wastes in construction industry is of significant importance from the environmental and economic aspects; this requires implementing tests and experiments on the different types of wastes after classifying it, to be examined for introducing this type of material to the new sustainable construction materials technologies. By classifying the construction wastes the following wastes were found to be of different characteristics regarding its chemical composition, shapes and forms, strength, and many other aspects. After studying the market and the construction industry especially in Egypt, the first material that was tested in the previous research was the ceramic waste, and its different properties as a specific material and also as new sustainable construction material. The scope of this research is to continue testing the construction wastes and to validate different types of materials and relate their behaviour to each other, reaching a design methodology or a design technique for the green construction materials.

Marble waste is one of the strongest materials that we can predict a good behaviour regarding the concrete strength; if it is introduced to the concrete design. Marble manufacturing and industry produces a huge amount of marble waste coming from two main resources. The first and the main resource is coming from the preparation of the marble and converting the raw blocks into the traditional tiles or sheets that is used in floorings, finishing, or any other application, which produces about 70% of the mineral as a waste during the mining, processing and polishing stages (Hebhoub et al. 2011). While producing marble the most important aspect is the aesthetics and hardness according to the type of application or how it would be used. It happens a lot that if the block is not looking good or aesthetically not qualified for the market demands and specifications that the whole block would not be used and it is considered as a waste. The other source comes from demolishing buildings and old or used tiles or sheets of marble all of these quantities could be considered as a waste and should be used in a way or another. The main idea is to use the marble waste as replacement for the natural aggregates in the concrete manufacture and replacing the cement by the marble dust which is less than 1 mm size.

2 Problem Statement and Motivation

Hebhoub et al. (2011), using the marble waste in the concrete manufacturing solves this problem environmentally and economically, especially with a 75% replacement value -of any formulation- under constant water to cement ratio. The use of the marble waste as replacement for coarse and fine aggregate separately or together leads to an increase in the concrete mechanical properties. Not only enhancing the concrete properties, the use of ceramic tiles waste also reduces the cost of concrete production and saves the environment from the huge amount of wastes that couldn't be easily get rid of, and save the natural non-renewable materials and resources as well.

3 Background and Previous Research

Researches were done to examine the sustainable concrete properties using different types of wastes. The characteristics of the produced concrete were handled in different ways; some researches studied only the mechanical properties or studied one of the mechanical properties only neglecting the other properties. After collecting different results and interpretations from previous researches the following data were found.

El-Hawary et al. (2019), introduced sustainable concrete using marble aggregates with different sizes as a replacement for the natural aggregates in concrete. The concrete mix was done according to the ACI standards and with water to cement ratio of 0.48. replacement percentages of natural aggregates with marble aggregates varied from 0% till reaching 100%. The research proved the applicability of using the full replacement of natural aggregates by marble aggregates; which improved the concrete mechanical and microstructural properties.

Binici et al. (2008), investigated the cement and aggregate replacement with marble waste in concrete with constant water to cement ratios. The results showed improvements in the mechanical and chemical properties of cement and concrete after adding the marble waste to the mix with fixed water to cement ratio of 0.4, shown in Table 1.

Ergun (2011), added marble to the concrete as a replacement for the coarse aggregate; which enhanced the concrete mechanical properties, workability and chemical resistance if compared to the traditional concrete as shown in Table 2. The reason behind using the marble in producing more durable concrete is not only economic but also environmental; for example in Turkey, which has huge amounts of marble waste due to the availability of the raw material. Experiments and tests done on replacing natural aggregates with recycled marble sand and recycled marble gravel showed better concrete mechanical properties and a significant increase in the concrete compressive and tensile strength, especially for the 25%, 50%, and 75% of replacement of natural aggregates by marble waste aggregates. The workability could be improved using the optimized water to cement ratio as mentioned in the results.

Table 1. Concrete mechanical properties after different aging Binici et al.

Mixture no.	Density hardened concrete	Compressive strength MPa					Flexural strength MPa	Split tensile strength MPa	7 vs 28 days	Average	28 vs 90 days	Average
		1 day	7 days	28 days	90 days	356 days	28 days	28 days				
MC1-1	**2353**	29.1	38.4	44.4	50	57.4	6.6	3.4	13.51	13.84	11.20	9.89
MC1-2	**2355**	30	37.9	44.6	49	57.1	6.2	3.5	15.02		8.98	
MC1-3	**2357**	28.5	38.2	43.9	48.5	28.2	6.4	3.1	12.98		9.48	
MC1 average	**2355**	29.2	38.2	44.3	49.2	57.6	6.4	3.3	13.77		9.96	
MC2-1	**2333**	31	41.1	46.6	55	62.6	7.2	3.6	11.80	14.94	15.27	12.73
MC2-2	**2344**	31.1	38.3	47.8	54.2	61.9	6.9	3.3	19.87		11.81	
MC2-3	**2340**	29.6	41	47.2	53.1	61.8	6.3	3.4	13.14		11.11	
MC2 average	**2339**	30.1	40.1	47.2	54.1	62.1	6.9	3.5	15.04		12.75	
GC1-1	**2352**	29.2	36.8	44.5	50.1	55.9	6.5	3.3	17.30	13.77	11.18	11.89
GC1-2	**2344**	27.8	35.9	42.8	49.4	56.8	6.1	3.1	16.12		13.36	
GC1-3	**2332**	28.1	39.7	43.1	48.5	57.7	6.3	3.2	7.89		11.13	
GC1 average	**2343**	28.4	37.5	43.5	49.3	56.8	6.3	3.2	13.79		11.76	
GC2-1	**2332**	30.7	38.3	42.1	49.5	57.8	6.6	3.5	9.03	12.42	14.95	12.77

(*continued*)

Table 1. (*continued*)

Mixture no.	Density hardened concrete	Compressive strength MPa					Flexural strength MPa	Split tensile strength MPa	7 vs 28 days	Average	28 vs 90 days	Average
		1 day	7 days	28 days	90 days	356 days	28 days	28 days				
GC2-2	**2328**	28.7	40.1	46	51.4	59.6	6.2	3.3	12.83		10.51	
GC2-3	**2315**	29.4	37.3	44.1	50.6	60.7	6.5	3.3	15.42		12.85	
GC2 average	**2325**	29.6	38.6	44	50.5	59.4	6.5	3.4	12.27		12.87	
C1-1	**2402**	8.5	16.1	26.2	31.5	37.9	4.1	2.2	38.55	34.68	16.83	22.18
C1-2	**2381**	8	16	24.1	33.2	37.5	3.8	2.1	33.61		27.41	
C1-3	**2390**	8.6	17.1	25.1	32.3	34.9	3.9	1.9	31.87		22.29	
C1 average	**2391**	8.4	16.4	25.1	32.3	36.8	3.9	2.1	34.66		22.29	
C2-1	**2388**	14.1	29.3	33.9	42	48.4	4.4	2.4	13.57	19.38	19.29	14.15
C2-2	**2373**	13.5	27.8	36.1	43.3	46.3	4.2	2.3	22.99		16.63	
C2-3	**2369**	13.6	28	35.7	38.2	46.9	4.2	2.5	21.57		6.54	
C2 average	**2377**	13.7	28.4	35.2	41.2	47.2	4.3	2.4	19.32		14.56	

Table 2. Concrete mechanical properties Ergun (2011)

