BOND STRENGTH OF CONCRETE CONTAINING DIFFERENT RECYCLED COARSE AGGREGATES

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Abstract

Some of the remnants of construction demolition wastes could be used after recycling as coarse aggregate in concrete industry. Among these wastes are ceramics, shale bricks and hardened concrete. This research was carried out to determine the effect of using such recycled aggregate (RA) as total or partial replacement of the natural dolomite coarse aggregate in concrete mixes on their compressive and bond strength with steel bars. Two types of concrete were investigated in this research which included normal concrete and self-compacted concrete. The main variables taken into consideration wee, the type of concrete, the type and percentage of the recycled aggregate and the age of testing. The consistency of the normal fresh concrete was measured by the slump test. However, the workability and flowability of the self-compacted fresh concrete were measured using slump test, V-funnel test. Out of the experimental test results, equations were predicted which correlated between the concrete compressive strength and bond strength of both the recycled aggregate ordinary concrete and the recycled aggregate self-compacted concrete. These equations were completely different than that of the steel-concrete bond equation of concrete with natural aggregate. Out of this research results, the recycled aggregate concrete could be used in both non structural applications and in some structural applications with special precautions.

Keywords: recycled concrete- recycled materials, Compressive Strength- bond strength, equations

1. Introduction

The remnants of construction demolition wastes represent environmental, health and economic tremendous problems. However, these problems could be partially solved by using these wastes after recycling as coarse aggregate in concrete manufacture. Among these wastes are ceramics, marble, cement bricks, red bricks and lightweight bricks. The tendency to use recycled materials helps in saving the limited landfill space. Among different types of materials, concrete waste represents about 50% of the total construction demolition wastes. Ready mixed concrete batching plant generates a significant quantity of fresh concrete waste through the over-order from construction sites [1, 2].

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The recycled grinded tire rubber was investigated by W. H. Yung *et al.*, [3] as fine aggregate in concrete manufacture. The effect of recycled materials on the properties fresh and hardened properties as well as the durability of self-compacted concrete mixes was studied.

The influence of recycled aggregates on the permeability properties of self-compacting concrete were studied by L. A. Pereira-de-Oliveira *et al.*, [4] with partial or total replacement of the natural aggregates (20 , 40 and 100%). The results showed that the feasibility of using the recycled aggregate as a replacement for coarse aggregate. The reuse of recycled lime powder (RLP) and recycled concrete (RCA) showed their effectiveness as deposed to landfill in sites in Cyprus. Results show that both (RLP) and (RCA) could produce good quality and robust concrete mixtures both in terms of mechanical and durability performance [A. Kanellopoulos *et al.*, [5]]. The properties of fresh and hardened recycled aggregate self-compacting concrete were studied by M. Kamal *et al.*, [6-9]. The prolonged properties of RSCC were improved by fibers with different percentages. Some types of recycled coarse aggregate (crush gravel and crush limestone) were used by Khaleel *et al.*, [10] to produce self-compacting concrete. It was found that the flowability of SCC decrease with the increase in the maximum nominal size of coarse aggregate when using crushed aggregate with the same water to powder ratio and superplasticizer dosage. The advantage of using self-compacted concrete on the sound environmental was stated [Z. J. Grdic *et al.*, [11]]. The using of crushed concrete as a recycled aggregate in self-compacted concrete manufacture showed much closed mechanical properties to the concrete cast with natural coarse aggregate. The mechanical properties were affected by the maximum nominal size texture and type of coarse aggregate [11]. The properties of fresh SCC which included the workability and density were investigated by P. B. Cachim, [12] using recycled crushed bricks as coarse aggregate. The compressive, splitting tensile strength, modulus of elasticity and stress–strain behavior were also investigated for the hardened concrete [12]. The Permeation properties which include permeability, absorption and diffusivity were widely used to quantify durability characteristics of SCC [W. Zhu and P. J. M. Bartos, [13]]. SCC mixes with characteristic cube strength of 40 and 60 MPa were designed containing either additional powder as filler or containing no filler but using viscosity agent. The results indicated that the SCC mixes had significantly lower oxygen permeability and absorptivity than the vibrated normal concretes of the same strength grades. The chloride diffusivity, however, appeared to be much dependent on the type of filler used. SCC mixes containing no additional powder but using viscosity agent showed higher diffusivity than the normal vibrated concrete mixes and the other SCC mixes.

2. Research significant

This research was carried out to determine the effect of using recycled materials out of the demolition on the building as coarse aggregate on the fresh and properties of normal concrete and self-compacted concrete mixes. The recycled demolition waste material used as partial or total replacement of the natural dolomite coarse aggregate with concrete mixes. The main variables of the study were the type of the demolition wastes (ceramics, shale bricks and hardened concrete). The ratio of replacement of the natural dolomite aggregate and the age of testing. Special attention was carried out regarding the cube compressive strength and the steel-concrete bond strength at different testing ages. New equations were achieved to correlate the relation between the compressive strength and the bond strength for mixes containing different percentage of recycled aggregates at different ages of concrete testing.

3. Experimental Study

To achieve the aim of the research, twenty-six mixes were prepared from recycled aggregate self-compacted concrete (RSCC) and recycled aggregate normal concrete (RC). Different types of recycled materials (crushed ceramic, crushed shale brick and crushed concrete) were used as coarse aggregate in the concrete mixes. The recycled materials replaced the dolomite aggregate partially or totally in the concrete mixes. The replacement ratios were 25, 50, 75 and 100 percent by weight. A total of 300 cubes $100 \times 100 \times 100$ mm were tested to determine the compressive strength of the mixes at 3, 7 and 28 days. A total of 300 Cylinders with 200 mm in height and 100 mm in diameter with central steel rod(ϕ10 mm) were tested to determine the bond strength of the mixes at 3, 7, 28 days.

3.1. Materials

Locally produced ordinary Portland cement (CEM I 52.5 N) conforming to the requirements of E.S.S. 4756-1/2007 [14] with specific gravity of 3.16 and Blain fineness of 4850 cm^2/gm was used. Well, graded siliceous sand was used with a specific gravity of 2.65, absorption of 0.78 %, and a fineness modulus of 2.63. Coarse aggregate of crushed dolomite with maximum nominal sizes of 10 mm was used, with a specific gravity 2.65, absorption of 2% and a crushing modulus of 19 %. Crushed shale brick, crushed ceramic and crushed concrete were used as recycled coarse aggregate. Crushed shale brick particles with maximum nominal size of 10 mm were used, with specific gravity 1.68, fracture modules 37.8 and absorption of 5.65%. Crushed ceramic with maximum nominal size of 10 mm was used, with specific gravity 2.7 and absorption of 3.48 %. Crushed concrete particles were produced by crushing of concrete cubes were used for compressive strength testing. The strength class

of concrete cubes was C30/37. Crushed concrete with maximum nominal size of 10 mm was used, with specific gravity 2.75 and absorption of 1.45%. Fig. 1 illustrates the grading and shapes of the different types of waste materials used as coarse aggregate. Imported class (F) fly ash meeting the requirements of ASTM C618 [15] with a specific gravity of 2.1 was used. The cement content was 400 kg/m^3 and the water powder (fly ash +cement) ratio (w/p) was 0.55. Tap water was used for mixing the concrete. A high range water reducer (HRWR) was used as superplasticizer meeting the requirements of ASTM C494 (type A and F) [16]. The admixture is a brown liquid having a density of 1.18 kg/liter at room temperature. The amount of HRWR was 2.5% and 0.5% of the powder (fly ash + cement) weight for RSCC and RC, respectively. Steel bars from high tensile ribbed steel bars of 10 mm diameter were cut into 230 mm long and inserted in the center of the concrete bond test specimens before the concrete casting (Fig. 2).

