Eco-Friendly Concrete Made with Recycled Aggregates

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Abstract: Construction and demolition waste (C & DW) represents an unavoidable product of construction industry. Industrial activities consume large amounts of natural resources and generate waste and by-products. The use of waste materials from other activities turns waste products into resources, instead of burning them or burying them in landfill sites or dumping into landfills. C & DW is usually discarded in landfills causing very serious environmental problems. Concrete is a sustainable material because it has very high thermal mass, is made from some of the most plentiful resources on earth, is produced with little waste, is produce durable structures, can be made with recycled materials,, is produced with local material, can consume industrial by-products such as iron blast-furnace slag, silica fume, fly ash and completely recyclable. The main objective of this study is to make use of waste materials as coarse aggregate for new concrete mixes. Two types of waste materials from construction activates are used: crushed waste concrete with compressive strength ranged from 30 to 35 MPa and waste ceramic floor and wall tiles. The waste ceramic and concrete are manually crushed and then tested for grading and water absorption. The main variable in this study is the ratio of coarse aggregate from recycled materials to the total weight of coarse aggregate in the new concrete mix. Workability of the fresh concrete was evaluated through slump test. Concrete specimens; cubes, and cylinders from mixes made out of recycled aggregate as a part of coarse aggregate are prepared and then tested for the uniaxial compression, splitting tension, and the modulus of elasticity. The results are then compared with those of the natural coarse aggregate from Dolomite. All strength properties are studied at three various ages of concrete at testing. The three considered ages are the 2, 7, and 28 days. The results showed that the compressive and splitting tensile of recycled ceramic concrete increased considerably than the normal aggregate concrete. Also, the results indicated that the strength dropped by about 4.5-22% when using recycled concrete aggregates. The utilization of recycled materials is confirmed and is an eco friendly material.
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1. Introduction

With the great development in all activities all over the world, the mass of waste materials has been increased to the extent that it is now representing a very serious environmental problem as it limits the right of the mankind to live in a clean and healthy environment. Therefore, the interest in recycling of waste materials is getting, nowadays, an increasing worldwide attention. Collecting and treating waste has an impact on the environment, health and economy. Industrial ecology responds in two ways to this problem: It encourages the optimization of the use resources and influences the amount of waste produced. It encourages the creation of new utilization networks by favoring the development of recycling. The practice of industrial ecology implies that waste products of one industry are recycled as substitutes for virgin raw materials of another industry, thereby reducing the environmental impact of both industries. About 1300 million tons of waste is generated in Europe every year, of which 40% or 510 million tons is construction and demolition waste (C & DW). The US produces about 325 million tons C & DW, and Japan about 77 million tons according to the report of World Business Council for Sustainable Development WBCSD [1]. Similarly, it was reported that construction activities takes 50% of raw materials from nature, consumes 40% of total energy, and creates 50% of total waste [2].

Concrete is the largest manufactured product used by human society. The concrete industry has both negative and positive environmental impacts. Concrete mixtures for general construction, on the average, are composed of 12 percent Portland cement, 8 percent mixing water, and 80 percent coarse and fine aggregate by mass. In 2010, approximately 33 billion tonnes yearly global concrete industry consumed nearly 27 billion tonnes of aggregate [3]. The mining, processing, and transport of such huge quantities of materials for making concrete, in addition to large amounts of limestone, clay, and fossil fuels for Portland-cement clinker manufacture, require considerable energy, and adversely affect the ecology of virgin lands. Waste concrete is produced because of the demolition of structures due to different reasons such as natural disasters like earthquake, fire, explosion, rejected concrete and leftover fresh batches. The testing of concrete specimens in testing laboratories is another source of concrete debris. As a result of the environmental and economical benefits, the concept of recycling waste aggregate and reusing it in another form has gained momentum in the last three decades. Recycled aggregate is derived from crushing inert construction and demolition waste. It may be classified as recycled concrete aggregate (RCA) when consisting primarily of crushed concrete or more general recycled aggregate (RA) when it contains substantial quantities of materials other than crushed concrete. RAC or recovering concrete has two main advantages: it reduces the use of new virgin aggregate and the associated environmental costs of mining, processing, and transportation and it reduces landfill of valuable materials.