	Compressive strength MPa			7 vs 28 days	28 vs 90 days	Flexural strength MPa			7 vs 28 days	28 vs 90 days
	7 days	28 days	90 days			7 days	28 days	90 days		
Control	27.2	35.4	35.6	23.16	0.56	5.1	5.3	5.7	3.8	7.0
D5	29.8	36.1	37.9	17.45	4.75	5	5.1	5.9	2.0	13.6
D7.5	33.4	40.4	41.5	17.33	2.65	5.1	5.2	5.5	1.9	5.5
D10	34.7	42.6	46.1	18.54	7.59	5.1	5.3	5.8	3.8	8.6
M5	30.3	39.4	40.9	23.10	3.67	5.1	5.3	6	3.8	11.7
M7.5	29.5	39.9	41.1	26.07	2.92	5.1	5.1	5.6	0.0	8.9
M10	25.8	31.1	31.3	17.04	0.64	4.8	5	5.1	4.0	2.0
D5M5	34.2	39.7	42.4	13.85	6.37	5.4	5.5	6.1	1.8	9.8
D10M5	35.3	42	43.8	15.95	4.11	5.3	5.5	6.1	3.6	9.8
D5M10	29.5	39.2	41.3	24.74	5.08	5.1	5.2	5.5	1.9	5.5
D10M10	30.3	37.5	40.5	19.20	7.41	5.1	5.3	5.4	3.8	1.9
	30.9	38.5	40.22	19.68	4.16	5.11	5.25	5.70	2.76	7.65

Hebhoub et al. (2011), stated that seventy percent of the marble considered as a waste during the process of mining and preparation of the materials. This huge amount of waste should be used in one way or another, to reduce the negative environmental impact of the marble. As the marble consumption grows and consequently, the production of marble increases, which in turn, decreases the strategic natural resources from the raw material. This waste is of alarming danger to the environment and require large areas of well-designed and prepared landfills.

The usage of ceramic waste has significant importance economically and environmentally; especially that it is considered as a safe disposal method for this type of construction wastes. Raval et al. (2013), tested the compressive strength and tensile strength of ceramic concrete concluded that, by increasing the replacement percentage of cement by ceramic powder up to 30% by weight, the compressive strength of the M20 grade concrete also increase. Any increase above this percentage in the cement replacement is accompanied by decrease in the strength. The 30% replacement for cement by ceramic powder gives 22.98 MPa for the compressive strength, and the cost of the cement reduced by 12.67% in the M20 grade concrete. Table 3, shows the design mix weights and volumes according to the Indian standard methods (IS 10262-2009), according to the same standards all the test samples were prepared. Table 4, identifies the design mix and the percentage of replacement for the cement in the concrete specimens.

This makes the concrete more economic without compromising its strength than the standard concrete and makes the concrete with ceramic powder used; technically and economically feasible and viable.

Table 3. Concrete mix design for cement replacement Raval et al. (2013)

	Water (Liter)	Cement (kg/m^3)	F.A. (kg/m^3)	C.A. (kg/m^3)		Chemical admixture
				20 mm	10 mm	
By Weight (kg)	169.3	325.5	730.2	759.2	506.1	2
By Volume (m^3)	0.52	1	1.8	2.35	1.49	–

Table 4. Different percentage of replacement Raval et al. (2013)

Number	Concrete type	Replacement percentage for cement by ceramic waste
1	A0	Standard concrete
2	A1	10% replacement
3	A2	20% replacement
4	A3	30% replacement
5	A4	40% replacement
6	A5	50% replacement

Giridhar et al. (2015), designed the concrete mix according to the Indian standard methods (IS 10262-2009), the mix proportions were as follows (0.48:1:1.53:2.88) - (Water: Cement: Fine Aggregate: Coarse Aggregate), as shown in Table 5. The mix design was done by weight for better concrete workability. As stated, the increase in ceramic waste coarse aggregate replacement in concrete, decreases the compressive strength values. At 100% replacement the compressive strength was found to be 32.15 MPa, which is more than the design target value –mean value- of the M20 grade concrete. Therefore, the 100% replacement concrete was assigned to be used as M20 grade concrete. The 40% replacement also gives a good compressive strength with loss for only 5.6%, which is marginal and could be tolerated. This ends up by the validity of using 40% replacement concrete to be used safely without taking into consideration the amount of loss in the compressive strength as it is not a significant value.

Split tensile strength results showed that the increase in the replacement percentage is accompanied by decrease in the tensile strength values. The results indicated that the decrease in the tensile strength is only 6.2% up to 20% replacement, which is a minor loss in the tensile strength. As a result, it was recommended that the usage of the 20% replacement concrete could be used safely instead of M20 grade concrete from the tensile strength tests.

Daniyal and Ahmad (2015), studied the fresh and hardened concrete properties for the replacement percentages from 0 to 50%-replacement of coarse aggregate by ceramic tiles aggregate-. The concrete mix was done according to the ratio (1:1.5:3) as shown in Table 6, and all the performed tests were according to the IS 516-1959. Slump,

Table 5. Concrete mix design with different replacement percentages Giridhar et al. (2015)

Number	Percentage of replacement	W/C ratio	Cement (kg/m^3)	FA (kg)	CA (kg)	Ceramic Aggregate (kg)	Water (Liter)
1	0	0.48	383	586	1103	0	183.8
2	20	0.48	383	586	882	221	183.8
3	40	0.48	383	586	662	441	183.8
4	60	0.48	383	586	441	662	183.8
5	80	0.48	383	586	221	882	183.8
6	100	0.48	383	586	0	1103	183.8

compressive strength, unit weight, and flexural strength were measured and the following results are obtained. For the fresh concrete, by increasing the replacement percentage the concrete workability decreases for all the mixtures by increasing the ceramic tile waste percentage. The concrete mass density decreases by increasing the water to cement ratio, also the density of concrete decreased by increasing the ceramic tile waste content. For the hardened concrete properties, regarding the concrete compressive strength, the concrete compressive strength increased by increasing the percentage of replacement up to certain limits, for example the 20% increase in the compressive strength for concrete with water to cement ratio of 0.4, 30% for concrete with water to cement ratio 0.5, and 40% for concrete with water to cement ratio of 0.6. The maximum compressive strength gained for concrete C5-10–10% replacement-. The increase in flexural strength was 32.2% higher than the flexural strength of the normal concrete, which means that the use of ceramic tile waste increases the flexural strength of concrete with considerable value. The use of ceramic tile waste in concrete has a useful effect, so as the usage of the ceramic waste in concrete enhance its properties, increase the compressive strength, the flexural strength, and also decrease its unit weight. The optimum use of ceramic tiles waste was found to be within the range of 10 to 30% of replacement.

Hemanth (2015), experimental program stated that the use of ceramic powder as replacement for fine aggregate, and the use of ceramic wastes as replacement of coarse aggregate enhanced the compressive strength by using 20% and 10% respectively. In case using both fine and coarse aggregate replacements simultaneously the compressive strength values increased in all cases. However, the optimum mix can be obtained by replacement of fine aggregate by 20% and the replacement of coarse aggregate by 10%. Also, by increasing the powder percentage, the workability of concrete increased, which means that the ceramic powder can be used in producing RMC “Ready Mix Concrete”. By using the ceramic as a replacement for the coarse aggregate minor improvements to the workability occurred. Regarding the concrete mix design, all the mixes were done according to the IS 10262:2009. Nine different mixes were done as shown if the following Table 7, showing the different percentages of replacement for the fine aggregate and coarse aggregate.

Table 6. Concrete mix design coarse aggregate replacement with different water-to-cement ratios Daniyal and Ahmad (2015)

Group	W/C ratio	Cement (kg/m^3)	Water (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Ceramic coarse aggregate (kg/m^3)
C4-0	**0.4**	300	120	450	900	0
C4-10		300	120	450	810	90
C4-20		300	120	450	720	180
C4-30		300	120	450	630	270
C4-40		300	120	450	540	360
C4-50		300	120	450	450	450
C5-0	**0.5**	300	150	450	900	0
C5-10		300	150	450	810	90
C5-20		300	150	450	720	180
C5-30		300	150	450	630	270
C5-40		300	150	450	540	360
C5-50		300	150	450	450	450
C6-0	**0.6**	300	180	450	900	0
C6-10		300	180	450	810	90
C6-20		300	180	450	720	180
C6-30		300	180	450	630	270
C6-40		300	180	450	540	360
C6-50		300	180	450	450	450

Shruthi et al. (2016), prepared a concrete mix –M20 grade- according to the IS 10262-2009, as shown in Table 8. The tests done on the specimens for the hardened concrete characteristics stated that, by the increase in the population the increase in the construction wastes also increase, which proves that the research on the usage of the construction wastes is a very important topic. The main concern of this study is to use the tiles wastes that come from the demolition of buildings, as partial replacement for aggregate in concrete mixes. The use of tiles in concrete has positive effects on the environment, also it helps in saving cost and non-renewable resources –natural aggregate–. The tile aggregate is cheaper than the natural aggregate. After all the experiments done on using tiles as a replacement for aggregate by certain amount of replacement the results are as follows, based on the compressive strength, split tensile strength tests. The maximum compressive strength was obtained from 30% replacement of natural aggregate by ceramic tile aggregate and the maximum split tensile strength was obtained from 30% replacement.