Crushed ceramic   Shale brick

Crushed concrete
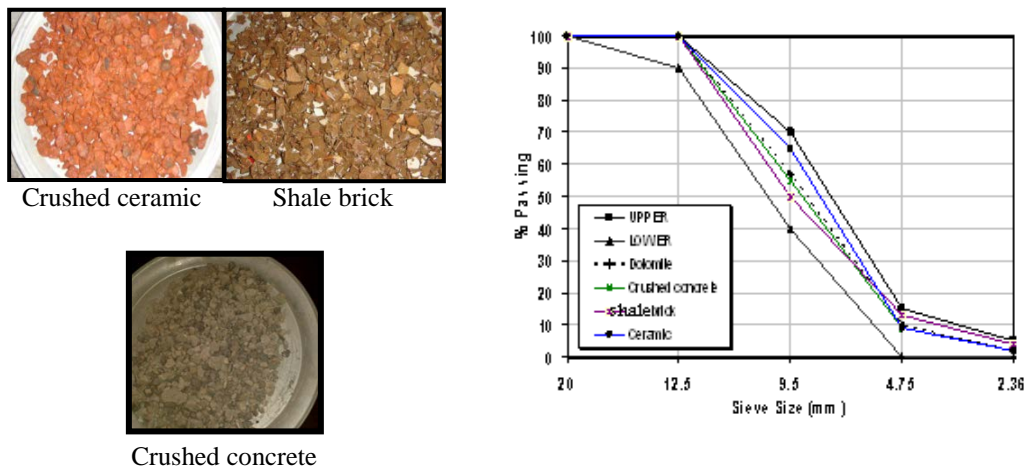
Figure 1: Waste materials used as a coarse aggregate.
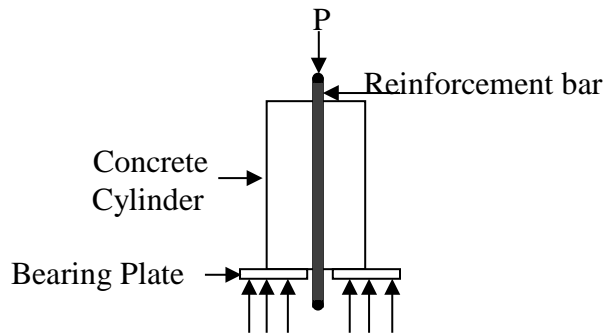
Figure 2: Configuration of push-out bond test.

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3.2. Casting and testing procedures

Coarse aggregate, fine aggregate, and the cement were mixed for 1 minute in the dry state before water and the admixtures were added. The mixing time after the slurry (water, fly ash, and HRWR) was added for (3-4) minutes to ensure full mixing. Recycled aggregate concrete (self-compacted concrete and normal concrete) was made using recycled aggregate with a maximum nominal size of 10 mm (shale brick, ceramic and crushed concrete) replaced by crushed dolomite.

The replacement levels by weight were 25%, 50%, 75%and 100% of the dolomite. The properties of fresh recycled aggregate self-compacted concrete (RSCC) were determined by different methods, which included the normal slump test, V-funnel test and J-ring test. The workability of recycled normal concrete (RNC) was determined by slump test. The concrete specimens were cast and kept at the steel moulds for 24 hours. After 24 hours, they were removed from the molds and submerged in water at 20°C until testing. 2000 KN capacity compressive strength testing machine was used in the determination of the compressive strength and bond strength.

Test specimens were designed by letter S or N for type of concrete used (S: for self-compacted concrete, N: Normal concrete) followed by C for control mix, R for Shale brick, E for crushed ceramic and N for crushed concrete followed by the percentage of recycle aggregate replacement. For examples, SR25 means that mixes are self-compacted concrete with 25% crushed shale brick as a recycled coarse aggregate. Table 1 shows the mix proportions of recycled concrete.

The basic requirements of flowability as specified by the technical specification for SCC, [17] are satisfied for the recycled self- compacted concrete (RSCC). Figure (3) to (6) show the properties of fresh RSCC. Also, slump test was used to measure the workability of the recycled normal concrete mixes. The workability of the RNC was 60 ± 5 mm.

3.3. Mix Proportions

Table 1 shows the proportions of the mixes under investigations. The primary mix proportion was based on the natural aggregate concrete mix and no extra alteration was made with the addition of recycled aggregate. Replacement level of recycled aggregate is based on the weight.

Table 1: A proportion of recycled aggregate concrete mixes (kg/m^3).

	Mix code	Cement	W/C	Sand	Dolomite	Recycled agg.	Fly ash	BVF1
Recycled self-compacted concrete	SC				663	0		
	SR25				534	134		
	SR50				440	220		
	SR75				380	285		
	SR100				0	668		
	SE25				465	116		
	SE50		220	974	364	182	40	11
	SE75				294	221		
	SE100				0	250		
	SN25				497	166		
	SN50				331	332		
	SN75				166	497		
	SN100	400			0	663		
Recycled normal concrete	NC				1132	0		
	NR25				852	284		
	NR 50				571	570		
	NR 75				286	559		
	NR 100				0	1149		
	NE25				741	247		
	NE50		200	566	435	436	40	2
	NE75				197	590		
	NE100				0	714		
	NN25				849	283		
	NN50				566	566		
	NN75				283	849		
	NN100				0	1132		

