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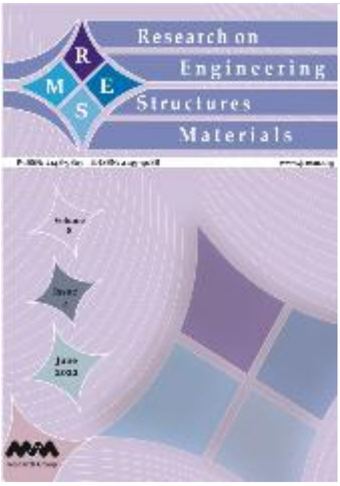

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Research Article

Studies on mechanical performance of treated and non-treated coarse recycled concrete aggregate and its performance in concrete-an Indian case study

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Abstract

In India, utilization of construction & demolition (C&D) waste-based coarse recycled concrete aggregate (CRCA) for RCC work is limited up to 20% for M25 grade of concrete as codified in IS 383:2016. However, enhanced utilization is not possible until classification based on quality grading of C&D waste-based aggregate is made available. One of the possible ways to classify C&D waste-based aggregate can be routed based on specific gravity and water absorption value of the parent rock which is generally affected by the adhered mortar. In the present study, C&D waste-based coarse recycled concrete aggregate (CRCA) sourced from two different sources was studied holistically. CRCA aggregates were subjected to mechanical treatment in a Los Angeles machine and Characteristics of CRCA before and after treatment were evaluated and compared. Further, a comparative study in fresh, hardened, and durability stages was conducted on the properties of concrete made with treated and non–treated CRCA. Fresh, hardened, and durability properties of concrete made with C&DW-based CRCA investigated for the (a) Fresh properties – workability in terms of slump, and air content. (b) Hardened properties–compressive and flexural strength, modulus of elasticity, drying shrinkage (c) Durability properties –resistance to chloride (RCPT, as per ASTM C1202), resistance to carbonation as per ISO 1920 Part 12 and resistance to water penetration as per IS 516 Part2 / Section-1. From the study, it can be concluded that physical properties such as specific gravity and water absorption of CRCA can be used as a tool for the grading of C&D waste-based CRCA. Based upon fresh, hardened, and durable behavior of concrete made with CRCA, it was observed that non-treated CRCA can be used up to 40 % for a grade of concrete up to M 30 whereas treated CRCA can be used up to 100 %. This was attributed to the improvement in the ITZ.

1. Introduction

Due to the non-availability of natural resources coupled with the rise in the demand for aggregates for infrastructural projects, the use of C&DW-based aggregate can serve the purpose. In India, about 30 million tonnes per year is the average rate of C&DW generation that accounts 20% to 25 % of Municipal solid waste (MSW) [1]. By utilizing C&DW-based aggregate, the demand for natural aggregates can be reduced, which is often obtained through resource-intensive mining processes. This reduces the strain on our environment and preserves natural resources for future generations. Additionally, the use of C&DW-based aggregate helps to decrease the amount of construction and demolition waste that ends up in landfills. Furthermore, incorporating RCA in construction projects reduces the

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need for energy-intensive production processes associated with traditional aggregates. However, the use of C&DW-based aggregate for construction activities is limited due to inconsistency associated with the quality of the C&DW-based aggregates that require immediate attention. Various international codes recommend the use of C&DW-based recycled concrete aggregate (RCA) up to a certain replacement level of natural aggregates for structural and non-structural applications with a cautionary note [1-5]. Recycled concrete aggregate (RCA) is generally derived from crushed concrete and primarily consists of natural aggregate with a layer of mortar attached to its surface and a certain amount of foreign materials or impurities that affects the properties of the concrete as a whole [5,6]. Unlike natural aggregates, RCA also consists of micro cracks. To date, due to its inherent characteristics, utilization of RCA has not been optimized. Some of the critical issues associated with the utilization of RCA for structural activities are addressed below. The ITZ generally refers to the transition area between the mortar and aggregate and is sometimes termed an Aggregate –paste interface [7,8]. The microstructure of the ITZ is mainly composed of crystals of calcium hydroxide, calcium silicate hydrate, and ettringite with a higher water-cement ratio than that of mortar resulting loose structure [9, 10]. With high porosity and loose microstructure, ITZ becomes the weakest link in concrete. A weak ITZ is fundamental reason for the reduced macro-mechanical properties of the concrete. RCA with a surface coated with adhered mortar layers creates two types of Interfacial Transition zones; a) old ITZ and b) new ITZ as shown in Figure 1. The old ITZ exists between the old motor and natural aggregate making the concrete microstructure more fragile due to higher porosity and cracks, thus serving as the weakest link and resulting in lower compressive strength [8, 11-13] whereas new ITZ has been defined as an interface zone between new mortar and old mortar as well as between new mortar and aggregate. Numerous studies on the microstructure of the interfacial transition zone of concrete made with RCA conclude that the strength development and durability characteristics of concrete are primarily influenced by the composition of ITZ and its thickness [12-15]. RCA generally decreases compressive strength because of higher aggregate water absorption and an inferior layer of residual mortar [16, 17]. The performance of recycled aggregate containing 50% and 100 % recycled aggregate (RA) had been studied by Olorunsogo et al. [18] who found that RA decreases the resistance of concrete against chloride ingress thus making concrete susceptible to chloride-induced corrosion.

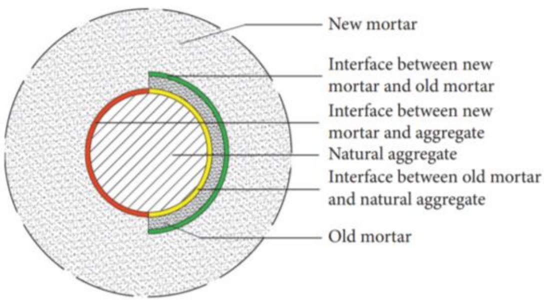

Fig. 1. Scanning electron microscope image of recycled concrete [8]

Overall durability indexes like sorptivity also increase with the addition of RA. A. Domingo et al. [19] found that concrete made with recycled aggregates has higher shrinkage strain and creep coefficient and lower modulus of elasticity in comparison to concrete made with natural aggregates. Otsuki et al. [20] investigated the influence of quality improvement techniques on RA. Properties like Vickers microhardness of ITZ including mechanical and durability performance of concrete were studied. From their study, it was observed that concrete made with recycled aggregates has lower resistance against chloride and CO2 ingress due to the presence of old ITZ and adhered mortar. Even mechanical properties were found to be inferior in recycled aggregate concrete. However, an improvement in mechanical and durability properties was seen in the case of treated aggregates. The test results also conclude that the quality of adhered mortar influences the characteristics of ITZ in a major way rather than its quantity. Zhang et al. [21] studied the ITZ of RCA under sulphate attack under alternate dry-wet cycles. The test results show that RCA offers lower resistance in comparison to concrete made with natural aggregate when subjected to external sulphate attack. Impurities or foreign materials present in an aggregate are those substances that result in detrimental effects on its performance in concrete. For instance, if present as a coating around the aggregates interferes with the bond characteristics, as a soft fragment can be considered as weak inclusion and may hinder the cement hydration process [22]. Excess amount of fines affects the workability of fresh concrete. Recycled concrete aggregate may contain foreign materials like metals, glass, soft fragments, clay lumps, bitumen, asphalt, filler (material finer than 75 um), ceramic material, wood, etc. [23, 24]. To avoid any damaging aftereffect due to presence of these foreign materials or impurities in RCA, it is desirable to limit their values, otherwise, their appearance will alter the concrete properties and decisively impact the long-term performance of concrete. For example, the presence of wood would generate voids [25] whereas the presence of metal like aluminum creates cracks and rock pockets within the concrete, thus diminishing its durability and mechanical properties [26]. As discussed above, the properties of concrete made with RCA are significantly affected by the adhered mortar layer. Therefore, it becomes of utmost importance to determine adhered mortar content in RCA. Since the direct estimation of adhered mortar content using techniques like Image analysis method (IAM) is time consuming and interpretation requires core-competency [27]. Therefore, eliminating techniques can be used as an indirect way for the quantification of adhere mortar content. Adhered mortar elimination from the RCA surface can be achieved through acid or mechanical treatment [28-30].