Table 7. Different percentage of replacement for fine aggregate and coarse aggregate Hemanth (2015)

Mix	Fine aggregate (%)		Coarse aggregate (%)	
	Sand	Tiles powder	C.A	Crushed tiles
A0	100	0	100	0
A1	100	0	90	10
A2	100	0	80	20
A3	90	10	100	0
A4	80	20	100	0
A5	90	10	90	10
A6	90	10	80	20
A7	80	20	90	10
A8	80	20	80	20

Table 8. Concrete mix design for different percentages of coarse aggregate replacement Shruthi et al. (2016)

Percentage of replacement of CTA	W/C ratio	Cement (kg/m^3)	Water (kg/m^3)	FA (kg/m^3)	CA (kg/m^3)	Ceramic coarse aggregate (kg/m^3)
0%	0.5	383.2	205.53	721.99	1099.66	NA
10%		383.2	220.79	721.99	989.7	94.7
20%		383.2	236.06	721.99	879.73	189.4
30%		383.2	251.33	721.99	769.76	284.1

Awoyera et al. (2016), focused in their study on the validity of using ceramic as a replacement for fine and coarse aggregate in concrete mix design. The concrete mix designed according to the British standards BS8110, as shown in Table 9 the concrete mix proportions. The results showed that the workability values for the ceramic waste aggregate concrete is better than the control concrete, for both coarse and fine aggregate replacements. The workability ranged between medium and high workability. And the mechanical properties of the ceramic waste aggregate (CWA) concrete enhanced, as the highest compressive strength and the highest split tensile strength were achieved from the 100% replacement of the natural aggregate by ceramic for both coarse and fine aggregate separately. The enhancement in the mechanical properties increase by the increase in the percentage of replacement, also within the scope of this study the ceramic waste aggregate concrete is suitable for construction. And also, if the strength is the main concern in the concrete mix design, the ceramic waste aggregate concrete is more efficient than the traditional concrete.

Table 9. Concrete mix for fine aggregate and coarse aggregate replacement Awoyera et al. (2016)

Mix	Cement (kg/m^3)	Fine aggregate (kg/m^3)		Coarse aggregate (kg/m^3)	
		Natural F.A.	CFA	Natural C.A.	CCA
CC	92	184	0	368	0
CFA-25	92	138	46	368	0
CFA-50	92	92	92	368	0
CFA-75	92	46	138	368	0
CFA-100	92	0	184	368	0
CCA-25	92	184	0	276	92
CCA-50	92	184	0	184	184
CCA-75	92	184	0	92	276
CCA-100	92	184	0	0	368

Adekunle et al. (2017), stated that concrete mixtures that uses ceramic waste is more sustainable and it uses the ceramic tiles as replacement for the aggregate in concrete with different replacement percentages making a new mixture with new properties – according to the ratio 1:2:4 Cement:FA:CA- as shown in Table 10 and 11. From the experimental results the compressive strength of concrete with 5% replacement can be used instead of the normal concrete as it deviates 11.37% from the strength of the control specimens after 28 days. Also, the deviation occurred due to the replacement of coarse aggregate by ceramic tile waste is 18.66% from the strength of the control specimens for compressive strength value corresponding to 25% replacement after 28 days. Regarding the ceramic tile fine replacement, it showed loss in concrete compressive strength up to 51.37% and 55.42% for 15% and 20% replacement respectively. These values are below the target strength of grade 20 concrete, so it is not recommended to use ceramic tiles as fine replacement in concrete with the mentioned percentages. For the coarse aggregate replacement, the concrete compressive strength reduced by using the replacement values 50% and 75% by 33.3% and 55.8% respectively corresponding to compressive strength values of 18.4 MPa and 12.2 MPa, which is also below the target strength values of grade 20 concrete. The optimum concrete mix design using ceramic tiles waste as a fine aggregate is 5% replacement, and the optimum concrete mix design using ceramic tiles as a coarse aggregate is 25% replacement. By increasing the percentage of replacement, the concrete mix for both fine and coarse aggregate replacement will not meet the target strength value of grade 20 concrete, which is from the code requirements as per BS 1881 part 4 (1997). Regarding the economical aspect, the use of ceramic tile as replacement of fine and coarse aggregate by 5% and 25% replacement respectively reduces the cost by 2.3% for every cubic meter of concrete.

Table 10. Concrete mix for fine aggregate replacement Adekunle et al. (2017)

Tile replacement (%)	W/C ratio	Cement (kg)	Sand (kg)	Granite (kg)
0	0.6	13.89	27.77	55.54
5		13.89	26.38	55.54
10		13.89	24.99	55.54
15		13.89	23.6	55.54
20		13.89	22.22	55.54

Table 11. Concrete mix for coarse aggregate replacement Adekunle et al. (2017)

Tile replacement (%)	W/C ratio	Cement (kg)	Sand (kg)	Granite (kg)
0	0.6	13.89	27.77	55.54
25		13.89	27.77	41.68
50		13.89	27.77	27.77
75		13.89	27.77	13.89

Sekar (2017), concluded that the usage of ceramic waste as a coarse aggregate replacement affect the concrete compressive strength, the optimum value in this study is 15% replacement. By experiments on the control beams and the beams using ceramic wastes, the ultimate load for the control beams is 610 KN, while the ultimate load for the 15% replacement is 600 KN, using the percentage of replacement shown in the following Table 12. The value of the ultimate load started to decrease by increasing the percentage of coarse aggregate by ceramic waste aggregate, as the ultimate load reached 565 KN and 550 KN for 30% and 45% replacement values respectively. So, the optimum percentage of replacement of coarse aggregate by ceramic is 15%.

Table 12. Concrete mix percentages of replacement Sekar (2017)

Mix	Percentage of replacement
C-15	15
C-30	30
C-45	45

Not only ceramic and marble; introducing RCA to the concrete is of main concern in research environmentally and economically. Concrete produced from the demolition of building and construction wastes contributes by 70% from the total amount of construction wastes, 14% for Asphalt concrete, 3% asphalt shingles, 2% brick and clay tiles, 1%

steel, 3% dry wall and plasters, 7% wood (USEPA 2016). This significant amount of concrete gives an indication on the importance of recycling this type of construction wastes and reusing it in the field of construction and especially in the concrete manufacture which is the second most consumed material (Ravindra et al. 2019).

The concrete compressive strength is the key characteristic property of concrete that is used to evaluate the concrete properties, quality and performance; as it has a significant correlation with other mechanical properties of concrete like tensile strength and flexural strength and also has a correlation with the concrete durability and its ability to resist abrasion, chemical penetration, and permeability. According to literature on the RCA collected from 79 publications used 977 different concrete mixes; the replacement of natural aggregates by RCA could not be studied just by studying the concrete mechanical properties; as the RCA concrete compressive strength at 28 days varied from a maximum and minimum values of 1.35 and 0.5 times the NA concrete compressive strength. This proves that the mechanical properties are not the only indication for the applicability of using such type of concrete (Ravindra et al. 2019).

