International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:12, No:3, 2018

Durability Aspects of Recycled Aggregate Concrete: An Experimental Study

Smitha Yadav, Snehal Pathak

Abstract**—**Aggregate compositions in the construction and demolition (C&D) waste have potential to replace normal aggregates. However, to re-utilise these aggregates, the concrete produced with these recycled aggregates needs to provide the desired compressive strength and durability. This paper examines the performance of recycled aggregate concrete made up of 60% recycled aggregates of 20 mm size in terms of durability tests namely rapid chloride permeability, drying shrinkage, water permeability, modulus of elasticity and creep without compromising the compressive strength. The experimental outcome indicates that recycled aggregate concrete provides strength and durability same as controlled concrete when processed for removal of adhered mortar.

Keywords**—**Compressive strength, recycled aggregate, shrinkage, rapid chloride permeation test, modulus of elasticity, water permeability.

I. Introduction

THE disposal of C&D waste has become a matter of concern with the precedential growth as seen in the construction Industry and thus the increasing demolition to accommodate the infrastructure needs. India presently is generating 48 million tonnes of solid waste, out of which C&D waste makes up 25% annually as reported in the International Society of Waste Management, Air and Water (ISWMAW) by Ghosh, 2011 [1]. Out of this 25%, around 23% is made up of concrete and around 31% is brick. C&D waste from demolition finds its way into waste storage depots or pile up on the roadsides making the municipal waste heavy and degrading its quality for treatments or energy recovery. Research in countries like Denmark, Netherlands, Japan, etc. are stepping grounds wherein the recycled percentage of C&D waste reutilised has been to an extent of 70-85% of the 20-22% of total C&D waste generated [2]. In Indian scenario also, it is essential to conserve the depleting natural aggregate resource considering the huge demand. These recycled aggregates can be re-used in making concrete, thus saving on the natural aggregates. However, assessment of the material for adequate strength and durability would be necessary. An attempt has been made in here to assess performance of second generation concrete made up of C&D waste material from Western Maharashtra.

II. Research Scope

The experimental study with recycled aggregates was undertaken by using the crushed concrete as aggregates which were angular in shape and rough in surface texture due to the adhered mortar content. The crushed aggregates were obtained from dilapidated and demolished concrete structures that were 20 to 30 years old and most likely made up of lean concrete M15 to M20 grade. The compressive strength of such concrete made up of these crushed aggregates was evaluated using the British method of concrete mix design (DOE) with 0, 50, 60 and 100% replacement of recycled aggregates. Good quality of concrete is normally determined by its ability to withstand compressive strength and also to provide long term durability.

The work presented in this paper necessarily deals with testing such recycled aggregate concrete for its compressive strength and also checking the durability parameters like drying shrinkage, rapid chloride permeation, water permeability, modulus of elasticity and creep of such concrete.

III. Material Used

Ordinary Portland cement (OPC) 43 grade satisfying the codal provisions of IS:8112 [3] was used in the present work. The cement used has been tested for various physical properties as per IS:4031 [4]. The fine aggregate used for the study was natural river sand confirming to zone 1 as per IS:383 [5].

Normal aggregates in the size range of 20 mm were procured from quarries in Pune, Maharashtra. The recycled aggregates were divided into two categories, i.e. agglomerated sample and individual samples from various places having a fineness modulus of around 7.10. Work was initially performed on agglomerated sample (R_P) which was a mix of recycled aggregates collected from various places in Pune, Maharashtra. The individual samples were collected from ten different zones from Western Maharashtra. The characteristics of recycled aggregates samples (R_P and R_1 to R_{10}) and normal aggregates are presented in Table I.

From the characterization of the aggregates, it is observed that recycled aggregates have lower specific gravity in comparison with the normal aggregate. The water absorption of recycled aggregates is also found to be higher in comparison to normal aggregates on account of the adhered mortar on the recycled aggregates. These recycled aggregates in the present work were used in concrete after the removal of adhered mortar content, which reduced water absorption to a considerable extent.

IV. Test Programme

Total 36 specimens of agglomerated recycled aggregate concrete with adhered mortar content were tested for their compressive strength at 7 and 28 days, respectively. Another

Smitha Yadav is with the National Institute of Construction management and Research, India (e-mail: smiyad01@gmail.com).