1.1. Research Significance

Fresh, hardened as well as durability properties of the concrete are chiefly influenced by the aggregate characteristics. According to the available literature, so far very limited work has been done to study these effects systematically as well as quantitatively in the case of construction & demolition (C&D) waste-based coarse recycled concrete aggregate (CRCA). In this paper, an attempt was made to study the use of C&DW based coarse recycled concrete aggregates (CRCA) available in our country for concrete production and its overall substitution level while replacing the natural aggregate. The study also investigated the impact of mechanical treatment over the characteristics of CRCA and its influence over concrete properties. The present study provides a comprehensive approach towards the utilization of C&DW- based coarse recycled concrete aggregates (CRCA) for structural work based on its physical characteristics which is presently not available in India.

2. Experimental Study

To achieve the aforementioned objectives, C&DW-based coarse recycled concrete aggregates (CRCA) from two different sources, one from the RCA plant in Delhi, India ,and the other produced through crushing of concrete samples at the laboratory were characterized for various physical and chemical parameters as per IS 383 [31] .Further, C&DW-based coarse recycled concrete aggregates (CRCA) were subjected to mechanical treatment where CRCA were exposed to more than 500 revolutions in a Los Angles abrasion test setup without any surcharge and physical properties like specific gravity ,water absorption, crushing value , abrasion value etc. were evaluated. Concrete mixes were designed at two water-to-cement ratios (0.45 and 0.65) with and without treated CRCA and detailed fresh, hardened, and durability properties of concrete were investigated. For the (a) Fresh properties – workability in terms of slump, and air content.

(b) Hardened properties – compressive and flexural strength, modulus of elasticity, drying shrinkage (c) Durability properties – drying shrinkage, resistance to chloride (RCPT, as per ASTM C1202 [32]) and chemical properties like acid & water-soluble chloride content as per IS 14959 Part 2 [33] as well as sulphate content as per IS 4032 [34]

2.1 Material Used

Portland Pozzalana Cement conforming to physical and chemical requirements of IS: 1489 Part 1(fly based) [35] was used and results are given in table 1. Natural coarse and fine aggregate conforming to IS-383 [31] was used and results are given in table 2. Fine aggregate with a water absorption value of 0.65 % and specific gravity as 2.65 has been used in the design of concrete mixes.

Table 1. Physical and chemical properties of cement

Sl.	Physical Properties	Results	Chemical properties	Results
1.	Fineness Blaine's (m2/kg)	356	Loss of Ignition (LOI) (%)	2.74
2.	Soundness by Autoclave (%)	0.06	Silica (SiO2) (%)	32.2
3.	Soundness by Le Chatelier (mm)	2	Iron Oxide (Fe2O3) (%)	3.57
4.	Setting Time Initial (minutes, min.)	155	Aluminium Oxide (Al2O3)	10.84
5.	Setting Time Initial (minutes, max.)	215	Calcium Oxide (CaO) (%)	43.42
6.	Compressive Strength, 72±1 hrs, MPa	24.55	Magnesium Oxide (MgO) (%)	1.35
7.	Compressive Strength, 168±2 hrs, MPa	32	Sulphate (SO3) (%)	2.15
8.	Compressive Strength, 672±4 hrs, MPa	43	Chloride (Cl) (%)	0.05
9.	Specific gravity	2.89	Insoluble Residue (%)	23.16

Table 3. Chemical properties of C&DW based coarse recycled concrete aggregates from RCA Plant, aggregates manufactured in laboratory

Sl. No	Characteristic	Results Obtained		
		RCA Plant, New Delhi (RCA –1)	Manufactured in lab (RCA–Lab)	Requirements of manufactured aggregate based on IS 383-2016
1	Total Alkali Content in terms of Na_2O equivalent, %	2.0	2.5	Maximum, 0.3%
2	Sulphate Content in terms of SO_3, %	0.13	0.16	Maximum 0.5%
3	Water soluble chloride Content, %	0.040	0.013	Maximum, 0.04%

C&DW-based coarse recycled concrete aggregate (CRCA): Two different sets of C&DW-based coarse recycled concrete aggregates (20mm and 10 mm), one set of aggregates from the RCA plant in Delhi, India, and another set of aggregates produced by crushing concrete samples with strength in compression around 25 MPa at laboratory and thereafter processed into different fractions were used in the study. Additionally, to study the quality grading of CRCA, two more sets of RCA samples of fractions 10 mm and 20mm were collected from RCA plant in Delhi, India. Some of the physical and chemical characteristics are given in Table 2 and Table 3 respectively.

2.2 Mix Design

The concrete mix design was carried out at two water to cement ratios i.e. 0.45 and 0.65. The natural coarse aggregates were replaced by CRCA by 20%, 40 %, and 100 % (by volume) for both set of aggregates. Naphthalene-based superplasticizer meeting IS 9103 [36] requirement was used to keep the workability in the range of 70-100 mm. Mixes were evaluated for fresh, mechanical and durability properties of concrete. The design mix was carried out using aggregates in saturated surface dry condition under laboratory conditions of temperature of 27±2oC and relative humidity of 65±5%. The details of the design mix are given in Table 4. Demoulding of samples cast was done after 24 hours and thereafter curing was continued till test age.