The compressive strength decreases by increasing the replacement percentage of the NA by RCA. (Teranishi et al. 1998; Dhir et al. 1999; Limbachiya 2004; Etxeberria et al. 2007; Yang et al. 2008; Akbarnezhad et al. 2011; Fan et al. 2016). The concrete strength is directly related to the water to cement ratio, cement type, cement content, grain sizes and sources of aggregates used, the properties of the natural aggregates or recycled aggregates, and many other factors. All these factors should be studied comprehensively and correlated to the concrete compressive strength to determine the RCA concrete behavior (Ravindra et al. 2019).

The previous researches indicated different values for the optimum design of the concrete mixes for the coarse aggregate, fine aggregate, and cement replacement. However, the hardened concrete properties were not addressed in a comprehensive way, which means that the determination of the hardened concrete properties under the same conditions and the same materials to be used is not possible. In this research all the concrete mixes share the same materials and surrounding conditions to compare between the different characteristics fairly and without any change in the external factors that may affect the results and comparing it together.

4 Methodology

The concrete mix was designed according to the ACI code and the European standards. Fresh and hardened concrete properties were tested and analyzed to be compared by the traditional concrete. The required concrete strength is 35 MPa using natural aggregates, cement, and water to produce traditional normal concrete. Water to cement ratio was fixed for all the concrete mixes and equals to 0.48. the percentages of replacements of natural coarse aggregates by recycled concrete was 0%, 25%, 50%, 75%, and 100% -by volume- to be tested after 7, 28, and 90 days. The sustainable recycled aggregate concrete was designed to replace natural coarse aggregates by recycled concrete. Aggregates replacement was done by volume for different grain sizes. Using different sizes of aggregates by different percentages has a great impact on the enhancement of concrete fresh and hardened properties.

All aggregates used was oven dried till reaching constant mass; which means that the water content of the used aggregates equals to zero. Aggregates of different sizes were separated and sieves to remove fine marble dust less than 1 mm. the curing process for the fresh concrete specimens were done at room temperature (23 °C), and then demolded and transferred to water during the whole curing period. Specimens tested after 7, 28 and 90 days after measuring the exact dimensions for each type of specimens and calculate the exact force and stress in MPa. The machine used and the setup of the testing shown in Fig. 1.

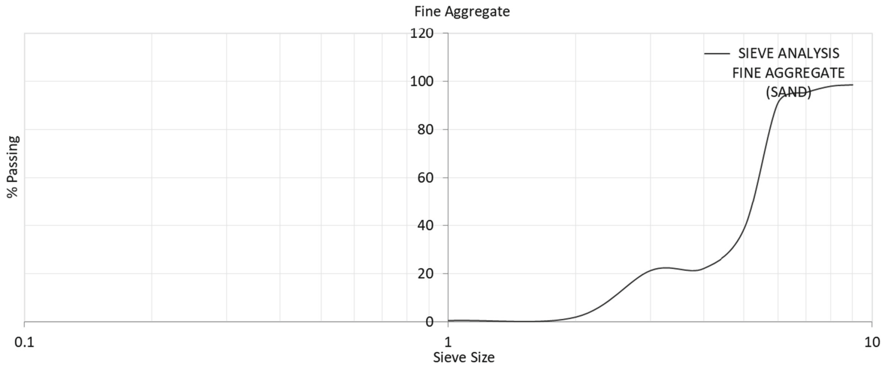

Fig. 1. Fine aggregate sieve analysis

After testing different types of sustainable concrete, a mathematical model was established and validated to estimate the mechanical properties of concrete taking into account the type of aggregates used and its properties. This mathematical model leads to an equation that could be used to determine the different mechanical properties compressive, split tensile and flexural strength; this equation involves some fresh and hardened concrete properties and the properties of the aggregates used.

5 Materials Used

Cement

Cement grade used is 42.5R, the initial setting time is 180 min and the final setting time is 280 min. The compressive strength of the cement after 2 days and 28 days is 34 MPa and 61.5 MPa, respectively.

Sand

Sand with grain size 0–2 mm is used in the concrete mix design with the following sieve analysis curves as shown in Fig. 2. The moisture content of sand is 0.1%.

Coarse Aggregates

Coarse aggregates, natural and recycled, with sizes from 2 mm to 16 mm are used with sieve analysis grading curves shown in Fig. 3. The used natural aggregates are well sieved, washed, and dried. recycled aggregate was used after being well dried until

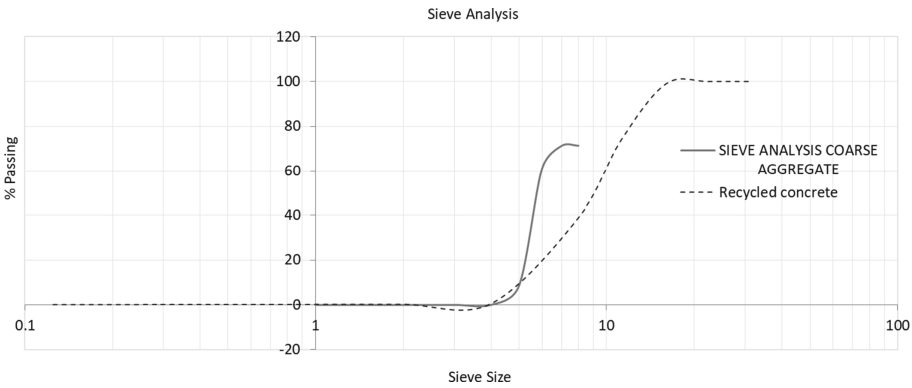

Fig. 2. Coarse aggregate sieve analysis (natural and recycled concrete aggregates)

constant mass. RCA abrasion, durability due to impact, moisture content and absorption were tested and found to be 30%, 25.6, 0 and 3.47 respectively. Same properties were tested for the natural aggregates to be able to compare the material properties and its effect on the green concrete behavior and found to be 41.1%, 30.6, 0.1 and 1.52 respectively.

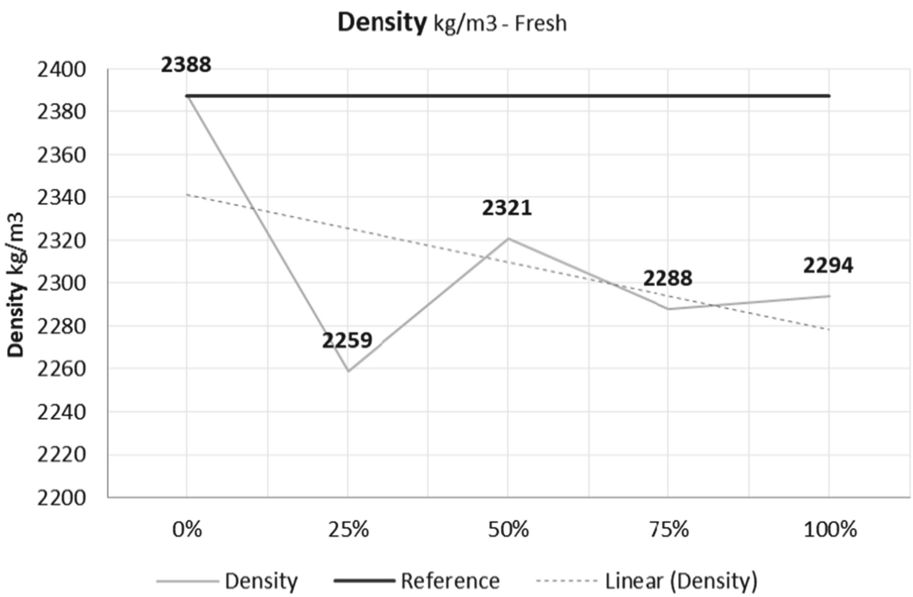

Fig. 3. Density of fresh concrete

Water

The properties of water as specified in the ACI, potable water should be used in concrete mixing with the accurate percentage and weight according to the design of the concrete mix.