Currently, only the use of coarse aggregate derived from construction or demolition waste is recommended for use in new concrete construction. Extensive research is being carried out globally on the use of such recycled aggregates as an alternative to natural aggregates because it is an efficient way to ensure sustainable development, environmental preservation and effective utilization of resources [4]. The observations revealed that the first crack appear around both the old interfacial zone (ITZs) and the new ITZs, and then propagate into the old and new mortar matrix. A series of experimental investigations on the mechanical properties and durability of recycled aggregate concrete (RAC) have been carried out in the last three decades to suggest the possible utilization of this waste material in construction industry so as to avoid threat to environment [5-9]. The results indicated that the mechanical properties and durability are lower than the conventional concrete. Ajdukiewicz and Kliszczewicz examined the mechanical properties of high performance concretes made with recycled concrete aggregates, produced from concrete with compressive strength 40–70 MPa [10]. The results indicated that the compressive strength dropped by about 10% when using recycled aggregates.

Ceramic products are part of the essential construction materials in most buildings. Ceramic industry generates wastes during production. Nearly 30% of the daily production of ceramic materials goes on waste during the manufacturing, transportation and usage of ceramic products [11]. Based on the previous researches, ceramic waste aggregate was durable, hard and highly resistant to chemical and physical degradation forces [11,12]. Mechanical properties were decreased when the percentage of replacement with ceramic waste aggregate increased due to smooth surface texture of ceramic aggregates and poor bonding properties of the matrix with aggregates [13, 14]. Recently, studies conducted on the performance of ceramics as aggregates material in concrete have shown that similar mechanical characteristics exist between concrete made with ceramic and the conventional concrete [15,16]

Most of the previous studies have considered some ceramic products such as sanitary wares and electrical insulators as natural aggregate replacement. However, there is limited information about the use of ceramic floor and wall tiles as coarse aggregate in RAC. Also, most of the previous studies have considered recycled concrete aggregate obtained from demolitions and construction sites without any information about its previous properties. Consequently, this study focused on the use of two types of recycled aggregate: ceramic floor and wall tiles and crushed waste concrete with compressive strength ranged from 30 to 35 MPa to partially or globally replace natural aggregate in the production of structural concrete.

Experimental Program

Materials

Cement

Ordinary Portland Cement (OPC) type CEM I 42.5 N, conforming to Egyptian Standard ES 4756-1/2013[17], and produced by Misr Beni-Suef Company was used through this study. Cement tests were carried out according to Egyptian Standard ES: 2421/2009. The physical and mechanical properties of the used cement are summarized in Table 1.

Table 1. Physical and mechanical properties of used cement CEM I 42.5N

Property	Specific surface area (cm^2/gm)	Setting Time (min)		Compressive strength (MPa)	
		Initial	Final	2 days	28 days
Test result	3300	180	220	20	47
Limits*	Not less than 2750	Not less than 60	NR	Not less than 10	Not less than 42.5

*The limits are according to Egyptian Standard ES 4756-1/2013.

Fine aggregate

Locally available natural siliceous sand has been used as fine aggregate in this study with maximum particle size 4 mm and fineness modulus of 2.9 and it was conformed CF according to ES 1109/2008 [18]. Specific gravity of sand was found as 2.65.

Natural coarse aggregate (NCA)

Crushed dolomite from Ataka Mountain in Suez city with size 4/16 mm has been used in the experimental work.

Recycled Concrete Aggregate (RCA)

Waste concrete aggregates **(RCA**) used in this study were obtained from crushing piles top in construction site (Figure 2 a). Keeping in mind the importance of the original strength of parent concrete for the recycled aggregate. Crushed waste concrete with compressive strength ranged from 30 to 35 MPa. The waste concrete are manually crushed and sieved into required aggregate sizes using a metal hammer and British Standard sieves respectively.

Ceramic Waste aggregate (CerWA)

Ceramic waste aggregates used in this study were mainly ceramic floor and wall tiles (Figure 2 b), collected from construction site within Mansoura, Egypt. The ceramic waste pieces are manually crushed using a metal hammer and sieved through British Standard sieves and the same sieve is used for Crushed dolomite. As the result of the crushing process and the brittle nature of CerWA, they were angular and cubical in shape irregular and also rough with respect to the surface texture. it seems that the shape and surface of aggregate influence considerably the strength of concrete. The flexural strength is more affected than the compressive strength [19]. Coarse aggregates from dolomite, crushed concrete and ceramic waste are subjected to experimental tests included, sieve analysis for grading, water absorption, and the bulk unit weight. All tests are conducted according to the Egyptian Standards ES 1109-2008 [18] and ES 2421-2005 [20]. The physical-mechanical properties are summarized in Table 2 for used aggregates. As shown from Table 2, the recycled aggregate is relatively weaker than the natural aggregate. The crushing values of recycled aggregate satisfy the Egyptian Standards ES 1109-2008 [18]. The water absorption of recycled aggregate ranges from 5.5 to 6.25%, which is relatively higher than that of the natural aggregates. The grading of recycled aggregates and sand is shown in Figure 1. The size distribution curves of all recycled materials are continuous and well graded, indicating that grading of the aggregate is correct in all sizes which produces a greater degree of compactness and mechanical strength in the recovered concrete.