18 specimens of agglomerated recycled aggregates concrete were tested after removal of adhered mortar content with reduction in water cement ratio, and 60 individual samples were tested without the adhered mortar content at 7 and 28 days, respectively. Six specimens of controlled concrete were also tested for compressive strength at 7 and 28 days respectively. This concrete of M25 grade made with recycled aggregates without adhered mortar content was also tested for various durability parameters. In total 120 cubes were tested for compressive strength, and 105 specimens were tested for various durability tests as shown in Table II.

TABLE I
CHARACTERISTICS OF RECYCLED AND NORMAL AGGREGATES

Sample Characteristics	Recycled Aggregates with Adhered Mortar											NorAgg
	R_P	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	
Specific gravity	1.83	1.92	1.90	1.89	1.86	1.92	2.00	1.98	2.08	2.02	2.00	2.82
Bulk density (kg/m^3)	1320	1453	1409	1543	1600	1623	1580	1609	1567	1465	1439	1510
Water abs. with adhered mortar (%)	8.60	5.07	5.18	5.70	7.30	3.93	5.12	5.28	5.5	5.67	6.05	1.28
Water abs. without adhered mortar %	5.90	3.40	2.64	2.66	5.55	3.05	2.61	2.48	3.08	4.25	4.13	-

TABLE II
TEST PROGRAMME

Test	Type of Specimen	Size of Specimen mm	No. of Specimens
Compressive Strength	Cube	150×150×150	120
RCPT	Cylinder	105 ϕ × 50	30
Drying Shrinkage	Rectangular	100×100×300	30
Water Permeability	Cube	150 ×150×150	30
Modulus of Elasticity	Cylinder	150 ϕ ×300	9
Creep	Cylinder	150 ϕ ×300	6

V. COMPRESSIVE STRENGTH TEST

The initial work with recycled aggregates necessarily dealt with assessing the impact of recycled aggregates in concrete. Thus, various proportions of replacement of recycled aggregates like 0, 50, 60 and 100% were undertaken by the DOE mix design method adopting a w/c ratio of 0.55 to maintain a workability of 100 mm. Recycled and normal aggregates in the size range of 10 mm and 20 mm in various combinations were used in preparing concrete mix, and compressive strength at 7 days and 28 days was determined.

The selection of the mix design method, proportions and size of aggregates was carried out based on the agglomerated recycled aggregate sample (R_p). Thus, in order to select the proportionate replacement, various combinations of concrete mixes were prepared which are designated as Set 1, Set 2, Set 3, Set 4, and Set 5 as shown in Table III.

TABLE III
COMBINATION OF NORMAL AND RECYCLED AGGREGATES

Concrete Mix	% Recycled Aggregates		% Normal Aggregates	
	20 mm	10 mm	20 mm	10 mm
Controlled Concrete (CC)	-	-	60	40
Set 1 (R_p)	60	40	-	-
Set 2 (R_p)	60	-	-	40
Set 3 (R_p)	50	-	-	50
Set 4 (R_p)	60	-	40	-
Set 5 (R_p)	50	-	50	-

Total 36 cubes, six for each Set 1 to Set 5 and controlled concrete were tested at 7 and 28 days with varying percentage replacements with combination of 20 mm and 10 mm size of normal and recycled aggregates. The comparison of the compressive strength results of all Sets (1 to 5) of recycled aggregate concrete with controlled concrete at 7 and 28 days is shown in Figs. 1 and 2.