6 Results and Discussion

Mechanical properties of concrete were tested using cubes (100 * 100 * 100 mm), cylinders (100 * 200 mm) and prisms (75 * 75 * 280 mm) to test concrete compressive strength, split tensile strength and flexural strength respectively.

Density

Density of fresh concrete shown in Fig. 4 slightly decreased by increasing the percentage of coarse aggregate in the concrete mix. The concrete density compared to the reference normal concrete decreased to reach 94.62%, 97.21%, 95.83% and 96.08% for 25%, 50%, 75% and 100% replacement of coarse aggregates by recycled aggregates; respectively.

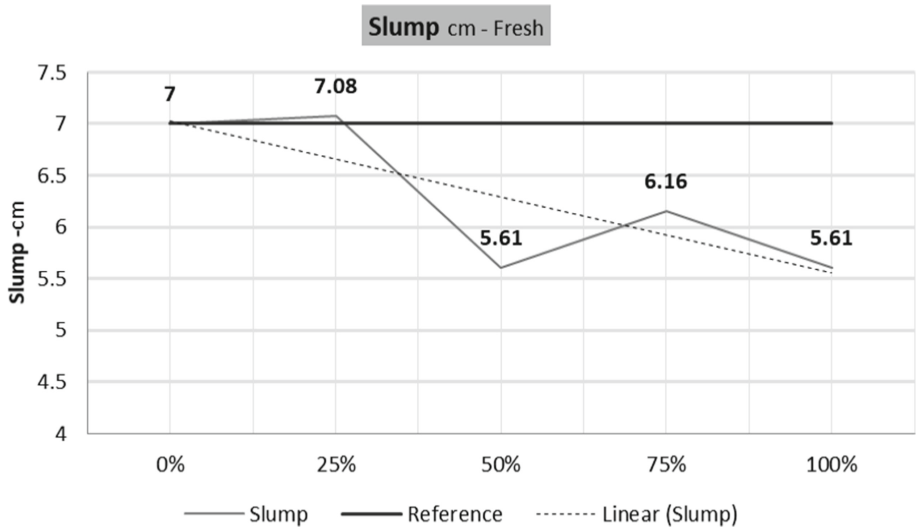

Fig. 4. Fresh concrete slump values

Slump

Slump values for the recycled aggregate concrete are all within the design range from 5 cm to 7 cm, as shown in Fig. 5. The slump values started to decrease by increasing the percentage of coarse aggregate replacement by recycled aggregate after the 25% replacement concrete which recorded slump value of 7.08 cm.

Shock Table

Shock table tests were performed on the recycled aggregate concrete to determine the quality of concrete concerning its consistency, as shown in Fig. 6, cohesiveness and its proneness to segregation. The reference value for the normal concrete was 40.5 cm and a slight decreasing behavior in the shock table test values was accompanied by increasing the percentage of replacement of natural aggregates with recycled aggregate. The minimum value was 37.5 cm and the maximum value was 41.5 cm which corresponds

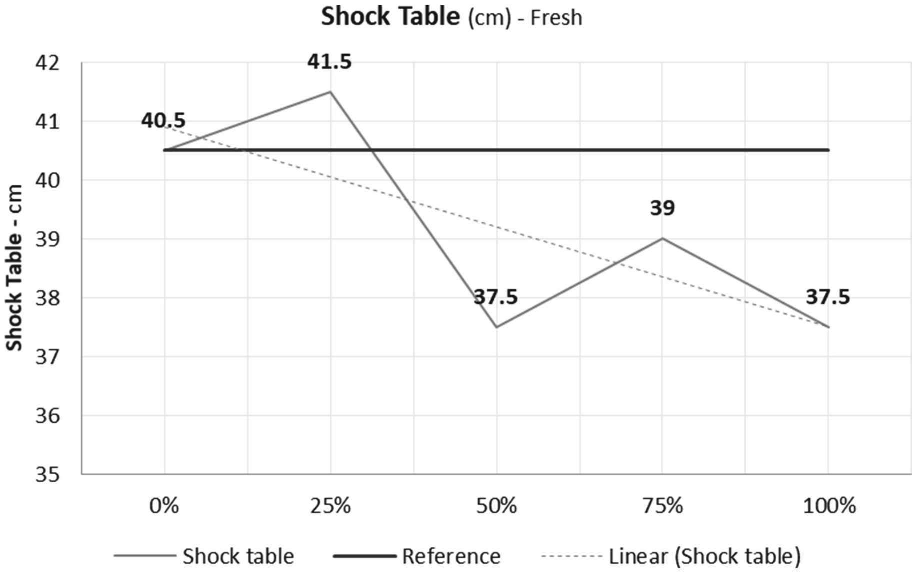

Fig. 5. Shock table values (measuring workability)

to the 50% and 25% replacement values, respectively. These values indicate concrete of class F2 (Plastic concrete), according to the European standards in the German index (DIN EN 206-1/DIN 1045-2); Table 13.

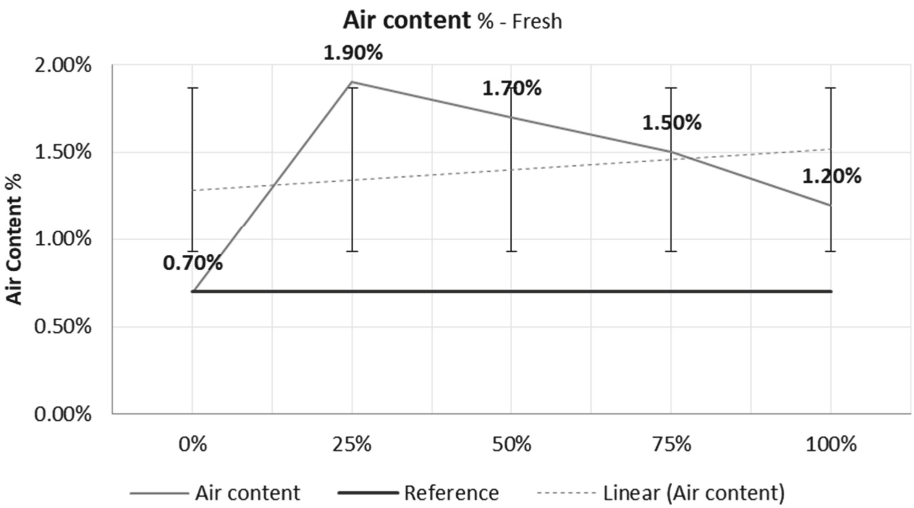

Fig. 6. Air content values for fresh concrete

Table 13. Workability classes as per the European standards

Grade	Slump values (mm)	Consistency range
F1	<340	Stiff
F2	350 to 410	Plastic
F3	420 to 480	Soft
F4	490 to 550	Very soft
F5	560 to 620	Very flowable
F6	≥630	Hardworking

Air Content

Air content values, as shown in Fig. 7, indicate all values are less than 2%, which is the value indicated by the requirements of ACI 318 match the recommended total air content values of ACI 210.2R, ACI 211.1, ACI 345, and ASTM C 94.

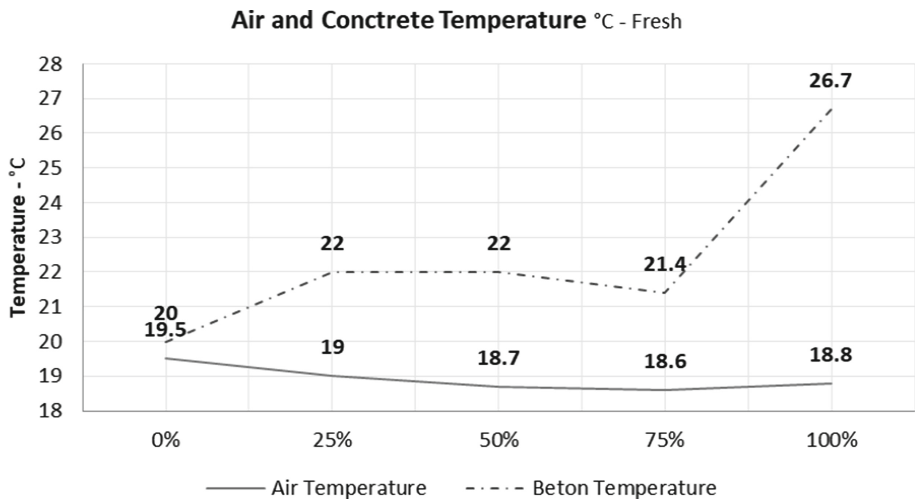

Fig. 7. Air and Concrete Temperature

Temperature

Concrete temperature had the same behavior of air temperature which indicates a strong relation between both temperatures; except for the 100% replacement of coarse aggregates by recycled aggregates which indicated an obvious increase in the concrete behavior as shown in Fig. 8.