4. Testing of Fresh Concrete

Figs. 2 to 5 show the properties of fresh recycled aggregate self-compacted concrete. The basic requirements of flowability were compared as specified by the technical specification for SCC, [17]. The results of slump and V-funnel test are shown in Figs. 2 to 5. Figs. 2 and 3 show the effect of percentage of recycled coarse aggregate on the flow diameter and flow time (T50 cm). Fig. 2 shows the increase in the flow diameter as a percentage of the recycled aggregate increases for all recycled aggregate types. All mixtures using recycled aggregate show a slump flow diameter between 700-1020 mm which achieves the requirements of SCC. This shows that all mixtures have enough deformability under their own weight. Fig. 3 illustrates an increase of T50 cm as percentage of recycled aggregate increases for all different types of recycled aggregate. T50 cm ranged from 2 to 3.6 sec for the different mixes. This shows that all mixtures achieve the requirements of SCC and have enough viscosity to flowability. This phenomenon depends on the type, the manufacturing process and properties of the recycle aggregated used in the concrete mix.
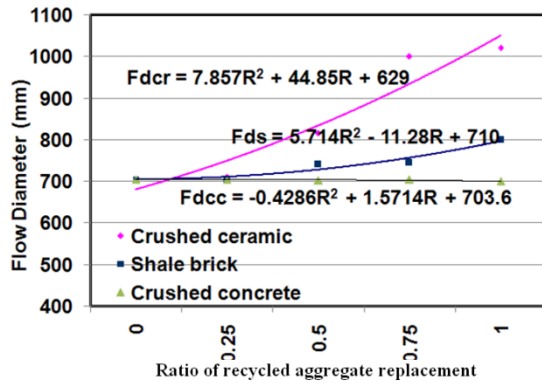
Figure 3: the relationship between the percentages of recycled and flow diameter for the recycled self-compacted concrete mixes.
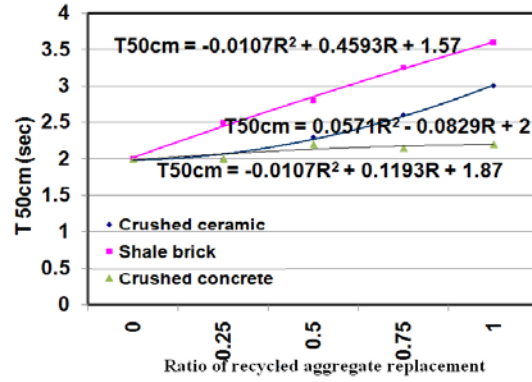

Figure 4: the relationship between the percentages of recycled and flow time for the recycled self-compacted concrete mixes.
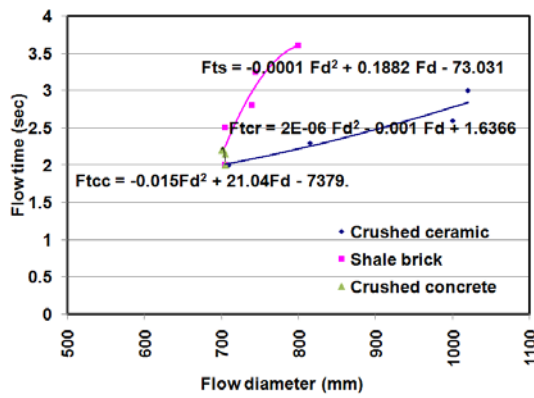

Figure 5: the relationship between the flow diameter and flow time for the recycled self-compacted concrete mixes.
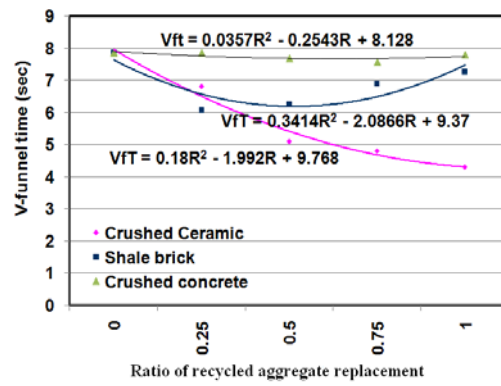

Figure 6: the relationship between the percentages of recycled and V-funnel time for the recycled self-compacted concrete mixes.

5. Bond Strength Measurement

Push-out test was carried out to determine the bond strength of recycled concrete mixes at 3, 7 and 28 days. ACI 318-08 [19] was proposed an equation to calculate the bond strength of the concrete. This equation is developed for the natural aggregate and for normal concrete. The equation depends on the diameter of the reinforcement bar (db) and the embedded length of the re-bar (l d). Fig. 2 illustrates the configurations of the bond test.

6. Test Results

6.1 Effect of recycled aggregate on the compressive and bond strength

The effect of the percentage of recycled aggregates on the compressive and bond strength for both normal and self-compacted concrete are shown in Figs. 7 and 8. 25, 50, 75 and 100% percentages of recycled aggregate were used. Crushed shale bricks, crushed ceramic and crushed concrete were used as a recycled aggregate compared to dolomite as a coarse aggregate. The age of test was

considered. An empirical equation was formulated for compressive strength and bond strength as a function of a percentage of recycled. The results showed that, as the percentage of recycled aggregate increases compressive and bond strength decreases.

These results were noticed for the shale bricks and crushed ceramic. This is due to the mechanical and physical properties of the crushed shale bricks and crushed ceramic. Also, the strength drop with these recycled aggregate (crushed shale bricks and crushed ceramic) can be attributed to the cracks in the aggregate itself (which could occur during the crushing). However, the compressive and bond strength was nearly the same when used crushed concrete compared to those of control mixes with dolomite as coarse aggregate. This yield to the crushed concrete was obtained from concrete cubes the compressive strength of this cubes ranged from 30 to 40 MPa.

For examples, Fig. 7-a illustrates the relations between the compressive strength and bond strength for the normal concrete mixes using crushed shale bricks as coarse aggregate with 25, 50, 75 and 100 percent as a replacement of dolomite at 3 days ages. The reduction of the compressive strength was ranged from 27% to 54%for the percentage of recycled aggregate replacement changed from 25% to 100% compared to the control mix. The reduction in the bond strength ranged from 25% to 58% for the percentage of recycled aggregate replacement changed from 25% to 100% compared to the control mix.