Table 4. Concrete mix design

Sample ID	w/c	Mix Constituents		Recycled concrete aggregate in terms % of total aggregate (volume based)	Recycled concrete aggregate as % replacement to natural coarse aggregate (by Volume)	Dosage of Admixture % by weight of cement	Remarks
		Cement content kg/m³	Water Content kg/m³				
M1B20	0.65	280	180	60	20	0.70	Experimental Mixes
M1B40	0.65	280	180	60	40	0.70	
M1B100	0.65	280	180	60	100	0.80	
M1L20	0.65	280	180	60	20	0.70	
M1L40	0.65	280	180	60	40	0.70	
M1L100	0.65	280	180	60	100	0.70	
M2B20	0.45	378	170	65	20	1.00	
M2B40	0.45	378	170	65	40	1.00	
M2B100	0.45	378	170	65	100	1.10	
M2L20	0.45	378	170	65	20	1.00	
M2L40	0.45	378	170	65	40	1.00	
M2L100	0.45	378	170	65	100	1.00	
M1C	0.65	280	180	60	-	0.70	Control Mix
M2C	0.45	378	170	65	-	1.00	

Note: B: C&DW coarse recycled concrete aggregate obtained from RCA plant, New Delhi, Sample1, and L: C&DW coarse recycled concrete aggregate produced in laboratory by crushing concrete of around 25 MPa strength

Additionally, concrete mix design was also carried out with treated CRCA to assess their performance after the removal of adhered mortar. While doing mix design with mechanically treated C&DW-based coarse recycled concrete aggregates (CRCA), concrete mix proportioning as mentioned in table 4 including fine aggregate to coarse aggregate ratio, the dosage of admixture was kept same as that of concrete mix designed with non-treated C&DW-based CRCA. The fresh, hardened, and durability study was carried out on concrete mixes made with and without mechanically treated C&DW-based coarse recycled concrete aggregate (CRCA).

2.3 Test Conducted

The details of the hardened and durability properties studied are given in Table 5. Compressive strength and flexural strength were the two basic engineering properties tested by IS 516 Part 1/Sec1 [37] at 7, 28, and 56 days. The modulus of elasticity as well as the Poisson ratio was evaluated on a concrete cylinder (150mm (Φ) x 300mm (h)) at an age of 28 days by IS 516 Part 8 / Sec1[38]. For the determination of the Modulus of elasticity, extensometers were attached in the longitudinal directions of the concrete specimens, and the load was applied at a rate of 14 MPa/min. The basic stress (σb) equals one-ninth of the average cube compressive strength (Fc /9 MPa) was maintained for 60 seconds and strain gauge readings were measured. Thereafter, stress was increased at a constant rate of 0.20 MPa/s until the stress equals one-third of the average cube compressive strength (σa = Fc /3). The stress was maintained for 60 sec and strain gauge readings were measured. In the last, the load was reduced at the same rate as during loading to the level of the basic stress. This cycle of loading and unloading was carried out thrice and in the fourth cycle, the final reading of strains was measured. For the determination of Poisson ratios, the loading as well as unloading cycle as mentioned for the Modulus of elasticity was kept the same, only the direction of extensometers was kept in the transverse directions of the specimens. The Modulus of elasticity (EC) and Poisson ratio (Pr) were calculated using the following equations

$$E_c = \frac{\sigma_a - \sigma_b}{\varepsilon_a - \varepsilon_b} \tag{1}$$

Where, σ_a is the upper loading stress, MPa

σ_a=F_c/3, σ_b is the basic stress=F_c/9, MPa

$$Pr = \frac{\Delta\, transverse\ strain}{\Delta\, longitudinal\ strain} \tag{2}$$

$$Pr = \frac{Transverse\ strain\ \sigma_a\ Transverse\ strain\ at\ \sigma_b}{Longitudinal\ strain\ at\ \sigma_a - Longitudinal\ strain\ at\ \sigma_b} \tag{3}$$

For the drying shrinkage test, 3 no's of concrete prism bars (75 mm x 75 mm x 300 mm) were cast as per IS 516 Part 6 [39]. The concrete specimens were cast as well as tested by the procedure given in IS 516 Part 6. After demoulding, concrete prism bars were stored in a controlled laboratory environment (Relative humidity = 65±5%, temperature = 27 ±2°C) for 7 days. After laboratory conditioning, concrete prism bars were immersed in water for up to an age of 28 days. At the age of 28 days, concrete specimens were removed from the water and initial readings were taken using a length comparator. Subsequently, concrete prism bars were placed in an oven maintained at a temperature of 50±1°C and Relative humidity of 17±2% for 44 hours. At the end of drying, the length of each specimen was measured. This cycle of drying and measuring was repeated until a constant length was achieved. The Drying shrinkage was calculated using the following equation

$$Drying\ shrinkage(\%) = \frac{[Initial\ length\ (after\ curing) - Final\ length\ (after\ drying)]x100}{original\ effective\ gauge\ length} \tag{4}$$

A rapid chloride penetrability test was conducted in accordance with ASTM C 1202 at the age of 28 days. In this test, concrete discs (3 no's) of 100 mm diameter and 50 mm thickness were extracted from a concrete cylinder (100 mm (Φ) x 200mm (h)). The test specimen was sandwiched between two cells, one cell contained 3.0% NaCl solution and the other cell contained 0.1M NaOH solution. A 60 V DC potential difference was maintained across the ends of the test specimen for 6 hours. At the end of the test, the total charge passed was measured and an average of the three specimens was reported as the test value.

Table 5. Details of casting and test conducted

Sl.	Test and specimen type	Dimension of specimen (mm)	Test age	Test method
1	Compressive strength on Cube	150 x150 x 150	7, 28 and 56 days	IS 516 Part1 / Sec1 [37]
2	Flexural strength on beam	100 x 100 x 500	7, 28 and 56 days	IS 516 Part1 / Sec1 [37]
3	Modulus of Elasticity and Poisson Ratio on cylinder	150 (Φ) x 300 (h)	28 days	IS 516 Part 8 /Sec1 [38]
4	Drying shrinkage on beam	75 x75 x300	28 days	IS 516 Part6 [39]
5	RCPT on cylinder	100 (Φ) x 200 (h)	28 days	ASTM C1202 [32]

Table 2. Physical Properties of Natural and C&DW based coarse recycled concrete aggregates (CRCA)