Concrete Compressive Strength

As shown in Fig. 9 the average concrete compressive strength increased by increasing the percentage of recycled concrete starting from 100% which is the reference normal

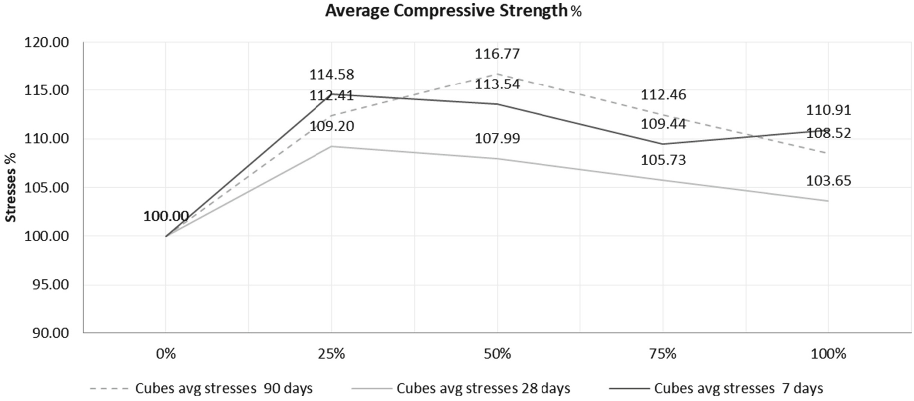

Fig. 8. Compressive Strength after different aging

concrete, then the compressive strength after the age of seven days increased to reach 114.58%, 113.54%, 109.44% and 110.91% for 25%, 50%, 75% and 100% replacement of coarse aggregates by recycled aggregates; respectively. After 28 days the concrete compressive strength improved to reach 109.2%, 107.99%, 105.73% and 103.65% for 25%, 50%, 75% and 100% replacement of coarse aggregates by recycled aggregates; respectively. the compressive strength after age of 90 days, reached an increase by 9% at the full replacement of the natural aggregates by the RCA when compared to the traditional concrete compressive strength at the same age. Traditional concrete compressive strength value after 90 days is 100%, reaching 112.41%, 116.77% and 112.46%, 108.52% for replacement percentages equivalent to 25%, 50%, 75% and 100% respectively.

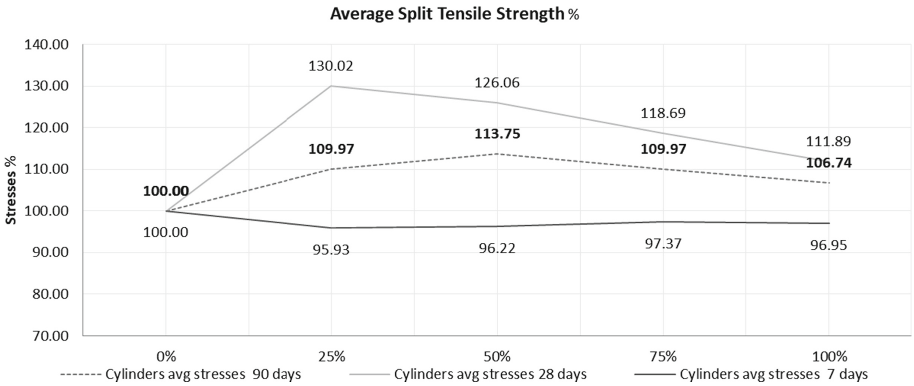

Fig. 9. Split tensile Strength after different aging

Concrete Split Tensile Strength

Figure 10 shows the concrete split tensile strength values which decreased slightly after the age of seven days and increased at the age of twenty-eight days. The concrete split tensile strength after 7 days decreased by approximately 4%, 4%, 3% and 3% for 25%, 50%, 75% and 100% replacement of coarse aggregates by recycled aggregates; respectively. An increase in the split tensile strength occurred after 28 days by 30%, 26%, 19% and 12% for 25%, 50%, 75% and 100% replacement of coarse aggregates by recycled aggregates; respectively. By increasing the recycled concrete aggregates in concrete after 90 days the concrete flexural strength increased reaching 109.97%, 113.75%, 109.97% and 106.74% for percentages of replacements 25%, 50%, 75% and 100% respectively. The value of seven percent gain strength was recorded for the 100% replacement when compared to the traditional concrete.

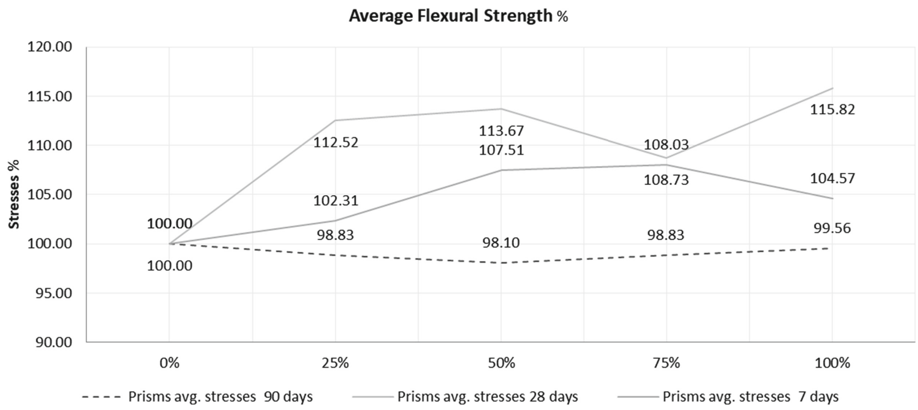

Fig. 10. Flexural Strength after different aging

Concrete Flexural Strength

The average flexural strength shown in Fig. 11 increased by increasing the percentages of replacement of coarse aggregates by recycled concrete aggregates after aging of seven and twenty-eight days. At the age of seven days the flexural strength increased from 100% to 102.31%, 107.51%, 108.03% and 104.57% for 25%, 50%, 75% and 100% replacement of coarse aggregates by recycled aggregates; respectively. After 28 days the flexural strength gained higher values of strength reaching 112.52%, 113.67%, 108.73% and 115.87% for 25%, 50%, 75% and 100% replacement of coarse aggregates by recycled aggregates; respectively. The flexural strength of concrete after age of 90 days which decreased from 100% for the traditional concrete reaching 98.93%, 98.1%, 98.83% and 99.56% for 25%, 50%, 75% and 100% replacement values for natural aggregates by RCA.

Microstructure Analysis

All the microstructure analysis tests showed a perfect bond between the concrete particles especially at the interfacial transition zone (ITZ), nonoccurrence of micropores, air voids and microcracks. The concrete microstructure images showed homogenous paste as shown in the following Figs. 11, 12, 13, 14 and 15.