Fig. 8-i shows the relation between the compressive strength and bond strength for the self-compacted concrete mixes using crushed concrete as coarse aggregate with 25, 50, 75 and 100 percent as a replacement of dolomite at 28 days. The compressive strength was nearly the same at all different percentages of crushed concrete. The variation of the percentage of recycled aggregate (crushed concrete) from 25% to 100% was 2% compared to the control mix. The percentage of increasing in the bond strength was nearly the same at the percentage of recycled from 25% to 100% of crushed concrete as a recycled concrete compared to the control mix.
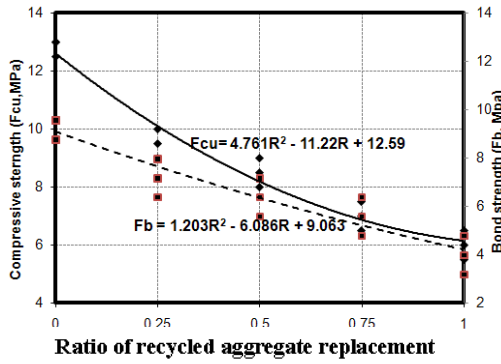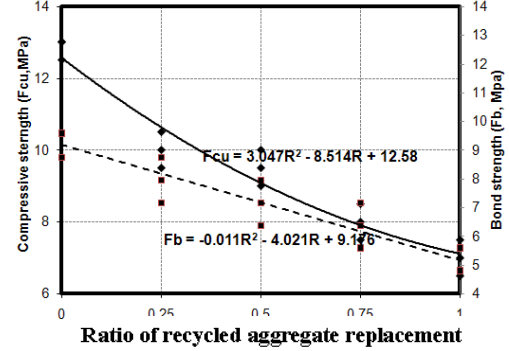
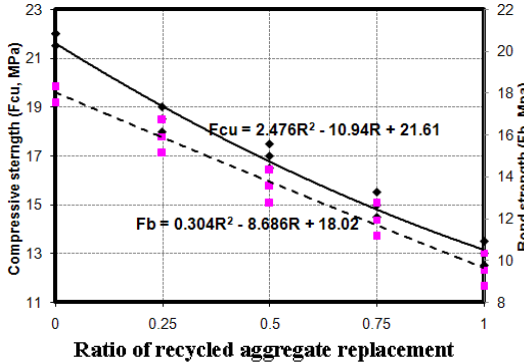(a) Mixes with Shale brick at 3 days ages.
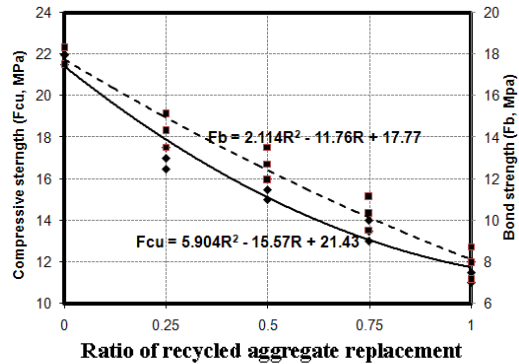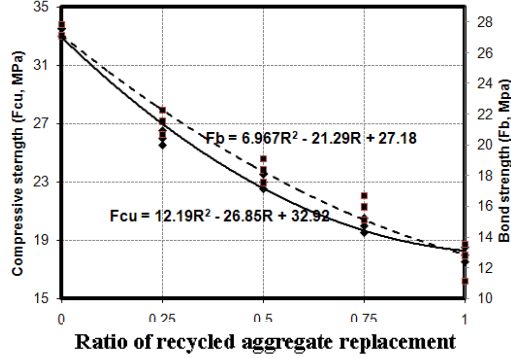
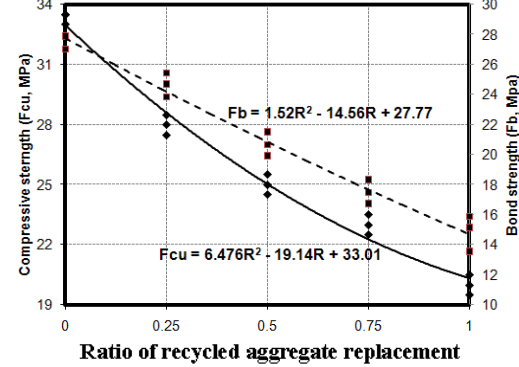(b) Mixes with Shale brick at 7 days ages.

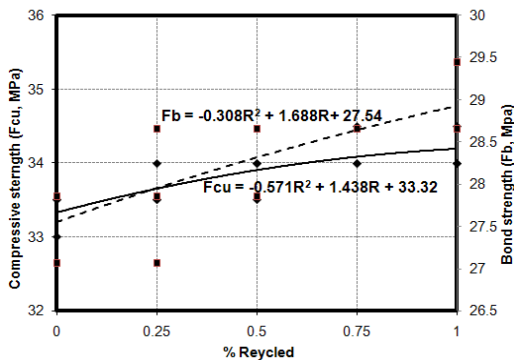(c) Mixes with Shale brick at 28 days ages.

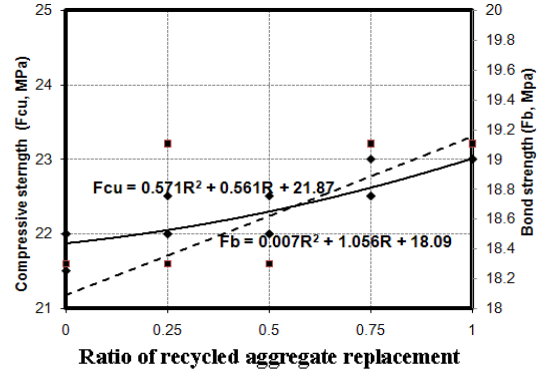(d) Mixes with crushed ceramic at 3 days ages.

(e) Mixes with crushed ceramic at 7 days ages.

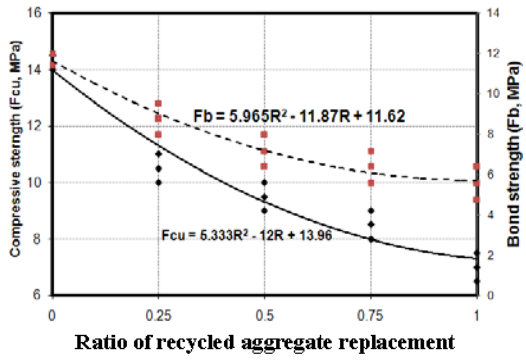(f) Mixes with crushed ceramic at 28 days ages.
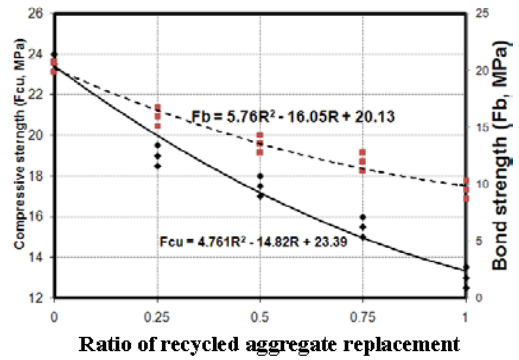
(g) Mixes with crushed concrete at 28 days ages.

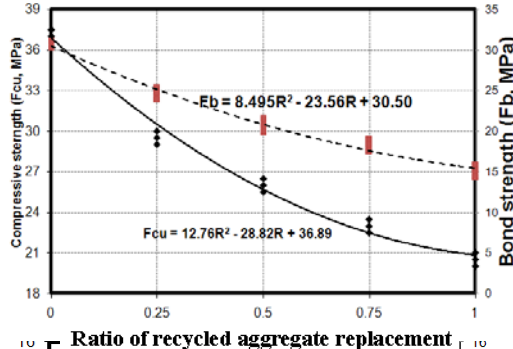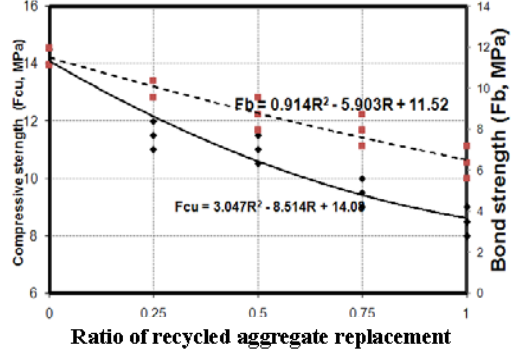(h) Mixes with crushed concrete at 7 days ages.

Figure 7: Compressive strength- recycled aggregate and bond strength- recycled aggregate for recycled normal concrete.

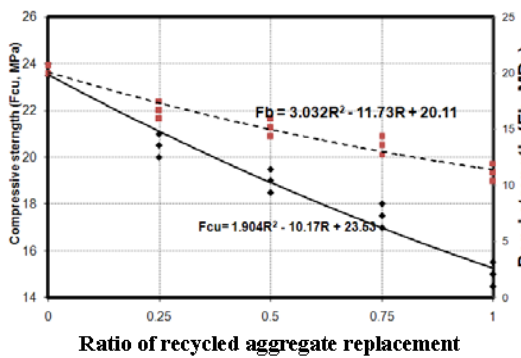(a) Mixes with Shale brick at 3 days ages.