S. No.	Test Conducted		Natural Aggregate		C&DW based coarse recycled concrete aggregates from RCA plant , New Delhi												C&DW based coarse recycled concrete aggregates manufactured in lab			
					RCA Delhi Plant – Sample 1		RCA Delhi Plant– Sample 1 (after 500 Revolution treatment without charge in Los Angeles machine)		RCA Delhi Plant – Sample 2		RCA Delhi Plant– Sample 2 (after 500 Revolution treatment without charge in Los Angeles machine)		RCA Delhi Plant – Sample 3		RCA Delhi Plant– Sample 3 (after 500 Revolution treatment without charge in Los Angeles machine)		RCA lab (as crushed)		RCA lab (after 500 Revolution treatment without charge in Los Angeles machine)	
					RCA / B1 /20	RCA / B1 /10	RCA/ B1/20 /500R	RCA/ B1/10 /500R	RCA /B2 /20	RCA / B2 /10	RCA/ B2/20 /500R	RCA/ B2/10 /500R	RCA / B3 /20	RCA / B3 /10	RCA/ B3/20 /500R	RCA/ B3/10 /500R	RCA / lab /20	RCA / lab /10	RCA/ lab/20 /500R	RCA/ lab/10 /500R
1	Sieve results	% Passing	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm	20 mm	10 mm
		20 mm	98	100	93	100	98	100	98	100	100	100	100	96	100	100	97	100	100	100
		10 mm	16	97	2	74	15	85	3	90	15	95	13	85	20	90	6	77	24	100
		4.75 mm	2	14	1	6	9	6	0	20	3	20	1	15	4	18	1	6	0.63	15
		2.36 mm	-	3	0	0	-	2	0	5	0	4	0	8	0	10	-	-	-	5
2	Total Deleterious content (%)		0	0	0.15	0.15	0.15	0.15	-	-	-	-	-	-	-	-	0.05	0.05	-	-
3	Specific Gravity		2.81	2.80	2.39	2.37	2.48	2.44	2.33	2.32	2.42	2.40	2.52	2.42	2.55	2.44	2.37	2.35	2.40	2.37
4	Water absorption %		0.40	0.40	4.58	4.75	3.87	3.93	5.10	5.40	4.10	4.30	3.70	3.73	3.30	3.40	4.41	4.43	4.16	4.28
5	Soundness test (Na_2SO_4),%		2.20	-	0.13	-	-	-	2.80	-	-	-	-	-	-	-	0.72	0.46	-	-
6	Abrasion value %		23.0	-	24.0	22.0	25.0	25.0	35.0	-	-	-	23.0	22.0	-	-	24.0	23.0	20.0	24.0
7	Crushing Value %		18.0	-	25.0	26.0	27.0	23.0	29.0	-	-	-	24.0	27.0	-	-	22.0	22.0	25.0	26.0
8	Impact Value %		21.0	-	20.0	17.0	20.0	20.0	25.0	-	-	-	24.0	22.0	-	-	23.0	21.0	23.0	20.0
9	Combined flakiness and Elongation Index %		19.0	-	15.8	20	18.8	18.2	17.0	-	-	-	-	-	-	-	21.3	29.6	19.6	23.3
10	Foreign Material, %		-	-	Nil	Nil	Nil	Nil	Nil	-	-	-	-	-	-	-	Nil	Nil	Nil	Nil

Note - “-” not tested

Apart from the above tests, the concrete mixes made with CRCA were also tested for pH, acid & water-soluble chloride content, and water-soluble sulphate content. The pH was measured using a pH meter. Acid and water-soluble chloride content was determined as per IS 14959 Part 2 [33] whereas water-soluble sulphate content was measured in accordance with IS 4032 [34].

3. Results and Discussion

3.1 Comparison of Physical and Chemical Characteristics of C&DW Based Coarse Recycled Concrete Aggregate (CRCA) Before and After Mechanical Treatment

Purushothaman *et al*. [28] classified various techniques as well as approaches to improve the quality of C&D waste-based concrete aggregate. It was suggested either to remove the adhered mortar in recycled concrete aggregates or to improve the quality of the adhered mortar through surface coating etc. Preliminary tests were carried out at 100, 200, and 500 revolutions in Los Angeles abrasion testing machine. It was found that mechanical treatment without any loading charge at 500 revolutions had given the best results (Table 2 & figure-2). These test results were also supported by the work done by other researchers [40]. Improvement in properties of CRCA such as specific gravity and water absorption after treatment was observed when compared with untreated CRCA.

RCA/ 20 mm Delhi plant

RCA/ 10 mm Delhi plant

RCA/ Lab/ 20 mm

RCA/Lab/ 10mm

RCA/ 20 mm Delhi plant after 500 revolutions

RCA/ 10 mm Delhi plant after 500 revolutions

RCA/ Lab/ 20 mm after 500 revolutions

RCA/Lab/ 10mm after 500 revolutions

Los Angeles Abrasion testing Machine

Fig. 2 C&DW based coarse recycled concrete aggregate (CRCA) from Delhi Plant as well as manufactured in Lab before and after mechanical treatment in Los Angeles abrasion testing machine

Table 6. Percentage change in specific gravity of as received and mechanically treated recycled concrete aggregate

Type of C&DW based coarse recycled aggregate	As received aggregate	Specific gravity Treated aggregate (After 500 revolution in Los Angeles machine without any charge)	Increase in specific gravity	% Increase in specific gravity over as received recycled concrete aggregate
RCA/B1/20	2.39	2.48	0.09	3.8
RCA/B1/10	2.37	2.44	0.07	3.0
RCA/B2/20	2.33	2.42	0.09	3.9
RCA/B2/10	2.32	2.40	0.08	3.4
RCA/B3/20	2.52	2.55	0.03	1.2
RCA/B3/10	2.42	2.44	0.02	0.8
RCA/lab/20	2.37	2.40	0.03	1.3
RCA/lab/10	2.35	2.37	0.02	0.9

$$\%\ Increase\ in\ specific\ gravity = \frac{(S.G\ .TA - S.G.AR\ ) * 100}{S.G\ AR} \quad (5)$$

Where, S.G.TA= specific gravity of treated recycled concrete aggregate (After 500 revolution in los Angeles machine without any charge), S.G.AR= specific gravity of as received recycled concrete aggregate

Some of the distinct qualities of C&DW-based coarse recycled concrete aggregate (CRCA) include water absorption, specific gravity /dry density, and porosity. These properties are primarily influenced by the quality as well as quantity of the adhered mortar content over the parent aggregate. From Table 2, it was observed that the sieve gradation of CRCA fulfils the requirement of IS 383:2016. A slight refinement in the gradation was observed in the mechanically treated coarse recycled concrete aggregate (CRCA) over non- treated coarse recycled concrete aggregate (CRCA) which was found in line with the results reported by Babu et al. [40]. The total deleterious content in all the CRCA samples was found to be less than 2 % i.e. within the permissible limit as defined in IS 383:2016.

The percentage increase in specific gravity was in the range of 0.80 % to 3.4% for 10 mm aggregate, with an average increase of 2.4% in specific gravity observed for RCA from the Delhi plant, and 0.9 % for crushed RCA manufactured in a lab. For 20 mm aggregate, an increase of 1.3 % in specific gravity was observed for crushed RCA manufactured in the lab, and 3.0 % for the RCA obtained from the Delhi plant. The results of specific gravity support removal of the adhered mortar after 500 revolutions without any loading charge in the Los Angeles machine.

Table 7. Percentage Change in water absorption of as received and mechanically treated recycled concrete aggregate

Type of C&DW based coarse recycled aggregate	Water absorption (%)			
	As received aggregate	Treated Aggregate (for more than 500 revolution without any charge in los Angeles machine)	Reduction in water absorption	% Reduction in water absorption over as received recycled concrete aggregate
RCA/B1/20	4.58	3.87	0.71	15.50
RCA/B1/10	4.75	3.93	0.82	17.26
RCA/B2/20	5.10	4.10	1.00	19.61
RCA/B2/10	5.4	4.30	1.10	20.37
RCA/B3/20	3.70	3.30	0.40	10.81
RCA/B3/10	3.73	3.40	0.33	8.85
RCA/lab/20	4.41	4.16	0.25	5.67
RCA/lab/10	4.43	4.28	0.15	3.39

$$\%\, Reduction\ in\ water\ absorption = \frac{(WA\,.TA - WA.AR\,) * 100}{WA.AR} \tag{6}$$

Where, WB.TA= Water absorption of treated recycled concrete aggregate (more than 500 revolution without any charge in Los Angeles machine), WB.AR= Water absorption of as received recycled concrete aggregate