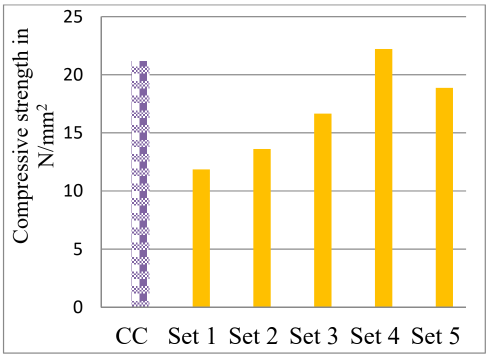

Fig. 1 Comparison of 7 days strength

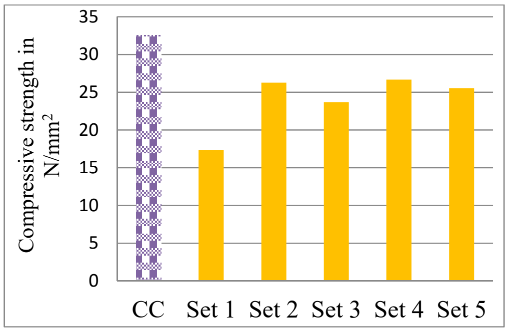

Fig. 2 Comparison of 28 days strength

On assessment of results, it is observed that the adhered mortar present on the recycled aggregates reduced the compressive strength of concrete by 44, 36, 21, and 19% for Set1, Set2, Set3, and Set5 respectively at 7 days in comparison to controlled concrete. From Fig. 1, it is also seen that Set4 concrete has shown the highest strength gain at 7 days (22.22 N/mm^2) and is noticed to be even higher than controlled concrete (21.18 N/mm^2). From the comparison of compressive strength at 28 days however, it is observed that Set1, Set2, Set3, Set4, and Set5 showed a decrease in strength in relation to controlled concrete by 47, 19, 27, 18, and 21%, respectively. Moreover, it is noticed from the analysis of the above Sets (1 to 5) in Fig. 2 that Set4 provided the highest compressive strength in comparison with the other sets but was still lower than that of controlled concrete. It is also inferred from the test results of all sets of recycled aggregate mix that the concrete made with 60% recycled aggregates and 40% normal aggregates both of 20 mm size, i.e. Set4 resulted in better 7 and 28 days strength.

Nevertheless, from all the tests conducted, it is clear that the conventional mix design method on recycled aggregates is not able to provide the desired compressive strength. This is attributed to the presence of adhered mortar which is evident with higher water absorption capacity of the recycled aggregates. Therefore, the removal of adhered mortar from recycled aggregates was carried out by using existing methods on all ten samples in the present work. However, reduction in adhered mortar content by these methods was not found to a considerable extent [6]. Therefore, authors of this paper devised a new method. The method consisted of environment cycles of wetting and drying followed by dry rolling. Wetting under the proposed method was achieved by soaking the aggregates for 48 h in water and then drying by exposing them to natural environment for 24 h corresponding to natural environmental cycles. The samples after drying were subjected to dry rolling in a rotary drum mixer for 20 minutes. This method was found to be more effective and convenient for removal of the adhered mortar traces in comparison with the methods available in literature, namely dry rolling, treatment with acids, thermal treatment, and combined mechanical and chemical treatment.

The percent reduction in water absorption of the recycled aggregates was associated with the adhered mortar present on the recycled aggregates. All recycled aggregate samples R_1 to R_{10} were tested for adhered mortar removal using this newly devised method. The results thus obtained are plotted with percent reduction in adhered mortar as ordinate and initial water absorption as abscissa in Fig. 3. The results were compared with earlier research work by Tavakoli and Soroushian [7] who used the simple dry rolling method for removal of adhered mortar content.

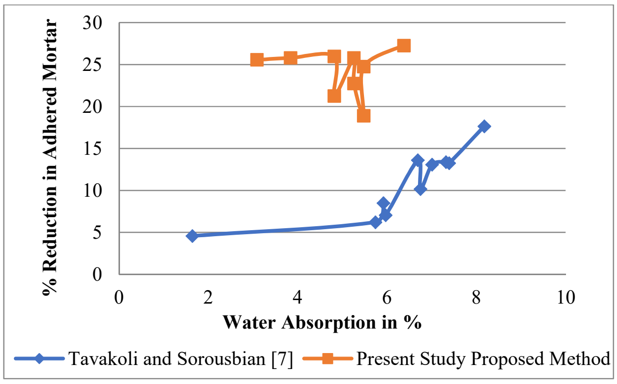

Fig. 3 Comparison of Proposed Method with Tavakoli and Sorousbian [7]

It is observed from the figure that the Tavakoli and Sorousbian [7] method of dry rolling is able to reduce the adhered mortar content in the range of 5 to 18% for initial water absorption ranging from 1.64 to 8.18%. On the other hand, the proposed method has been able to reduce mortar content 44% higher in comparison to dry rolling for an initial water absorption in the range of 3.93 to 7.30%, thus establishes the validity of the proposed method which consisted of wetting and drying cycle followed by 20 minutes of dry rolling for the removal of adhered mortar content. Thus, the further work consisted of processing of recycled aggregates by the method devised in the present study and testing the concrete made by such aggregates for its compressive strength.