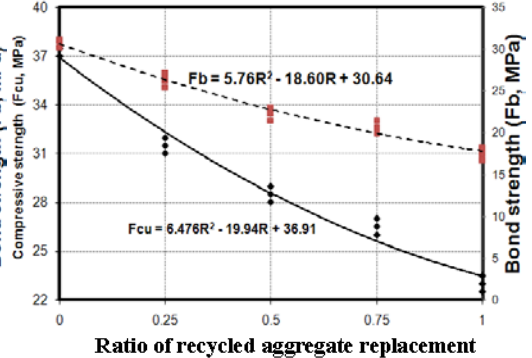(b) Mixes with Shale brick at 7 days ages.
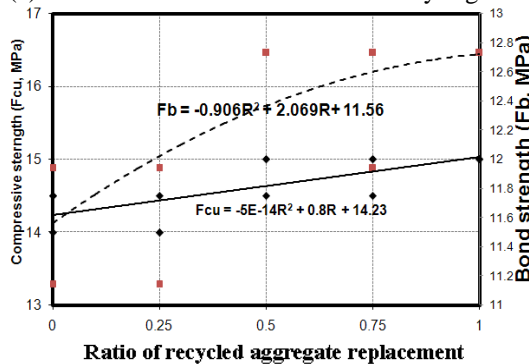
(c) Mixes with Shale brick at 28 days ages.
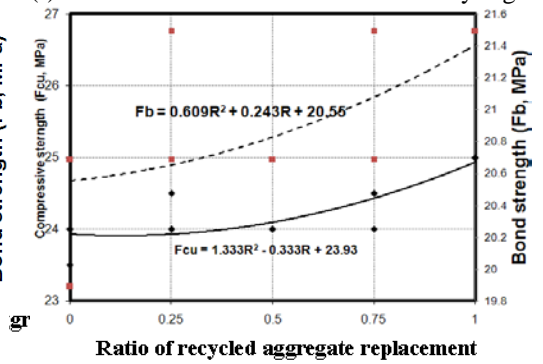
(d) Mixes with crushed ceramic at 3 days ages.
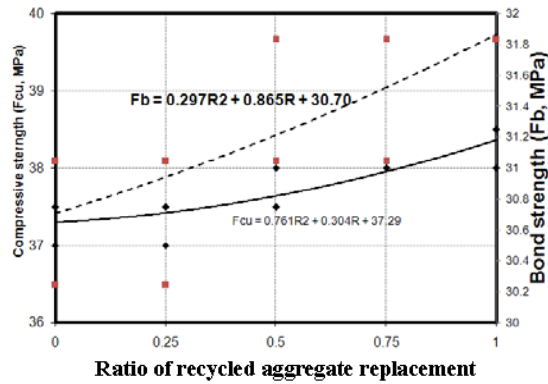
(e) Mixes with crushed ceramic at 7 days ages.

(f) Mixes with crushed ceramic at 28 days ages.

(g) Mixes with crushed concrete at 3days ages.

(h) Mixes with crushed concrete at 7 days ages.
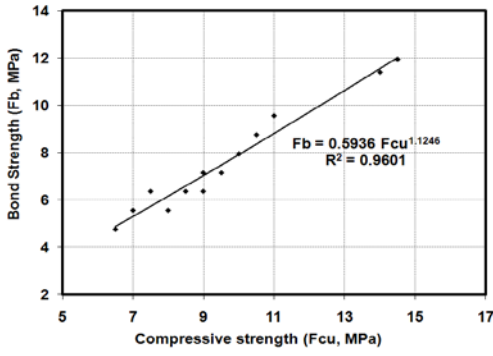
(i) Mixes with crushed concrete at 28 days ages.

Figure 8: Compressive strength- recycled aggregate and bond strength- recycled aggregate for recycled normal concrete.

6.2 Effect of the compressive strength on the bond strength for the recycled aggregate concrete

Figs. 9 and 10 illustrate an empirical coloration for the bond strength as a function of compressive strength for recycled aggregate self-compacted concrete and recycled aggregate normal concrete at 3, 7 and 28 days. The figures illustrate that; as the compressive strength decreases the bond strength decreases. Fig. 9-b shows the compressive and bond strength for recycled aggregate self-compacted concrete mixes with crushed shale brick as a coarse aggregate at 7 days. The ratio of the bond strength (Fb) to the compressive strength (Fcu) changed from (16% to 27%) as the percentage of recycled aggregate changes from 25% to 100%.

Figure (10-f) shows that, the ratio of bond strength (Fb) to compressive strength (Fcu) for the recycled aggregate normal concrete mixes with crushed ceramic as a coarse aggregate at 28 days was changed from (12% to 25%) as the percentage of recycled aggregate changed from 25% to 100%.

Figs. 10-g, 10-h and 10-i explain relationship between compressive strength (Fcu) and bond strength (Fb) for recycled aggregate normal concrete mixes with crushed concrete as a coarse aggregate at the different percentage of recycled at 3,7 and 28 days, respectively. The ratios of bond strength (Fb) to compressive strength (Fcu) were 25%, 16% and 18% at 3, 7 and 28 days, respectively.

(a) Mixes with Shale brick at 3 days ages.
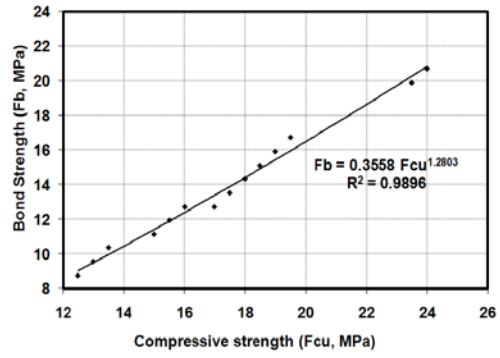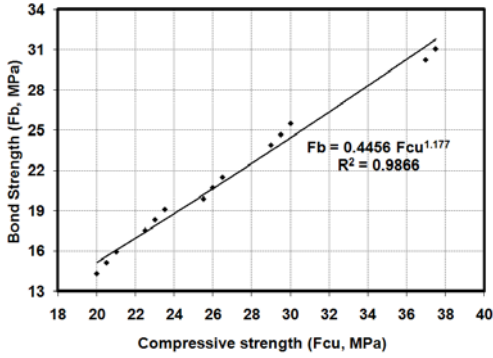
(b) Mixes with Shale brick at 7 days ages.

(c) Mixes with Shale brick at 28 days ages.

(d) Mixes with crushed ceramic at 3 days ages.

(e) Mixes with crushed ceramic at 7 days ages.

(f) Mixes with crushed ceramic at 28 days ages.

(g) Mixes with crushed concrete at 3days ages.

(h) Mixes with crushed concrete at 7 days ages.

(i)   Mixes with crushed concrete at 28 days ages.