For 10 mm aggregate obtained from the RCA plant, a percentage reduction in the water absorption was found in the range of 3.39 % to 20.37%, with an average reduction of 15.50 % whereas in the case of RCA manufactured in the lab, a reduction in the water absorption was found to be 3.39%. For 20 mm aggregate, the percentage reduction in water absorption value was observed as 5.67 % for crushed RCA manufactured in lab, and 15.30% (average) for the RCA obtained from the Delhi plant. The results of water absorption also support removal of the adhered mortar after 500 revolutions without any charge in a Los Angeles machine which was found in line with the results reported by Babu et al. [40]. The abrasion, impact, and crushing value test on CRCA conforms to a maximum limit of 30 % as per IS: 383 for concrete structures subjected to wearing. The value of the combined flakiness and elongation index was between 15-25 % and it also conforms to IS: 383 requirements. From the chemical results as given in table 3, it was observed that none of the C&DW-based coarse recycled aggregates (CRCA) complied with the total alkali requirements of IS 383 because of existence of the adhered mortar whereas other chemical parameters like chloride content and sulphate content were found to be within the permissible limits.

3.2 Fresh Concrete Properties

Freshly prepared concrete was evaluated in terms of workability and air content as per IS 1199 Part 2 [41] and IS 1199 Part 4 [42] respectively. Test results of fresh concrete properties are given in table 8.

Table 8. Fresh properties – workability (slump) and air content

Sl. No.	Specimen ID	w/c ratio	Aggregate replacement %	Slump (mm)	Air content (%)	Slump (mm)	Air content (%)
				With non–mechanically treated C&DW based CRCA		With mechanically treated C&DW based CRCA	
1	M1C	0.65	-	95	1.80	-	-
2	M2C	0.45	-	100	2.00	-	-
3	M1B20	0.65	20	90	1.90	100	1.80
4	M1B40		40	85	2.10	90	2.00
5	M1B100		100	75	2.30	80	2.10
6	M2B20	0.45	20	85	2.20	95	2.00
7	M2B40		40	80	2.30	85	2.10
8	M2B100		100	70	2.50	85	2.20
9	M1L20	0.65	20	95	2.00	100	1.80
10	M1L40		40	90	2.10	90	1.90
11	M1L100		100	80	2.30	95	2.10
12	M2L20	0.45	20	85	1.90	95	1.90
13	M2L40		40	80	2.30	100	2.00
14	M2L100		100	75	2.50	90	2.20

From the earlier studies [43,44], it was established that the presence of adhered mortar in C&DW-based coarse recycled concrete aggregate (CRCA) not only leads to a loss in workability but also increases the air content value. In the present study, when natural aggregates were replaced with C&DW-based coarse recycled concrete aggregate (CRCA) at various replacement levels, a reduction in the consistency of fresh mixes was observed. This was probably due to higher water absorption of CRCA in comparison to natural aggregate. In addition to high water absorption value, its grain shape and texture as reported in past studies were also responsible for loss of workability [43, 45-48]. By using saturated surface dry recycled aggregate, the consistency of the concrete mixes made with or without C&DW-based coarse recycled concrete aggregate (CRCA) did not differ that much, and the same was supported by the test results as given in Table 8. The concrete mixes made with 100 % C&DW-based coarse recycled concrete aggregate (CRCA) showed the highest degree of workability loss. It should be noted that concrete mixes with or without mechanically treated C&DW-based coarse recycled concrete aggregate (CRCA) were designed at the same admixture dosage as that of the corresponding control mix. The air content in the concrete mixes prepared from C&DW-based coarse recycled concrete aggregate was found to be 5-25 % higher than that of the control mix. Based on the observation, it can be concluded that the admixture requirement in the concrete mixes prepared with C&DW-based coarse recycled concrete aggregate (CRCA) may be slightly higher to achieve the same level of slump as that of the control mix. In the case of concrete mixes made with treated C&DW-based coarse recycled concrete aggregate (CRCA), an improvement in the workability, as well as air content value was observed. This improvement in the fresh properties of the concrete made with treated C&DW-based coarse recycled concrete aggregate may be due to refinement in the water absorption value, due to the removal of the adhered mortar during the mechanical treatment. Such improvement in the fresh properties due to the removal of the adhered mortar was also reported by Lavado et al.[43], Poon et al. [47] and Faleschini et al . [48].

3.3 Results of Mechanical Performance in Concrete

Concrete mixes made with non-treated C&DW- based coarse recycled concrete aggregate (CRCA) and mechanically treated C&DW- based coarse recycled concrete aggregate (CRCA) were evaluated for physical parameters like compressive strength, modulus of elasticity; and Poisson ratio. The quality of aggregate in terms of its physical properties governs the strength of concrete [49, 50]. In most of the reported studies, researchers found that the addition of CRCA in concrete reduces compressive strength because of higher aggregate water absorption, and inferior quality of the adhered mortar layer [7, 51-53]. The formation of double ITZ also weaken the concrete [3-6]. On the perusal of the test results, as shown in Fig. 3 and Fig. 4, it was observed that the compressive strength of the concrete mixes made with C&DW- based coarse recycled concrete aggregate (CRCA) was significantly affected by the w/c ratio. From fig. 3, it was observed that when natural aggregate was replaced with non-treated CRCA aggregate up to 40 %, the 7-day compressive strength of concrete mixes with made non- treated C&DW coarse recycled concrete aggregate (CRCA) was slightly higher or at par in comparison to control mix whereas compressive strength of all concrete mixes made with treated C&DW coarse recycled concrete aggregate (CRCA) was higher than that of control mixes. From Fig 4., it was noticed that at 28 days, concrete mixes designed at 0.65 w/c with non- treated C&DW coarse recycled concrete aggregate (CRCA) up to 40%, compressive strength of the mixes was found comparable to that of the control mix. However, the compressive strength of concrete mixes designed at lower w/c of 0.45 with non-treated C&DW coarse recycled concrete aggregate (CRCA), irrespective of replacement percentage was lower than that of the control mix. In case of treated C&DW coarse recycled concrete aggregate (CRCA), the compressive strength of concrete mixes designed with treated CRCA up to 40 % was at par to the control mixes.