Table 2 Physical and mechanical properties of used Coarse Aggregate

Property	Natural aggregate	Waste Ceramic	Waste Concrete
Bulk Density (Kg/m^3)	1670	1525	1575
Water Absorption (%)	1.1	6.25	5.50
Aggregate crushing value (%)	18	24	22

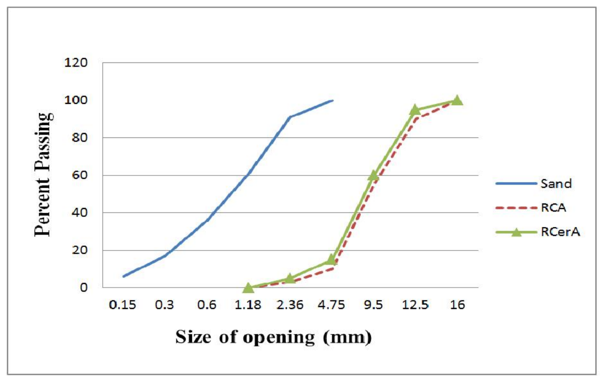

Figure 1. Particle size distribution curves of sand and recycled aggregates

a- Waste Concrete b- Waste ceramic

Figure 2. Recycled Concrete Aggregate

Concrete mix proportions

Nine different concrete mixes were designed: one control mix with only natural aggregates (NAC) and four recycled aggregate concrete mixes, each using recycled concrete aggregate: RCA- 25, RCA- 50, RCA- 75 and RCA- 100 and four recycled ceramic concrete mixes: RCerA- 25, RCerA- 50, RCerA- 75 and RCerA- 100. Thus, 25%, 50%, 75% and 100% by weight of natural coarse aggregate were replaced by recycled aggregates. A constant water to cement ratio of 0.55 by weight was adopted for all nine concrete compositions. Keeping in mind the greater water demand of recycled aggregates compared to natural aggregates, both natural and recycled aggregates were used in saturated and surface-dry (SSD) conditions. The details of various mix proportions are given in Table 3. All mix proportions are by weight. Mechanical mixing and mechanical compacting in moulds using table vibrator is maintained for all mixes. All moulds are removed after 24 hours from casting and all specimens are kept in water for 28 days for curing.

Table 3 Concrete Mix Proportions (kg/m^3)

Mix	Cement	Sand	Coarse Aggregate			Water	Water to Cement Ratio
			Dolomite (NAC)	Waste Concrete (RCA)	Waste Ceramic (RCerA)		
NAC	350	700	1140	-	-	192.5	0.55
RCA- 25	350	700	855	285	-	192.5	0.55
RCA-50	350	700	570	570	-	192.5	0.55
RCA-75	350	700	285	855	-	192.5	0.55
RCA-100	350	700	-	1140	-	192.5	0.55
RCerA-25	350	700	-	-	285	192.5	0.55
RCerA- 50	350	700	-	-	570	192.5	0.55
RCerA -75	350	700	-	-	855	192.5	0.55
RCerA -100	350	700	-	-	1140	192.5	0.55

Experimental Tests on Hardened Concrete

Figure 3. Experimental Set-Up for Modulus of Elasticity Test

Hardened concrete made out of the nine mix proportions are tested for, the compressive strength, splitting tensile strengths and the modulus of elasticity. The compressive strength is studied through 150 x 150 x 150 mm cubes while the 150 x 300 mm cylinders are used for the splitting tensile strength and the value of Young's modulus. The standard compresso-meter is used to measure the values of vertical strain of concrete cylinders. The experimental set-up used for the measurements of the values of strains is shown in Figure 3. All of the examined strength properties are studied for three various ages of concrete at testing. The three considered ages are the 2, 7, and 28 days.

Test Results and Discussion

Workability of RAC

Workability is one of the key properties that affect constructability. To study the behavior of RCA in fresh state, slump-cone tests were performed. Slump test results of the concrete mixes are presented in Figure 4.. Workability of RAC and NAC is almost the same (90± 20 mm). However, workability of mixes RCerA100 (100% crushed ceramic) was low, with slump values of 50 mm. This low value of slump of RCerA100mix could be attributed to the cubical, irregular shape and rough texture of waste ceramic.