Figure 9: Relationship between compressive strength and bond strength for RSCC.
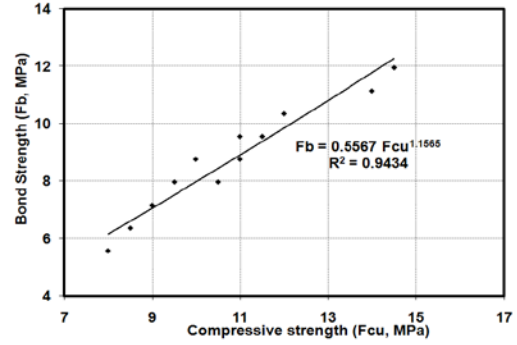

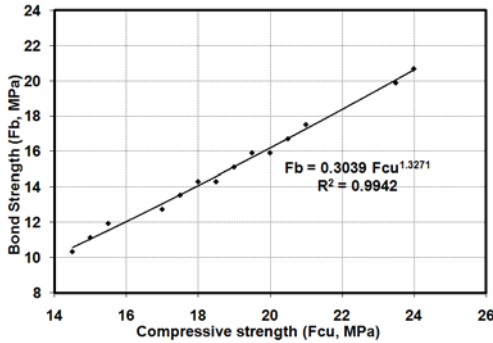(a)   Mixes with Shale brick at 3 days ages.

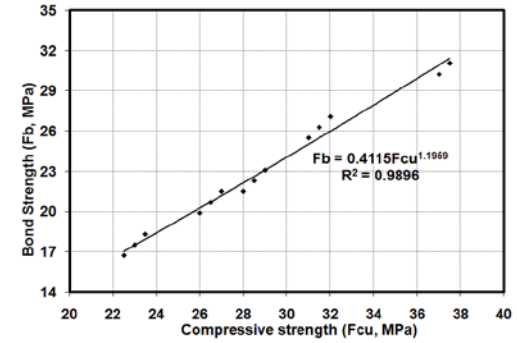(b)   Mixes with Shale brick at 7 days ages.

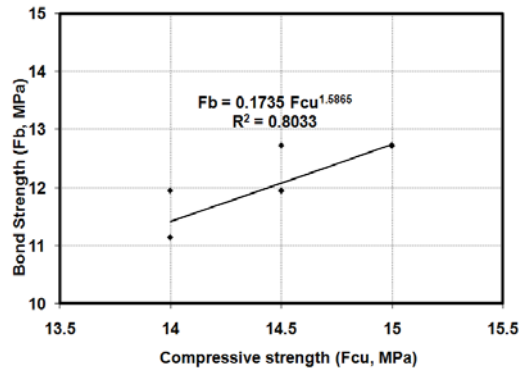(c)   Mixes with Shale brick at 28 days ages.
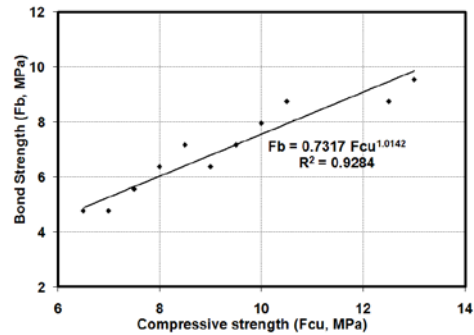
(d)   Mixes with crushed ceramic at 3 days ages.
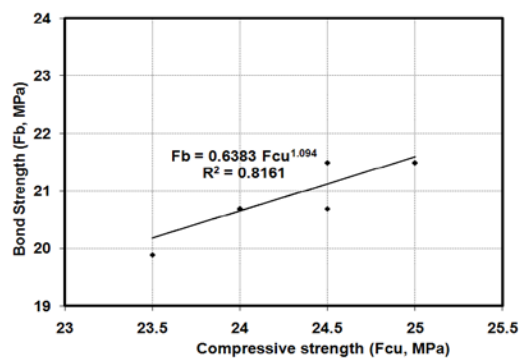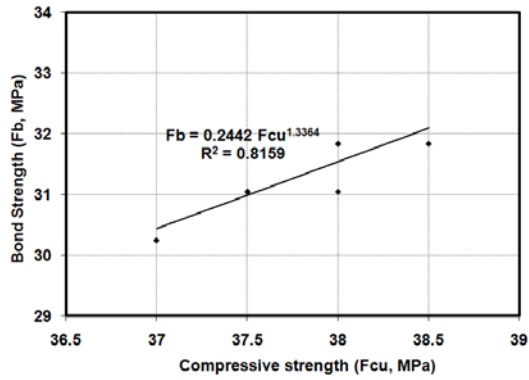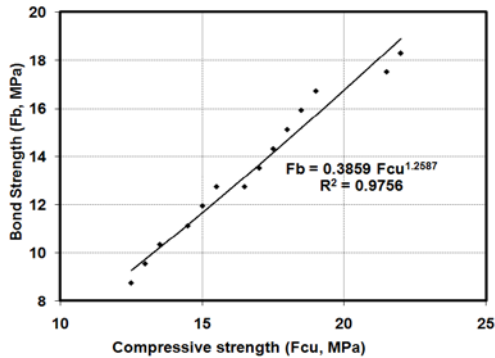