VI. Compressive Strength after Processing of Recycled Aggregates

The recycled aggregates after the removal of adhered mortar content were used in making of M25 grade concrete and tested for compressive strength at 7 and 28 days by DOE method [8]. The agglomerated sample (R_p) was used for the determination of strength improvement after the removal of adhered mortar content.

The compressive strength of concrete at a given age is assumed to be primarily dependent on the water cement ratio. The relationship between water cement ratio and compressive strength of concrete was established by Duff Abrams in 1919. As per his relationship, the compressive strength of concrete is inversely proportional to the water cement ratio, i.e. lower the water cement ratio higher would be the compressive strength. Therefore, in the further work, a reduction in water cement ratio was undertaken. Different w/c ratios 0.50, 0.45 and 0.42 were adopted to check its influence on compressive strength. The water cement ratio was gradually changed from 0.55 which was adopted in the previous work where recycled aggregates were used with adhered mortar. However, the water cement ratio reduction was limited to a minimum value of 0.42, as beyond this point, the concrete with recycled aggregates became harsh and the necessary workability was affected. The comparison of this concrete was made with controlled concrete designed by DOE method that provided the desired compressive strength at water cement ratio of 0.55. To investigate the implication of water cement ratio on compressive strength, around 18 cubes each of size 150×150×150 mm with a workability of 90 mm were cast by the DOE method with the required modifications and tested for their compressive strength.

The comparison of the compressive strength values obtained at 7 and 28 days by reducing the w/c ratio in the mix in relation to the controlled concrete designed by DOE method is represented in Fig. 4.

From Fig. 4, it is distinctly clear that recycled aggregates without adhered mortar content were able to provide higher or comparable compressive strength than the corresponding control concrete at a reduced w/c ratio. The reduction in w/c ratio from 0.50 to 0.42 was only possible since the recycled aggregates without adhered mortar did not absorb further additional water from the fresh concrete. Thus, from Fig. 4, it can be concluded that Set4 combination of recycled aggregate concrete with appropriate changes for percentage water absorption played an important role in the strength achievement of concrete prepared with recycled aggregates. Thus, for the same combination of recycled aggregates and normal aggregates as used in Set4, all ten recycled aggregates samples (R_1 to R_{10}) were tested for 7 and 28 days compressive strength.

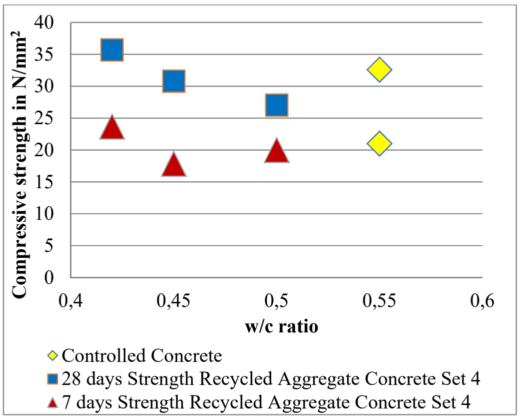

Fig. 4 Compressive strength for different w/c ratios for set 4

Concrete with these recycled aggregates was prepared after removal of adhered mortar content with 60% replacement of normal aggregates. The comparison of this concrete was made with controlled concrete that provided the desired compressive strength at water cement ratio of 0.55.

The compressive strength of concrete of all ten samples from different zones of Western Maharashtra was determined in accordance with Indian Standards IS:516 [9] as shown in Table IV. The compressive strength values have been shown in relation to water absorption and adhered mortar content, since higher water absorption of recycled aggregates influences the compressive strength of concrete.

From Table IV, it is seen that all recycled aggregate samples have provided a compressive strength of the corresponding concrete comparable to that of controlled concrete, and 0.45 was thereby found to be the optimum water cement ratio at which desired strength could be obtained.

The water absorption of recycled aggregates was seen as a key factor influencing the compressive strength. The results of compressive strength at 7 and 28 days have been plotted in reference to water absorption as shown in Fig. 5 and Fig. 6, respectively. The compressive strength values of normal aggregate concrete referred as controlled concrete (CC) have also been plotted on the same figure for comparison.