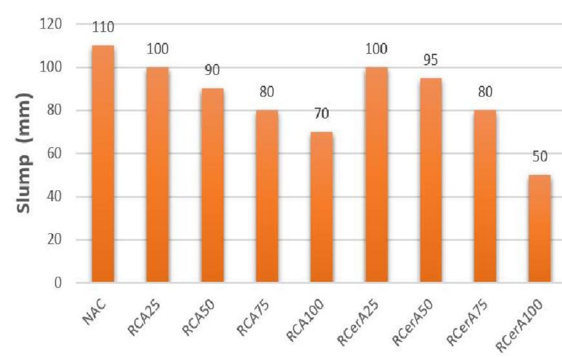

Figure 4. Particle size distribution curves of sand and recycled aggregates

Compressive strength

The final test results are given in Table 4. Each of the presented values are calculated as the averages of three replicate runs of tests performed on concrete specimens. The values of compressive strength, splitting tensile strength and the value of the modulus of elasticity are normalized as percentage ratios to those of the control mix (NAC of 100 % natural coarse aggregate from Dolomite). The reported values of the modulus of elasticity are the secant values at 40 percent stress of the ultimate stress of each mix. Figure 5 shows a histogram for the values of the compressive strength of various concrete mixes at different ages of concrete at testing while. As shown in Figure 5 and referring to Table 4, one can easily notice that the value of the compressive strength reduces with the increase in the percentage of the crushed concrete as a part of coarse aggregate. This happened for all ages of concrete at testing. At two days of the concrete age, the control mix of 100 % Dolomite as coarse aggregate, mix NAC, developed a compressive strength of 16 MPa. This value reduced to 14.1 MPa when 25 % of the coarse aggregate is crushed concrete. The later value is equivalent to 88 % of the compressive strength of the control mix. The normalized ratio again reduces to 82 % with the increase in the percentage of crushed concrete to 50 % while the ratio is 74.5 % for the mix with 75 % of the coarse aggregate from crushed concrete. For the extreme case of 100 % crushed concrete as coarse aggregate, the recycled concrete developed a compressive strength of 11MPa, which is normalized as 68.5 % of the strength of the control mix. When testing concrete at age of 7 days, although the values of the compressive strength develop the expected increase, the normalized ratios also increase. For examples, the recycled concrete from mix with 50 % coarse aggregate from crushed concrete develops 84.5 % of the compressive strength of the control mix while the mix with 100 % crushed concrete develops 72 % of the strength of the control mix.

For the 28-days compressive strength, the normalized ratios again increase although the values of the strength jump to very high values. The concrete mix with 25 % crushed concrete as a part of coarse aggregate developed 95.5 % of the compressive strength of the control mix while the ratio is 91.5 % for the mix with 50 % crushed concrete. Finally the extreme case of 100 % crushed concrete as a part of coarse aggregate developed a value of compressive strength of 21.8MPA. This value is corresponding to a normalized ratio of 78 % of the compressive strength of the control mix. Waiting for a moment keeping an eye on Table 4 and Figure 4, it is easy to realize that the loss in the compressive strength due to the use of crushed concrete as a part of coarse aggregate is not that much to wary. The maximum loss is about 22 % in case of 100 % of the coarse aggregate is from crushed concrete. This means that the percentage of the coarse aggregate from crushed concrete can be utilized to meet the required strength of various structural members without losing the environmental benefit of recycling the available amount of waste concrete. For the worst cases, concrete mixes with high ratios of crushed concrete as a part of coarse aggregate may be utilized for relatively low strength members.

For recycled ceramic concrete (RCerC), it can be observed in Figure 5 and Table 4 that the compressive strength increased with increasing recycled ceramic content. At all ages of testing RCerC mixes yielded higher strength than the control concrete. This is due to adequate bonding between recycled crushed ceramic and cement paste. The maximum increase of 21% in compressive strength was observed in concrete with a substitution 100 %. This results are similar to those reported by Awoyera et al. [15] and Medina et al. [16].