(e)   Mixes with crushed ceramic at 7 days ages.
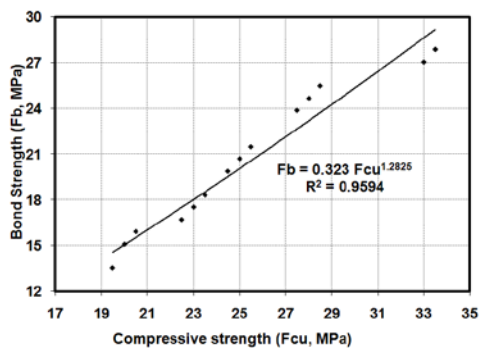
(f) Mixes with crushed ceramic at 28 days ages.
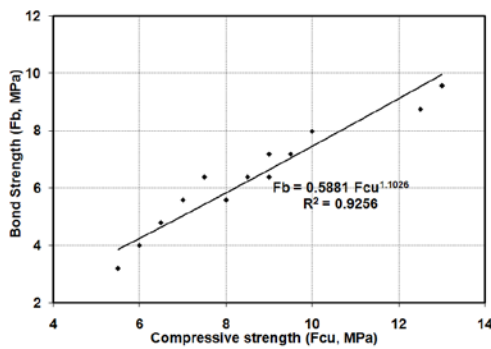
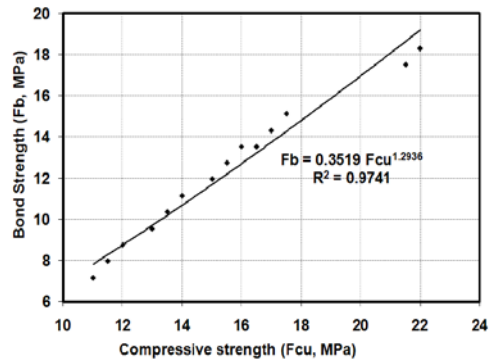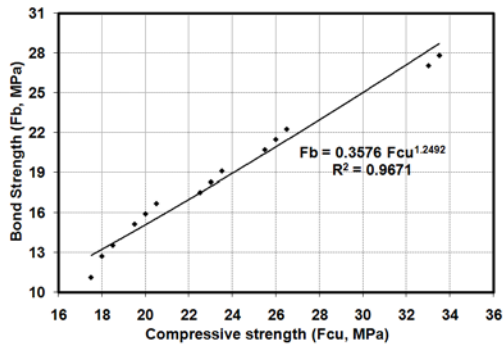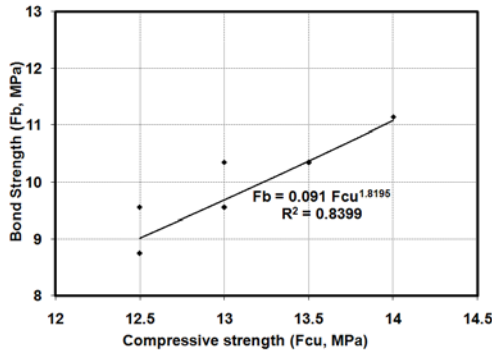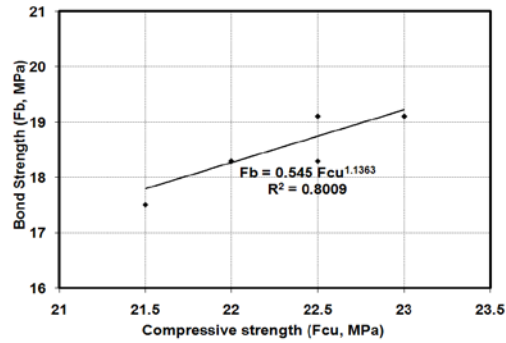(g) Mixes with crushed concrete at 3days ages.   (h)Mixes with crushed concrete at 7 days ages.
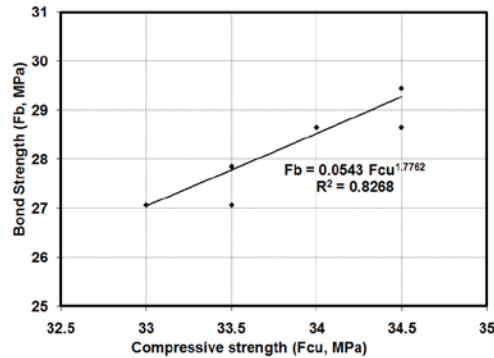
Mixes with crushed concrete at 28 days ages.

Figure 10: Relationship between compressive strength and bond strength for RNC.

7. Bond Strength Characteristics of Recycled Aggregate Concrete

As illustrated by the previous results, the recycled aggregate greatly affected the compressive strength of the mixes. The drop in the compressive strength was affected by the percentage of the recycled aggregate and the type of aggregate. This paper presented experimental equations to predict bond strength of recycled aggregate concrete. In these equations, the percentage of the recycled used was considered as illustrated in Figs 7 to 10. The bond strengths for the different mixes were calculated in Table 3. The values of the bond strength varied from 1.27 MPa to 2.94 MPa. These values are almost 8% of the compressive strength for the different mixes. Also the bond strength was calculated according to the equations which were considered in some codes and some researches [18-21]. Theses equations are developed for the natural aggregate and for normal concrete as shown in Table 3. The equations depending on the diameter of the reinforcement bar (db) and the embedded length of the re-bar (l d). The experimental results illustrate that; the bond strength decreased as the percentage of the recycled aggregate increase. ACI 318-08 code [19] was applied the bond strength in the calculations of the development length. ACI 318 -08 code [19] proposes that the bond strength is linearly proportional to the square root of the compressive strength, the values of bond strength are thus normalized bond

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strength, and the effect of variations in compressive strength eliminated [23 and 24]. Test results of bond strength of recycled concrete are presented in Table 4. The normalized bond strength ratios of the mixes are shown in Table 5. The normalized bond strength for design purposes is taken 0.53 in favorable design conditions that require the development of satisfactory bond strength levels [25]. As illustrated in Table 5, the ratio of bond strength (fb) to compressive strength ($\sqrt{fc'}$) of recycled aggregate normal concrete ranged from 0.37 to 0.51, and the ratio of bond strength to compressive strength of recycled aggregate self-compacted concrete is ranged from 0.36 to 0.52 for shale bricks and crushed ceramic. While for crushed concrete as a coarse aggregate the ratio of bond strength to compressive strength was 0.54 and 0.56 for recycled aggregate normal concrete and recycled aggregate self-compacted concrete, respectively.

Table 3: Equations of bond strength.

Equation	Bond strength equation
Direct calculation	$\tau_{max} = \dfrac{P_{max}}{\Pi D\, l_d}$
CEB-FIP MC90[18]	$\tau_{max} = 2.0\sqrt{f_{ck}}$
ACI 318-08[19]	$\tau_{max} = 5.91\dfrac{\sqrt{f_{ck}}}{d_b}$
Orangun[20]	$\tau_{max} = [0.2652 \times (1.2 + \dfrac{3c}{d_b} + \dfrac{50d_b}{l_d})] \times \sqrt{f_{ck}}$
MacGregor[21]	$\tau_{max} = 0.59\sqrt{f_{ck}}(\dfrac{c}{d_b} - 0.5)$

8. Empirical equations

Imperial formulas were driven from the previous Figs. 7 and 8 which indicated empirical formulas for the bond strength and compressive strength as a function percentage of recycled aggregate. By substitute between the two equations we can formulate these imperial equations for each type of recycled concrete as follow:

Table 4: Comparison between predicted and experimental value of Bond strength.

	Mix Code	Compressive strength (MPa)	Bond strength (MPa)	CEB-FIP MC90	ACI 318-08 (MPa)	Orangun correlation (MPa)	MacGregor correlation (MPa)
Recycled normal concrete mixes	NC	33.5	2.79	10.51	7.01	26.06	13.95
	NR25	26	2.15	9.26	6.17	22.96	12.29
	NR 50	23	1.83	8.71	5.81	21.60	11.56
	NR 75	20	1.59	8.12	5.41	20.14	10.78
	NR 100	18	1.27	7.70	5.14	19.10	10.23
	NE25	28	2.46	9.61	6.41	23.83	12.76
	NE50	25	2.07	9.08	6.05	22.52	12.05
	NE75	23	1.75	8.71	5.81	21.60	11.56
	NE100	20	1.51	8.12	5.41	20.14	10.78
	NN25	33.5	2.71	10.51	7.01	26.06	13.95
	NN50	34	2.87	10.59	7.06	26.26	14.06
	NN75	34	2.87	10.59	7.06	26.26	14.06
	NN100	34.5	2.94	10.67	7.11	26.45	14.16
Recycled Self-compacted concrete mixes	SC	37.5	3.1	11.12	7.41	27.58	14.76
	SR25	29.5	2.47	9.86	6.58	24.46	13.09
	SR50	26	2.07	9.26	6.17	22.96	12.29
	SR75	23	1.83	8.71	5.81	21.60	11.56
	SR100	20.5	1.51	8.22	5.48	20.39	10.92
	SE25	31.5	2.63	10.19	6.79	25.27	13.53
	SE50	28.5	2.23	9.69	6.46	24.04	12.87
	SE75	26.5	2.07	9.35	6.23	23.18	12.41
	SE100	23	1.75	8.71	5.81	21.60	11.56
	SN25	37.5	3.10	11.12	7.41	27.58	14.76
	SN50	37.5	3.10	11.12	7.41	27.58	14.76
	SN75	38	3.18	11.19	7.46	27.76	14.86
	SN100	38.5	3.18	11.27	7.51	27.94	14.96

Table 5: Normalized bond strength of recycled concrete mixtures.