TABLE IV
COMPRESSIVE STRENGTH OF ALL RECYCLED AGGREGATE SAMPLES

Sr. No.	w/c ratio	Mix Proportion (in weight)	Water Absorption (%)	Adhered Mortar Removal (%)	7 days strength (N/mm^2)	28 days strength (N/mm^2)
R_1	0.42	1 : 1.22 : 2.14	3.40	24.75	20.69	33.92
R_2	0.45	1 : 1.28 : 2.34	2.64	21.63	23.69	35.69
R_3	0.45	1 : 1.28 : 2.34	2.66	25.94	32.21	40.07
R_4	0.45	1 : 1.30 : 2.26	5.55	22.57	26.34	31.92
R_5	0.45	1 : 1.31 : 2.30	3.05	20.78	27.52	34.21
R_6	0.44	1 : 1.23 : 2.25	2.61	20.90	27.72	37.78
R_7	0.44	1 : 1.24 : 2.26	2.48	25.80	31.83	40.74
R_8	0.45	1 : 1.30 : 2.36	3.08	20.56	25.18	35.45
R_9	0.45	1 : 1.30 : 2.36	4.25	22.43	27.09	35.06
R_{10}	0.45	1 : 1.28 : 2.32	4.13	24.37	25.41	32.07
CC	0.55	1 : 1.78 : 2.06	1.28	NA	21.18	32.59

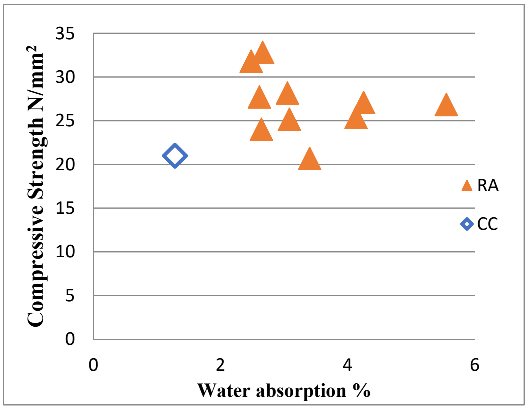

Fig. 5 Compressive strength 7 days with recycled aggregates

From Figs. 5 and 6, it is observed that all ten samples of recycled aggregate have provided the adequate design strength at 7 and 28 days in relation to controlled concrete at replacement level of 60% after the removal of adhered mortar content. It is also seen from Fig. 6 that recycled aggregate having water absorption of 2.66% was able to provide a higher 28 days compressive strength of 40.07 N/mm^2, while the one having relatively higher water absorption of 5.55% provided lesser strength 31.92 N/mm^2 at the same age. Recycled aggregates with lesser water absorption resulted into better strength in comparison with those samples with higher water absorption for the samples tested in the present work.

This concrete which provided the desired compressive strength was then tested for its long term performance. Thus, performance of such recycled aggregate concrete was studied in terms of durability parameters such as chloride permeability, water permeability, drying shrinkage, creep and modulus of elasticity.

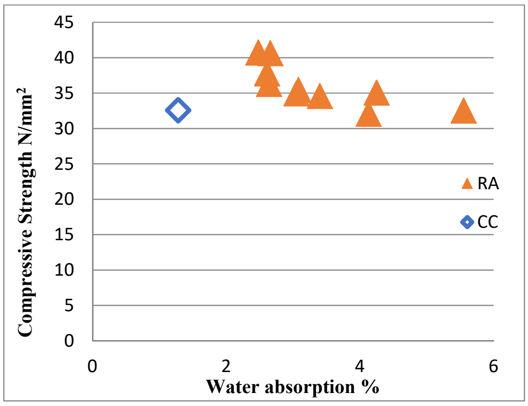

Fig. 6 Compressive strength 28 days with recycled aggregates

VII. Rapid Chloride Ion Penetration Test (RCPT)

Recycled aggregates as obtained from C&D wastes are highly porous in nature on account of adhered mortar content. These pores by themselves can give rise to paths for chloride transfer into the concrete. Chloride ions additionally on account of the chemical admixtures and impurities present in the demolition waste may also enter concrete thus subjecting it to higher deterioration. Research work by Hansen [10] and Abou-Zeid et al. [11] signifies that new concrete, produced from recycled coarse aggregate fails to meet the current recommended limits for chloride ion in concrete. On account of chloride permeation, the steel rusts and expands up to four times its original volume, and thereby create tensile stresses in concrete. BCSJ [12] reported that reinforcement in recycled aggregate concrete may corrode faster than reinforcement in the corresponding conventional concrete. Thus, it becomes significant to test the property of chloride permeability in the case of recycled aggregate concrete. However, it is observed that a lower water cement ratio adopted in the mix design of concrete can resist this permeation.