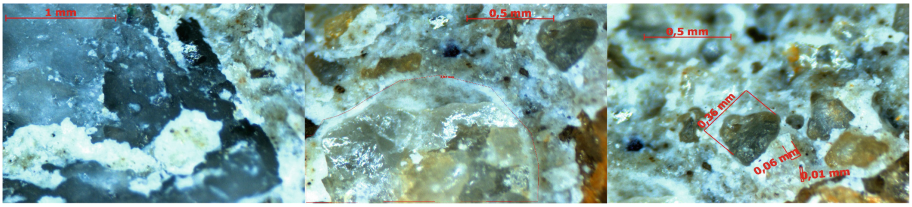

Fig. 11. Microstructure analysis for reference concrete

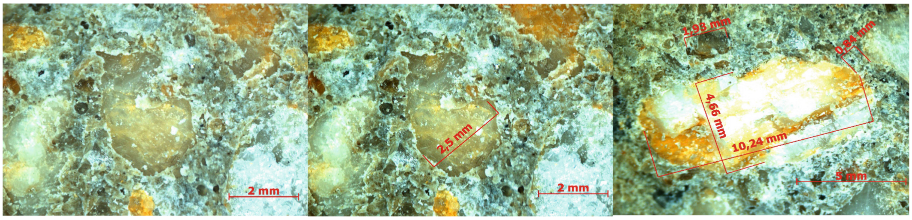

Fig. 12. Microstructure analysis for RCA concrete 25%

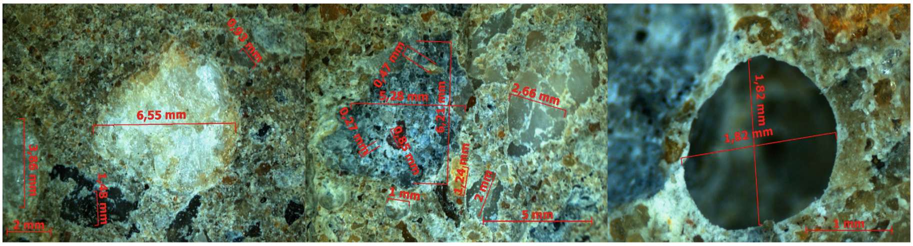

Fig. 13. Microstructure analysis for RCA concrete 50%

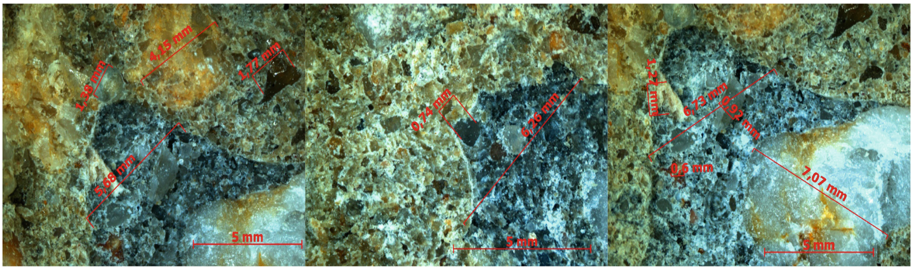

Fig. 14. Microstructure analysis for RCA concrete 75%

Resistance to Abrasion

The concrete resistance to abrasion was tested according to the DIN 52108 standards, for both the normal concrete and the RCA concrete and the results showed a decrease in the resistance to abrasion by increasing the percentage of the RCA in concrete till

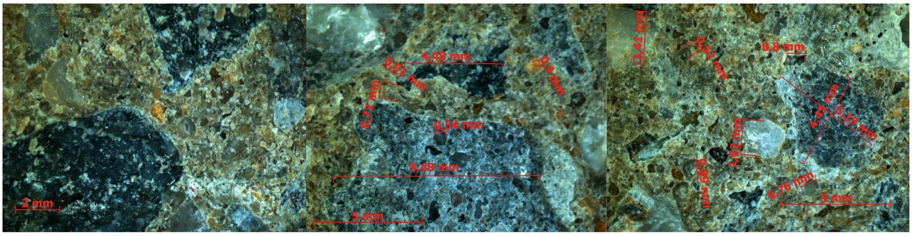

Fig. 15. Microstructure analysis for RCA concrete 100%

reaching 50% replacement. The behavior of the RCA after the 50% replacement showed an increase in the concrete abrasion resistance for the 75% and 100% replacement. However, the 100% replacement of natural aggregates by RCA showed a decrease in the resistance due to abrasion by 13% when compared to the normal concrete, as shown in Fig. 16.

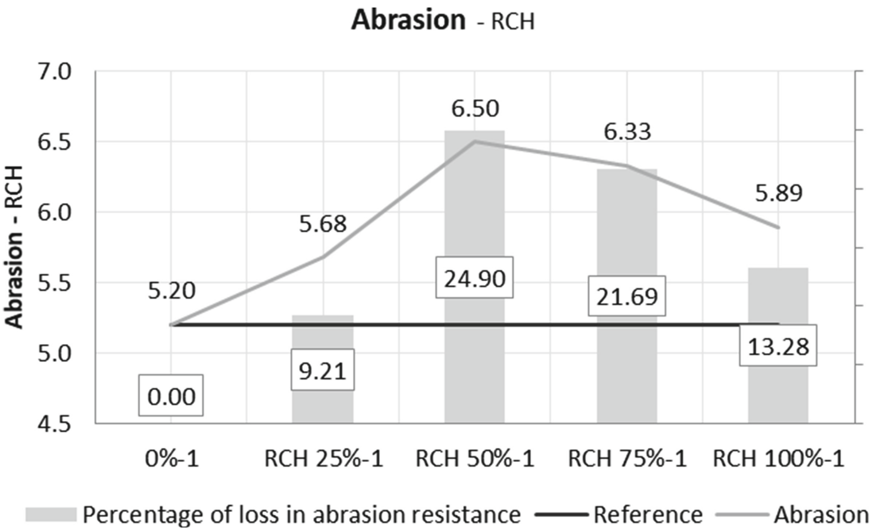

Fig. 16. Abrasion resistance for RCA concrete

7 Failure Modes

All failure modes were observed and photographed; compared to the traditional concrete failure mode and were found similar in all percentages of replacement. The cracking and failure behavior of specimens were observed to determine the ductile behavior of the manufactured concrete. After testing all the failure modes and the cracking behavior of the different kinds of specimens -cubes, cylinders, and prisms- the concrete behavior was determined as ductile -including the reference specimens- compared to other specimens from other batches.

8 Mathematical Model and Design Equation

A design equation concluded from the green concrete fresh and hardened properties Eq. (1), estimates the average concrete compressive strength after seven days of curing. The design equation includes the fresh concrete density, concrete air content at fresh state, slump values, air temperature at the time of mixing, and the concrete temperature at mixing time. The aggregates hardness factor could be selected from the Tables 14 a, b, and c.

Table 14. (a, b & c) Aggregates properties that determines the concrete mechanical properties and factors in the green concrete design equation first mathematical model

Shape	
Aggregates Roughness Factor	
Normal Aggregate	1
Marble	1
Ceramic	1.45
Recycled Concrete	1.55

Hardness tests	
Aggregates Hardness Factor	
Normal Aggregate	1
Marble	0.95
Ceramic	0.35
Recycled Concrete	0.78

Cumulative	
Aggregates Hardness Factor	
Normal Aggregate	1
Marble	0.95
Ceramic	0.5
Recycled Concrete	1.2

Where; density in kg/cm^3, Air content in %, Slump and shock table in centimeters, Air and concrete temperatures in °C, Aggregates Hardness Factor from Table 14-c.

$$\text{Average Concrete Compressive Strength (7 days)} = ((\text{Density} + \text{Air content} + \text{Slump} + \text{shock table} + \text{Air Temperature} + \text{Concrete Temperature}) * \text{AHF})/55.2 \quad (1)$$

9 Conclusions

Using recycled concrete aggregates in sustainable green concrete manufacture enhanced the fresh and hardened concrete properties significantly especially at the full replacement of natural aggregates by the recycled concrete aggregates; after testing different percentages of replacements -25%, 50%, 75% and 100%- in green concrete and comparing the results by the reference normal concrete. The benefit from this full replacement of coarse aggregates by sustainable recycled concrete aggregates has environmental and economical benefits in addition to the improvement of the concrete characteristics under the same water to cement ratio and external factors with high quality control and restrictions during concrete mixing, pouring curing and testing.