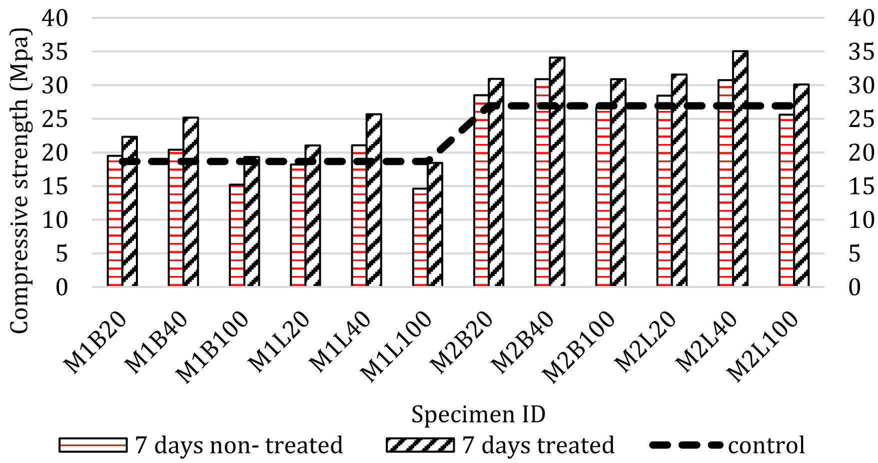

Fig. 3. Compressive strength of 7 days matured concrete mixes made with treated and non –treated C&DW-based coarse recycled concrete aggregate (CRCA

According to existing international codes and standards [3], about 20% to 60 % of the coarse recycled concrete aggregate (CRCA) is allowed to be used for structural application depending upon its properties like water absorption, specific gravity, etc. Studies reported by Tam et al. [3], Seara et al. [7,], and Silva et al. [52,53] indicate a general declining trend in the compressive strength value with the increase in the replacement level of natural aggregate with recycled concrete aggregate (RCA) due to the formation of double ITZ. However, some of the studies also report that it is possible to develop concrete with RCA with a strength equivalent to that of conventional mixes. This is possible only if the moisture condition of RCA is controlled [17]. In the present study, the moisture level of CRCA aggregates was controlled by the use of saturated surface dry recycled aggregate in concrete mix design. Based on the available data and present experimental results, it can be observed that natural coarse aggregate can be replaced with coarse recycled concrete aggregate (CRCA) up to 40%.

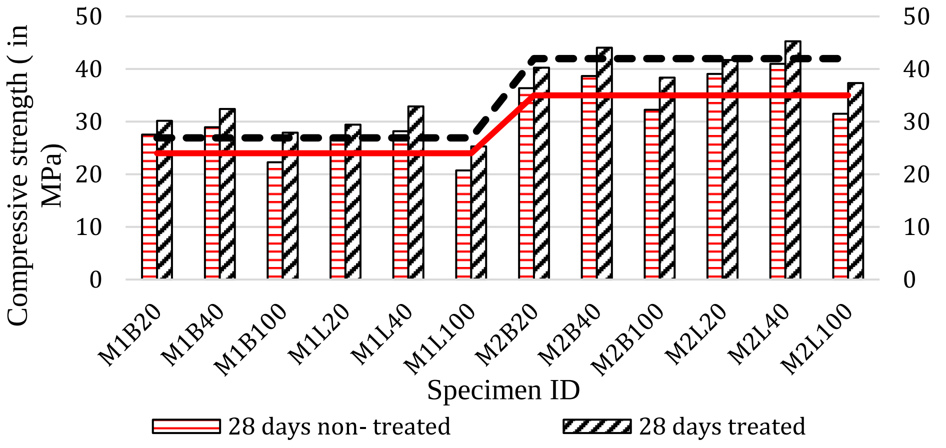

Fig. 4 Compressive strength of 28 days matured concrete mixes made with treated and non –treated C&DW-based coarse recycled concrete aggregate (CRCA)

Test results shown in Fig. 4. and Fig. 5., indicate that the quality of non-treated C&DW-based coarse recycled concrete aggregate (CRCA) obtained from the RCA plant or manufactured in the laboratory was not good enough to design concrete mixes that can perform equivalent to that of the concrete mix made with natural aggregates at lower w/c i.e. 0.45. Indeed, the strength obtained by using C&DW-based coarse recycled aggregate (CRAC) was lower in comparison to the control mix which was in line with the result reported by the various researchers [7, 51, 54]. However, concrete mixes made with C&DW coarse recycled aggregate up to 40 % can qualify the requirement to be accepted as per site condition which was in accordance with the site acceptance criteria of IS 456 [55] i.e. acceptance criteria for concrete mixes designed at 0.65 w/c which is equivalent to M20 grade of concrete and 0.45 w/c which is equivalent to M30 grade of concrete is 24 MPa and 34 MPa respectively as per IS 456(i.e. Fck +4). From Table 9, it was observed that concrete made with C&DW-based coarse recycled concrete aggregate either sourced from the RCA plant or manufactured in the laboratory by crushing concrete cube samples after treatment in Los Angeles abrasion machine shows significant improvement in strength at 7 days as well as 28 days in comparison to concrete produced from non-treated C&D waste aggregates which were in line with results reported by Purushotham et al.[28], Saravanakumar et al [56], Verma et al. [57]

From the fig. 5, it can be seen that concrete mixes designed with mechanically treated C&DW-based coarse recycled concrete aggregate at a lower w/c ratio of 0.65 can completely replace natural aggregates. However, concrete mixes designed with mechanically treated C&DW-based coarse recycled concrete aggregate at a lower w/c ratio of 0.45 can replace natural aggregates up to 40 %. Concerning the IS 456 acceptance criteria as discussed above for different grades of concrete, natural coarse aggregates can be replaced completely with mechanically treated C&DW-based coarse recycled concrete aggregates (CRCA). C&DW-based coarse recycled concrete aggregate (CRCA) after mechanical treatment will have an improved microstructure which is the result of loss in the quantity of adhered mortar. With the removal of adhere mortar possibility of the formation of double ITZ gets minimized and C&DW aggregates will act like parent rock [58]. The percentage improvement in the 28 days' strength of concrete mixes made with mechanically treated C&DW aggregates over non–treated C&DW coarse recycled concrete aggregate (CRCA) was found in the range of 6.78 % to 18.97 %, refer to Table 9 and maximum improvement in strength characteristics has been noticed in concrete mixes designed with 100 % C&DW coarse recycled concrete aggregate.

Table 9. Percentage increase in compressive strength of concrete mixes made with mechanically treated C&DW aggregates over non –treated C&DW coarse recycled concrete aggregate

Specimen ID	M1 B20	M1 B40	M1 B100	M2 B20	M2 B40	M2 B100	M1 L20	M1 L40	M1 L100	M2 L20	M2 L40	M2 L100
At 7 days	14.52	23.49	27.15	8.52	10.36	15.77	15.53	21.83	26.2	11.04	13.98	17.62
At 28 days	9.51	12.03	25.26	10.67	13.85	18.97	9.12	16.7	22.15	6.78	10.49	18.50

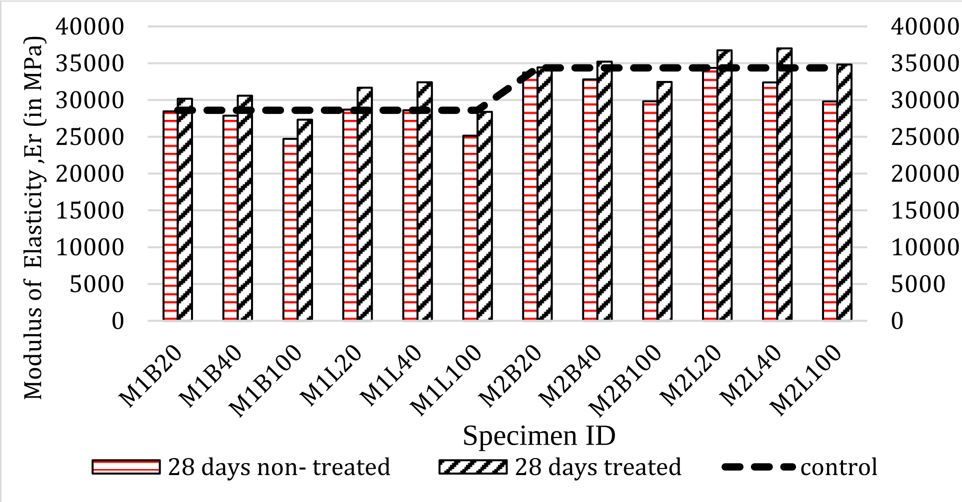

Fig. 5. Modulus of elasticity of 28 days matured concrete mixes made with mechanically treated and non –treated C&DW-based coarse recycled concrete aggregate (CRAC)