Splitting Tensile Strength

Figure 6 shows histograms for the values of splitting tensile strengths of concrete with various ratios of recycled aggregates as a part of coarse aggregate. As shown in this figure and referring to Table 4, it is noticed that the values of splitting tensile strengths also reduce with the increase in the percentage of the crushed concrete as a part of coarse aggregate. At two days of the concrete age, the concrete mix with 25 % crushed concrete developed a value of splitting tensile strength of 1.33 MPa which is about 92 % of that of the control mix. The increase in the percentage of crushed concrete to 50 % reduced the splitting tensile strength to 1.24 MPa, which are equivalent to normalized ratios of 86 % of the values of the control mix. The extreme case of 100 % crushed concrete as coarse aggregate developed splitting tensile strength of 75 % of the values of the control mix. As the case in the compressive strength, although the values of strength increases at 7 days of the concrete age, the normalized values of both strengths also increase. At 28-days, the normalized ratios of the splitting tensile strengths of mixes with ratios 25 %, 50 %, 75 %, and 100% crushed aggregate are 93 %, 86 %, 81 %, and 78 % of the strength of the control mix. Again one can notice that the loss in the tensile strength due to the use of crushed concrete, as a part of coarse aggregate may be acceptable. It is also noticed that the percentage loss in the tensile strength, due to the use of crushed concrete as a part of the coarse aggregate, is less than the loss in the compressive strength.

The split tensile strength of concrete mixes with ceramic waste aggregate substitution are shown in Figure 6 and Table 4. Splitting tensile strength was adequately developed at 28 days of curing. the tensile strength results indicated that concrete made with recycled ceramic is as strong in tension as corresponding concrete made with natural aggregate. The 28-days splitting tensile strength of recycled concrete ranged between 2.57 and 2.9 MPa. However, about 16% increase in split tensile strength was observed in concrete made with 100% replacement level. The same reasons which influence the compressive strength will also influence the splitting tensile strength. Similar results were obtained by other researchers (Awoyera et al. [15] and Medina et al. [16]).

TABLE 4. Mechanical Properties of Recycled Aggregate Concrete (RAC) and NAC

Age of Concrete at Testing	Mix	Compressive Strength		Splitting Tensile Strength		Young's Modulus	
		MPa	Normalized %	MPa	Normalized %	GPa	Normalized %
2 days	NAC	16	100	1.45	100	18	100
	RCA- 25	14.1	88	1.33	92	16.7	93
	RCA-50	13.1	82	1.24	86	16.4	91
	RCA-75	11.9	74.5	1.17	81	15.7	87
	RCA-100	11	68.5	1.08	75	14	78
	RCerA-25	16.5	103	1.39	96	17.5	97
	RCerA -50	16.1	101	1.37	95	17.1	95
	RCerA-75	16.8	105	1.45	100	16.9	94
	RCerA-100	17.1	107	1.42	98	17.5	97
7 days	NAC	22	100.0	2.1	100	22	100.0
	RCA- 25	20	91	1.93	92	20.7	94
	RCA-50	18.6	84.5	1.78	85	20.2	92
	RCA-75	17.7	80.5	1.68	80	19.4	88
	RCA-100	15.8	72	1.61	77	17.6	80
	RCerA-25	22.7	103	2	95	20.9	95
	RCerA -50	23.1	105	1.9	90	21.1	96
	RCerA-75	23.5	107	1.95	93	20.7	94
	RCerA-100	24.2	110	2	95	21.3	97
28 days	NAC	28	100.0	2.5	100.0	26	100.0
	RCA- 25	26.7	95.5	2.32	93	24.5	94
	RCA-50	25.6	91.5	2.15	86	24	92
	RCA-75	24.2	86.5	2.02	81	23	88
	RCA-100	21.8	78	1.95	78	20.8	80
	RCerA-25	29	103	2.57	103	25	96
	RCerA -50	30	107	2.6	104	25	96
	RCerA-75	31	110	2.65	106	24.5	94
	RCerA-100	34	121	2.9	116	25.5	98