The tests done on the concrete mechanical and microstructure properties proved the usability of RCA-concrete for high strength structural elements reaching 66.2 MPa, 3.96 MPa and 6.8 MPa for concrete compressive, split tensile and flexural strength after 90 days respectively.

References

Adams, M.P.: Alkali-silica reaction in concrete containing recycled concrete aggregates (Doctoral dissertation) (2012)

Adekunle, A.A., Abimbola, K.R., Familusi, A.O.: Utilization of construction waste tiles as a replacement for fine aggregates in concrete. Eng. Technol. Appl. Sci. Res. **7**(5), 1930–1933 (2017)

Akbarnezhad, A., Ong, K.C.G., Zhang, M.H., Tam, C.T., Foo, T.W.J.: Microwave-assisted beneficiation of recycled concrete aggregates. Constr. Build. Mater. **25**(8), 3469–3479 (2011)

Ananda Ramakrishna, K., Sateesh Babu, K., Guravaiah, T., Naveen, N., Sk, J.: Effect of waste ceramic tiles in partial replacement of coarse and fine aggregate of concrete. Int. Adv. Res. J. Sci. Eng. Technol. **2**(6), 13–16 (2015)

ASTM, C.: Standard test method for flexural strength of concrete (using simple beam with third-point loading). American Society for Testing and Materials, Philadelphia, PA (1999)

Basri, H.B., Mannan, M.A., Zain, M.F.M.: Concrete using waste oil palm shells as aggregate. Cem. Concr. Res. **29**(4), 619–622 (1999)

Binici, H.: Effect of crushed ceramic and basaltic pumice as fine aggregates on concrete mortars properties. Constr. Build. Mater. **21**(6), 1191–1197 (2007)

Binici, H., Shah, T., Aksogan, O., Kaplan, H.: Durability of concrete made with granite and marble as recycle aggregates. J. Mater. Process. Technol. **208**(1–3), 299–308 (2008)

Code, E.: Egyptian Code of Practice for Concrete Structures, HBRC. Arabic, Cairo, Egypt (2007)

Daniyal, M., Ahmad, S.: Application of waste ceramic tile aggregates in concrete. Int. J. Innov. Res. Sci. Eng. Technol. **4**(12), 12808–12815 (2015)

Ergün, A.: Effects of the usage of diatomite and waste marble powder as partial replacement of cement on the mechanical properties of concrete. Constr. Build. Mater. **25**(2), 806–812 (2011)

Etxeberria, M., Vazquez, E., Mari, A., Barra, M.: Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete. Cem. Concr. Res. **37**(5), 735–742 (2007)

Fan, C.C., Huang, R., Hwang, H., Chao, S.J.: Properties of concrete incorporating fine recycled aggregates from crushed concrete wastes. Constr. Build. Mater. **112**, 708–715 (2016)

Giridhar, V., Rao, H.S., Kumar, P.S.P.: influence of ceramic waste aggregate properties on strength of ceramic waste aggregate concrete. Int. J. Res. Eng. Technol. **4** (2015)

Hebhoub, H., Aoun, H., Belachia, M., Houari, H., Ghorbel, E.: Use of waste marble aggregates in concrete. Constr. Build. Mater. **25**(3), 1167–1171 (2011)

Heidelberg Cement, AG: Concrete technical data (2014)

Heidelberg Cement, AG: Concrete technical data (2017)

IS 10262-2009: Concrete mix proportioning—guidelines

Kavitha, B., Sundar, M.L.: Experimental study on partial replacement of coarse aggregate with ceramic tile wastes and cement with glass powder (2017)

Khalaf, F.M., DeVenny, A.S.: Recycling of demolished masonry rubble as coarse aggregate in concrete. J. Mater. Civ. Eng. **16**(4), 331–340 (2004)

Kou, S.C., Poon, C.S., Lam, L., Chan, D.: Hardened properties of recycled aggregate concrete prepared with fly ash. In: Limbachiya, M.C., Roberts, J.J. (eds.) Proceedings of the International Conference on Sustainable Waste Management and Recycling: Challenges and Opportunities, London, UK, pp. 189–197 (2004)

Kumar, P.S., Mannan, M.A., Kurian, V.J., Achuytha, H.: Investigation on the flexural behaviour of high-performance reinforced concrete beams using sandstone aggregates. Build. Environ. **42**(7), 2622–2629 (2007)

Manso, J.M., Polanco, J.A., Losanez, M., Gonzalez, J.J.: Durability of concrete made with EAF slag as aggregate. Cem. Concr. Compos. **28**(6), 528–534 (2006)

Medina, C., De Rojas, M.S., Frías, M.: Reuse of sanitary ceramic wastes as coarse aggregate in eco-efficient concretes. Cem. Concr. Compos. **34**(1), 48–54 (2012)

El-Hawary, M.T., Hanna, N.F., El-Nemr, A.M., Koenke, C.: Using construction wastes and recyclable materials in sustainable concrete manufacture. In: ICSBMCT 2020: 14 International Conference on Sustainable Building Materials and Construction Technologies at Barcelona, Spain (2020)

Nataraja, M.C., Nagaraj, T.S., Reddy, A.: Proportioning concrete mixes with quarry wastes. Cem. Concr. Aggreg. **23**(2), 81–87 (2001)

Nehdi, M., Khan, A.: Cementitious composites containing recycled tire rubber: an overview of engineering properties and potential applications. Cem. Concr. Aggreg. **23**(1), 3–10 (2001)

Obe, R.K.D., de Brito, J., Silva, R.V., Lye, C.Q.: Sustainable Construction Materials: Recycled Aggregates. Woodhead Publishing, Sawston (2019)

Palmquist, S.M., Jansen, D.C., Swan, C.W.: Compressive behavior of concrete with vitrified soil aggregate. J. Mater. Civ. Eng. **13**(5), 389–394 (2001)

Vanghiyan, R.: Workability by replacement of cement with waste glass. Int. J. Innov. Res. Sci. Eng. Technol. **3**(7) (2013)

Raval, A.D., Patel, I.N., Pitroda, J.: Ceramic waste: Effective replacement of cement for establishing sustainable concrete. Int. J. Eng. Trends Technol. (IJETT) **4**(6), 2324–2329 (2013)

Senthamarai, R.M., Manoharan, P.D.: Concrete with ceramic waste aggregate. Cem. Concr. Compos. **27**(9–10), 910–913 (2005)

Taj, S., Pasha, S.R.: Reuse of Ceramic Waste as Aggregate in Concrete (2016)

Teranishi, K., Dosho, Y., Narikawa, M., Kikuchi, M.: Application of recycled aggregate concrete for structural concrete. Part 3-production of recycled aggregate by real-scale plant and quality of recycled aggregate concrete. In: Sustainable Construction: Use of Recycled Concrete Aggregate: Proceedings of the International Symposium Organised by the Concrete Technology Unit, University of Dundee and held at the Department of Trade and Industry Conference Centre, London, UK, 11–12 November 1998, pp. 143–156. Thomas Telford Publishing (1998)

Tests, C.S.: ASTM C 39/C 39 M; test one set of two laboratory-cured specimens at 7 days and one set of two specimens at 28 days. a. Test one set of two field-cured specimens at, 7

USEPA: Construction and Demolition Debris Generation in the United States. U.S. Environment Protection Agency, Office of Resource Conservation and Recovery (2016). 23 p

Yang, K., Chung, H., Ashour, A.: Influence of type and replacement level of recycled aggregates on concrete properties. ACI Mater. J. **105**(3), 289–296 (2008)

Zimbili, O., Salim, W., Ndambuki, M.: A review on the usage of ceramic wastes in concrete production. Int. J. Civ. Archit. Struct. Constr. Eng. **8**, 91–95 (2014)