Research suggests that the modulus of elasticity of concrete was influenced by the type and amount of coarse aggregate within concrete [40, 59-66]. In fact, a 20 % reduction in the modulus of elasticity (MOE) was observed in concrete made with recycled coarse aggregate (RCA) in comparison to concrete made with natural coarse aggregate. Also, it was noteworthy to observe that up to 30 MPa strength, the difference in modulus of elasticity between recycled aggregate concrete (RCA) and conventional concrete was almost negligible, while on the other hand, for concrete with strength value more than 30 MPa, the difference between the subjected modules was increased [64-68]. The modulus of elasticity of the control mixes i.e. M1C and M2C was 28605 MPa and 34364 MPa respectively. From our study, as shown in Fig. 5, it can be observed that with the increase in the substitution level of C&DW aggregates, there was a decrease in the modulus of elasticity value. A significant reduction in MOE value in the range of 12-14 % was observed for concrete made at 100 % replacement level of natural aggregate with non –treated CRCA. However, up to 40 % replacement level of natural aggregate with non –treated CRCA, MOE values were comparable to that of the control mix. This finding was found in line with the results reported by Silva et al [69] where they had observed that replacement of the natural aggregate with recycled concrete aggregate (RCA) up to 30 % had minimal effect on the MOE value. In some of the concrete mixes made with 40 % C&DW coarse RCA i.e. M2B40, M2L40, a slight reduction in MOE value in the range of 3-5 % was observed with respect to the control mix which seems to be reasonable in comparison to 14% reduction observed. The modulus of elasticity (MOE) of concrete mixes made with treated C&DW-based coarse recycled concrete aggregates (CRCA) was found to be higher than that of control mixes. The test results of the compressive strength and MOE of concrete mixes made with or without treated C&DW-based coarse recycled concrete aggregates (CRCA) showed a constitutive relationship. The Poisson ratio test was conducted in accordance with IS 516-part 8 Section 1 on a set of concrete cylinder specimens. From Table 10, no conclusive inference was drawn from Poisson's ratio results. The Poisson ratio value of treated and non-treated C&DW coarse recycled concrete aggregate was found to be in the range of 0.110 to 0.0127 which was in line with the reported range of 0.10-0.20 in Euro code 1992 [64-76]

Table 10. Poisson Ratio of concrete mixes made with mechanically treated and non –treated C&DW coarse recycled concrete aggregate

Specimen ID	M1 B20	M1 B40	M1 B100	M2 B20	M2 B40	M2 B100	M1 L20	M1 L40	M1 L100	M2 L20	M2 L40	M2 L100
28 days non-treated	0.113	0.110	0.115	0.105	0.109	0.107	0.12	0.128	0.121	0.124	0.121	0.112
28 days treated	0.118	0.115	0.106	0.111	0.115	0.115	0.123	0.129	0.127	0.126	0.126	0.121

3.4 Test Results of Durability Properties

The durability of concrete is a prime parameter in the service life design of concrete structures and is generally measured through performance-based tests. The concrete mixes made with non-treated C&DW-based coarse recycled concrete aggregate (CRAC) and mechanically treated C&DW-based coarse recycled concrete aggregate (CRAC) were tested for Rapid chloride penetrability test and drying shrinkage test. Since C&DW-based coarse recycled concrete aggregate (CRAC) was porous in nature due to the presence of adhered mortar. Therefore, it was expected that the permeability of such type of concrete mixes would be more than natural aggregate. The test results of RCPT are shown in Fig. 6. In general, RCPT values for the concrete made at 0.45 w/c were found to be in the category of low chloride ion penetrability class as defined in ASTM C1202 whereas concrete made at 0.65 w/c, falls in moderate category. The test results shown in Fig 6., showed that the amount of charge passed through the concrete increases in proportion to the substitution percentage of natural coarse aggregate with C&DW -based coarse recycled concrete aggregate (CRAC).

The chloride ion penetrability class of concrete made with and without mechanically treated C&DW- based coarse recycled concrete aggregate (CRAC) was found to be the same for all the replacement levels except for 100 % substitution. They also correspond to the same chloride ion penetrability class as that of control mix. However, concrete made with 100 % treated as well as non-treated C&DW-based coarse recycled concrete aggregate (CRAC) shows the least resistance against chloride ion penetration in comparison to other replacement levels and 20 % and 40 % in terms of charge passed. Even concrete mixes made with 100 % C&DW-based coarse recycled concrete aggregate perform miserably when compared to the control mixes. The performance of the concrete mixes made with treated and non-treated C&DW-based coarse recycled concrete aggregate (CRAC) up to the replacement level of 40 % against chloride ingress was comparable to that of control mixes. The reduction in the charge passed was observed in the case of concrete mixes made with mechanically treated C&DW-based coarse recycled concrete aggregate (CRAC) over concrete mixes made with non-treated C&DW-based CRAC. This reduction was found to be in the range of 6-14 % at 20 % replacement level, 19-37 % at 40 % replacement level, and 33-36 % at 100 % replacement level. It indicates with the removal of adhered mortar the quality of C&DW-based coarse recycled concrete aggregate improves and it offers better against chloride attack.

A drying shrinkage test was conducted on a hardened concrete prism bar of dimension 75x75x300 mm at 28 days in accordance with IS 516 Part6. The drying shrinkage values of control mixes M1C and M2C were 0.0250 % and 0.0182% respectively. From Table 11, it can be observed that the drying shrinkage value of hardened concrete mixes made by non-treated C&DW-based coarse recycled concrete aggregate (CRCA) was quite high in comparison to the corresponding control mix.