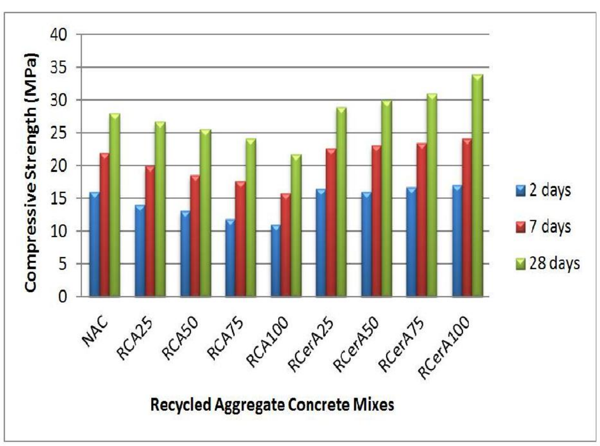

Figure 5 Compressive Strength of Recycled Concrete with Various Mixes

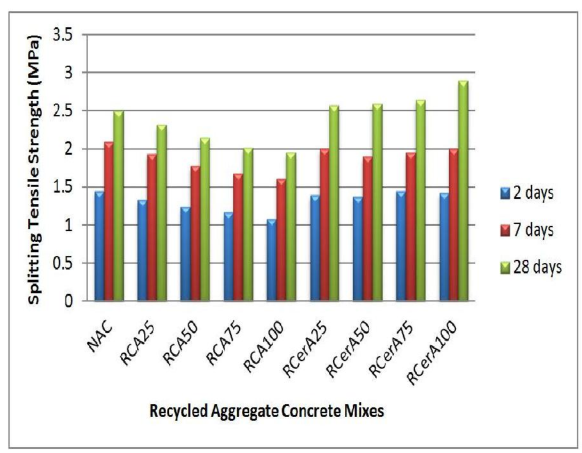

Figure 6 Splitting Tensile Strength of Recycled Concrete with Various Mixes

Modulus of Elasticity

Figure 7 shows histograms for the values of modulus of elasticity of concrete with various ratios of recycled aggregates as a part of natural aggregate. The value of modulus of elasticity of RAC has almost the same trend as in case of compression strength results. The major difference between various mixes is that, with the increase in the ratio of recycled crushed concrete as a part of the coarse aggregate, the RAC exhibits more deformations and consequently lower values of the modulus of elasticity. The secant value of the modulus of elasticity is calculated at 40 % of the ultimate stress of each mix. The corresponding values are reported in Table 4. As shown in Table 4, RAC developed values of Young's modulus ranged from 80 % to 94 % of the value of the control mix. This decrease in value of modulus of elasticity is mainly due to the significant quantity of cement mortar attached to recycled concrete aggregate. the which makes the concrete more porous and less stiff.

From Figure 7, it is clear that the modulus of elasticity of concrete made with recycled ceramic almost the same modulus of elasticity as that of the concrete made with natural aggregate. This due to the ceramic waste aggregate was hard and durable.

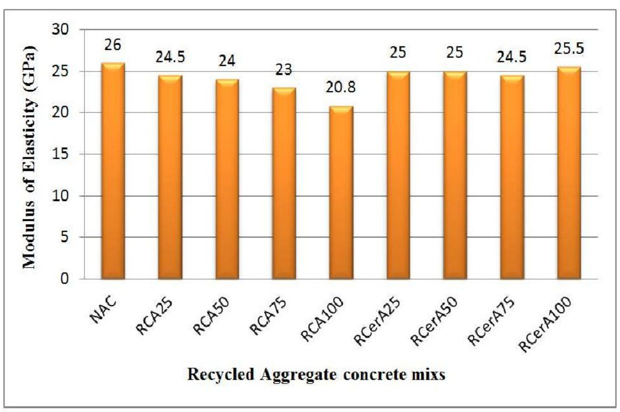

Figure 7. Compressive Strength of Recycled Concrete with Various Mixes

Conclusions

Based on the present experimental investigation, the following conclusions can be drawn:

1. The compressive strength of recycled aggregate concrete (RAC) reduces with the increase in the percentage of recycled concrete aggregate (RCA) as a part of natural aggregate. The loss in the 28-days compressive strength is about 4.5 % only for the RAC with 25 % crushed concrete as a part of coarse aggregate. The maximum loss is about 22 % in case that the recycled concrete is totally made out of RCA. The environmental benefit of recycling waste concrete should not be lost for such small loss in the compressive strength. This makes us think if it is possible to utilize the percentage of RCA with the required strength.
2. The RAC requires longer time to develop the desired value of compressive strength.
3. The water absorption of recycled aggregate (RA) is higher than that of the natural aggregate. This problem can be solved using pre-saturation method of the aggregate (SSD conditions).
4. Up to 25% replacement of natural aggregate with RCA, mechanical properties are almost similar to that of normal aggregate concrete.
5. The recycled concrete exhibits lower values of the modulus of elasticity. This may be considered as an advantage if a relatively high deformation capacity of the structural member is required.
6. The compressive strength and splitting tensile strength of recycled ceramic concrete improved as the replacement percentage of natural aggregates increased.
7. It safe and feasible to use recycled waste ceramic to produce recycled ceramic concrete as a structural eco-friendly material.

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