Recycled normal concrete					Recycled self-compacted concrete				
Mix Code	F_{cu}	F_b	$\sqrt{f_{cu}}'$	$fb/\sqrt{f_{cu}}'$	Mix Code	F_{cu}	F_b	$\sqrt{f_{cu}}'$	$fb/\sqrt{f_{cu}}'$
NC	33.5	2.79	5.26	0.530	SC	37.5	3.1	5.56	0.558
NR25	26	2.15	4.63	0.464	SR25	29.5	2.47	4.93	0.500
NR 50	23	1.83	4.35	0.420	SR50	26	2.07	4.63	0.447
NR 75	20	1.59	4.06	0.392	SR75	23	1.83	4.35	0.420
NR 100	18	1.27	3.85	0.330	SR100	20.5	1.51	4.11	0.368
NE25	28	2.46	4.80	0.512	SE25	31.5	2.63	5.10	0.515
NE50	25	2.07	4.54	0.456	SE50	28.5	2.23	4.85	0.460
NE75	23	1.75	4.35	0.402	SE75	26.5	2.07	4.67	0.443
NE100	20	1.51	4.06	0.372	SE100	23	1.75	4.35	0.402
NN25	33.5	2.71	5.26	0.515	SN25	37.5	3.104	5.56	0.558
NN50	34	2.87	5.29	0.541	SN50	37.5	3.104	5.56	0.558
NN75	34	2.87	5.29	0.541	SN75	38	3.183	5.60	0.569
NN100	34.5	2.94	5.33	0.552	SN100	38.5	3.183	5.63	0.565

8.1 For recycled aggregate self-compacted concrete:

8.1.1 Crushed shale brick as a coarse aggregates

$$f_b = 85\alpha \left[\left(\frac{0.08f_{cu} - 2.89}{R - 2.26} \right)^2 - 2.77 \left(\frac{0.08f_{cu} - 2.89}{R - 2.26} \right) + 3.59 \right]$$

8.1.2 Crushed ceramic as a coarse aggregates

$$f_b = 57.6\alpha \left[\left(\frac{0.15f_{cu} - 5.7}{R - 3.08} \right)^2 - 3.23 \left(\frac{0.15f_{cu} - 5.7}{R - 3.08} \right) + 5.32 \right]$$

8.1. 3 Crushed concrete as a coarse aggregates

$$f_b = 3\alpha \left[\left(\frac{1.31f_{cu} - 49}{R + 0.4} \right)^2 + 2.9 \left(\frac{1.31f_{cu} - 49}{R + 0.4} \right) + 102.33 \right]$$

8.2 For recycled aggregate normal concrete:

8.2.1 Crushed shale brick as a coarse aggregate.

$$f_b = 70\alpha \left[\left(\frac{0.05f_{cu} - 1.72}{R - 1.4} \right)^2 - 3.06 \left(\frac{0.05f_{cu} - 1.72}{R - 1.4} \right) + 3.9 \right]$$

8.2.2 Crushed ceramic as a coarse aggregate.

$$f_b = 16.2\alpha \left[\left(\frac{0.15f_{cu} - 5.097}{R - 2.96} \right)^2 - 8.99 \left(\frac{0.15f_{cu} - 5.097}{R - 2.96} \right) + 20.38 \right]$$

8.2.3 Crushed concrete as a coarse aggregate

$$f_b = -3\alpha \left[\left(\frac{-1.75f_{cu} + 58.36}{R - 2.52} \right)^2 - 5.48 \left(\frac{1.75f_{cu} - 58.36}{R - 2.52} \right) - 89.42 \right]$$

Where α= 0.33 and 0.67 for 3 and 7 days, respectively.

9. Conclusions

In this study, the compressive strength and the steel bond performance for two types of concrete (recycled aggregate normal concrete and recycled aggregate self-compacted concrete) using crushed shale brick, crushed ceramic and crushed concrete were investigated. Based on the available test results, the following conclusions can be drawn:
1. Using crushed ceramic as a recycled aggregate improved the flowability of the recycled self-compacted concrete mixtures compared to the use crushed shale bricks or crushed concrete as a recycled aggregate. While the behavior of the recycled crushed aggregate concrete mix in the fresh state was nearly similar to the control mix containing natural dolomite aggregate.
2. The compressive strength for the self-compacted and normal concrete mixes cast with normal dolomite was 37.5 and 33.5 MPa at 28 days, respectively.
3. Compressive strength decreased by using different percentage of recycled aggregate (crushed ceramic and shale bricks). However when using the crushed concrete as a recycled aggregate the compressive strength was nearly equal to the compressive strength of the control mix cast with

natural dolomite.

4. Using 25, 50, 75 and 100% of Shale brick as coarse aggregate replacement, the compressive strength for recycled self-compacted concrete mixes decreased by 21.3%, 30.6%, 38.6% and 45.3%, respectively. While for recycled normal concrete mixes, the compressive strength decreased by 22.3%, 31.4%, 40.3% and 46.2%, respectively.

5. Using 25, 50, 75 and 100% of crushed ceramic as coarse aggregate replacement, the compressive strength for recycled self-compacted concrete mixes decreased by 16.1%, 23.9%, 29.3% and 38.6%, respectively. While for recycled normal concrete mixes, the compressive strength decreased by 16.4%, 25.4%, 31.3% and 40.3%, respectively.

6. Using crushed concrete as a coarse aggregate replacement, the compressive strength for recycled self-compacted recycled concrete mixes was nearly equal to the control mixes for all percentage of replacement at all ages.

7. In general, the bond strength of the recycled concrete was about 8% of the compressive strength.

8. For the recycled aggregate self-compacted concrete, the reduction in bond strength of the mixes with shale bricks, crushed ceramic and crushed concrete was 37% and 30 % and 1.3% compared to the control mix. The reduction of bond strength of the mixes with shale bricks is more than the crushed ceramic by 7 %.

9. The bond strength for the self-compacted concrete was increased by 11% compared to the bond strength for normal concrete.

10. Bond strength decreased with the decrease of the compressive strength. The normalizes bond strength (fb/ √fcu) was in the same range for both aggregate recycled self-compacted concrete and aggregate recycled concrete.

11. Different equations were formulated from the experimental results to calculate the bond strength of the aggregate recycled concrete (normal and self-compacted concrete).

12. According to the wide span of workability and mechanical properties of the mixes investigated in this research recycled aggregate could be applied in the manufacture of building units, with special precaution and surface protection according to the surrounding conditions and the purpose of applications.

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