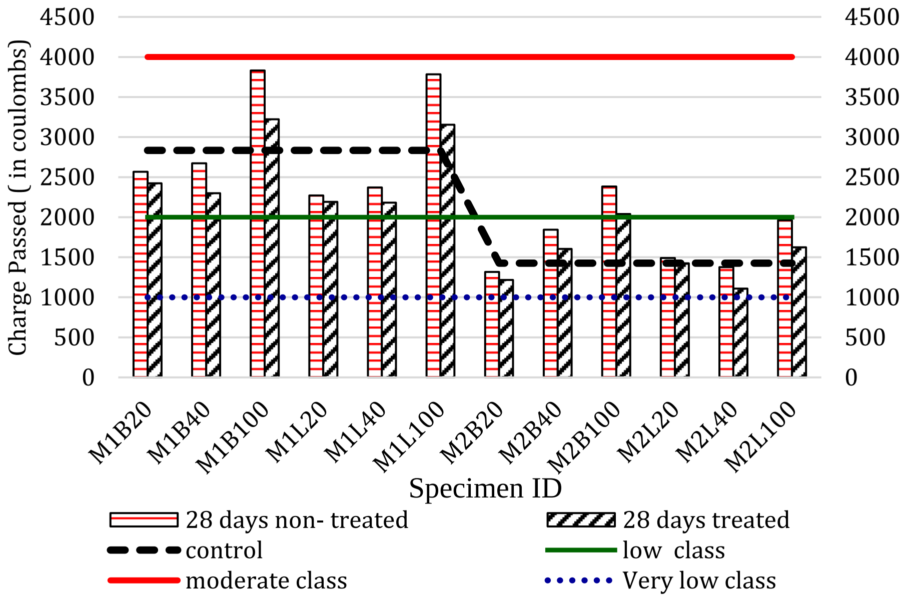

Fig. 6. Rapid chloride penetrability test (RCPT) of concrete mixes made with mechanically treated and non –treated C&DW-based coarse recycled concrete aggregate (CRAC)

Even the effect of the w/c ratio on shrinkage value was found to be quite prominent i.e. concrete mix designed at 0.45 w/c had lower shrinkage value in comparison to concrete mix designed at 0.65 w/c. The shrinkage value of concrete mixes prepared with treated and non-treated C&DW-based coarse recycled concrete aggregate (CRCA) up to a replacement level of 40 % was found to be comparable to the control mixes. At 100 % replacement level, the shrinkage percentage found to be in the range of 0.0273 % to 0.0340% which seems to be very high when compared to control mixes. However, a 4-15 % decrease in shrinkage was noticed in the case of concrete made with mechanically treated CRCA over non –treated CRCA but still shrinkage percentage was found to be high in comparison to the corresponding control mix at 100% replacement. The finding of the durability test results i.e. RCPT and drying shrinkage so obtained were in line with the study reported by various researchers [53, 77-82].

Additionally, certain concrete mixes made with non-treated C&DW-based coarse recycled concrete aggregate (CRCA) obtained from the RCA plant and manufactured in the laboratory were also tested for chemical parameters like pH, acid & water -soluble chloride content, and water-soluble sulphate content. The pH, chlorides and sulphate tests were conducted on 28 days of matured concrete samples and at various replacement levels. Table12 represents chemical results of pH, chloride, and sulphate conducted on concrete samples. The pH level at all replacement levels was observed in concrete mixes prepared with C&DW-based coarse recycled concrete aggregate (CRCA). This increase in chloride and sulphate content value may be attributed to the presence of adhered mortar which is rich in chlorides as well as sulphates.

The results of chlorides and sulphates present in the aggregates were discussed in 3.1.2. Indeed, the value of water-soluble sulphate content in concrete mixes made with non-treated C&DW-based coarse recycled concrete aggregate (CRCA) was very high in comparison to control mix but found to be within the permissible limit of 4 % by mass of cement as per IS 456 i.e. 0.86% to 3.34 % by mass of cement.

Table 11. Drying shrinkage of hardened concrete mixes made with mechanically treated and non –treated C&DW coarse recycled concrete aggregate

Specimen ID	M1B20	M1B40	M1B100	M1L20	M1L40	M1L100	M2B20	M2B40	M2B100	M2L20	M2L40	M2L100
28 days non-treated	0.0269%	0.0260%	0.0340%	0.0240%	0.0262%	0.0308%	0.0193%	0.0173%	0.0285%	0.0186%	0.0176%	0.0273%
28 days treated	0.0248%	0.0230%	0.0296%	0.0230%	0.024%	0.0269%	0.0185%	0.0156%	0.0240%	0.0174%	0.0153%	0.0230%

The acid-soluble chloride content in concrete mixes made with non-treated C&DW-based coarse recycled concrete aggregate (CRCA) was almost double in comparison to the control mixes. The value of water-soluble chloride content was found in the range of 0.480 to 0.960 kg/m^3 whereas acid soluble chloride content was found in the range of 0.816 to 1.512 kg/m^3. Various researchers have suggested chloride a threshold value between 0.9 to 1.2 kg/m^3 or 0.3% by mass of cement for the initiation of corrosion [62,63]. In the present study, concrete mixes made with non-treated C&DW based coarse recycled concrete aggregate (CRCA) exhibit a higher value than threshold value. Therefore, it is suggested to conduct a corrosion test to further examine the performance of concrete mixes made with C&DW-based coarse recycled concrete aggregate with respect to chloride-induced corrosion.

Table 12. Chemical results

Specimen ID	pH	Chlorides (in kg/m^3)		Sulphates (%) by mass of cement
		Water soluble	Acid soluble	
M1C	12.26	0.480	0.572	1.03
M2C	12.35	0.408	0.592	0.95
M1B20	12.27	0.816	1.440	2.31
M1B40	12.30	0.744	1.512	2.57
M1B100	12.33	0.840	1.320	3.34
M2B20	12.29	0.960	1.152	2.03
M2B40	12.24	0.672	1.272	1.52
M2B100	12.26	0.792	1.176	1.65
M1L20	12.32	-	-	-
M1L40	12.22	-	-	-
M1L100	12.27	0.480	0.816	0.86
M2L20	12.26	0.624	1.200	0.95
M2L40	12.32	0.576	1.032	1.08
M2L100	12.35	0.635	1.215	-

Note "-" Not tested

4. Conclusion

The test results of fresh, hardened, and durability characteristics of concrete made with C&DW-based coarse recycled concrete aggregate (CRCA) either obtained from the RCA plant or manufactured at a Laboratory demolished building indicates that it is not possible to completely replace the natural coarse aggregate with CRCA for structural works. The quality of aggregate plays a significant role; therefore, it becomes prerogative to evaluate the quality of C&DW-based coarse recycled concrete aggregate before producing any type of concrete. Following are the board findings of the study

- A mechanical treatment method involving 500 revolutions in a Los Angeles machine without any charge can be used as a technique for the quality improvement of the

C&DW-based coarse recycled concrete aggregate (CRCA). From the test results, it was observed that the physical properties of the coarse recycled concrete aggregate (CRCA) such as specific gravity and water absorption improve significantly due to mechanical treatment. This was mainly due to the removal of adhered mortar

- The properties of the concrete made with non-treated C&DW-based coarse recycled concrete aggregate (CRCA) show that natural coarse aggregate can be replaced up to 40 %.
- The concrete produced with treated C&DW-based coarse recycled concrete aggregate (CRCA) had shown better mechanical as well as durability properties in comparison to non-treated C&DW-based coarse recycled concrete aggregate (CRCA) as well as control mixes. Therefore, natural coarse aggregate can be completely replaced by treated C&DW-based coarse recycled concrete aggregate (CRCA). It is mainly due to improvement in the ITZ, as coarse recycled concrete aggregate (CRCA) after treatment will lose a certain quantity of adhere mortar which is responsible for the creation of double ITZ in concrete made with C&D waste-based aggregate.

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