The RCPT test in the present work was conducted confirming to ASTM:C1202 [13]. This test method consists of monitoring the amount of electrical current passed during a 6-hour period through 50 mm thick slices of 105 mm nominal diameter cores or cylinders of concrete.

All ten recycled aggregate samples consisting of 30 specimens satisfying the requirement of desired compressive strength were tested for rapid chloride permeation test. The results of each sample consisting of average value of three specimens, tested for RCPT are displayed below in Fig. 7. These RCPT values in coulombs are compared with those obtained by other researchers considering the percentage replacement of recycled aggregates providing compressive strength in the same range.

In the present work, the recycled aggregate sample R_9 was found to be least permeable to chloride permeation as the charge passed was 1588 C, the lowest value of all the samples tested in the present work, whereas sample R_6 provided RCPT value 3695 C, the highest of all the samples tested. The variation in the RCPT values was from 1588 to 3695 coulombs for range of compressive strength of 31.92 N/mm^2 to 40.74 N/mm^2. Further it is also noted that the values of RCPT for all ten recycled aggregate samples obtained represent permeability in low to moderate chloride ion penetration range as per ASTM:C1202 [13] standard as shown in Table V.

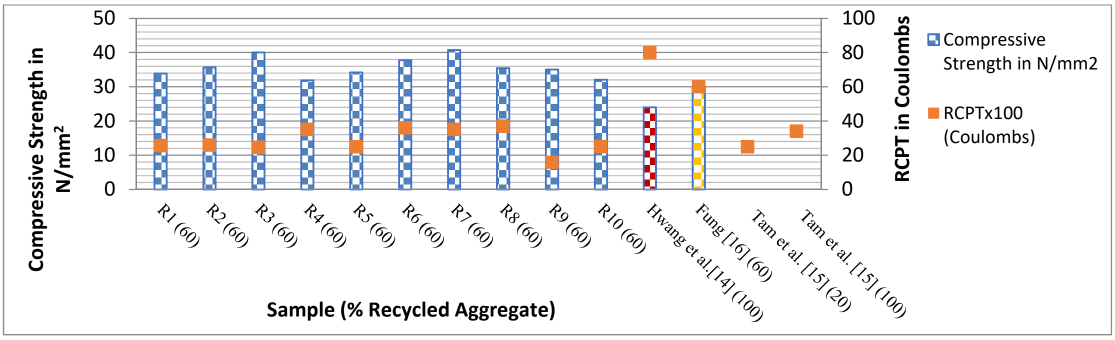

Fig. 7 Comparison of RCPT Readings

TABLE V
Chloride Ion Permeability Based on Charge Passed (ASTM-1202) 2012

Charge Passed (Coulombs)	Chloride Ion Permeability
> 4,000	High
2000- 4000	Moderate
1000-2000	Low
100-1000	Very Low
< 100	Negligible

From the comparative study with other researcher's works, it is seen that recycled aggregate concrete with 100% replacement of normal aggregate with recycled aggregates as reported by Hwang et al. [14] has higher ingress of chloride ion penetration, and this concrete was not able to provide the desired compressive strength of 30 N/mm^2. A decrease in compressive strength of around 20% was observed at 100% replacement even though the water cement ratio maintained was 0.40. Tam et al. [15] noticed the RCPT values in moderate range between 2487 to 3394 C for 20 and 100%

replacement respectively by adopting a TSMA process (Two Stage Mixing Approach) with a water cement ratio of 0.45; however, the compressive strength achieved has not been reported. A similar work carried out by Fung [16] with a 60% replacement for both M20 and M30 grade of concrete at 0.45 water cement ratio represented a higher ingress of chloride penetration. However, the present investigation resulted in low to moderate range of chloride ion penetration for all the samples of recycled aggregates tested adopting a water cement ratio of 0.42 to 0.45. The lower ingress in chloride permeation may be due to the use of recycled aggregates after processing them for removal of adhered mortar which in turn reduced the porosity. Thus, such recycled aggregates when used in making M25 grade concrete are not only found to provide the desired compressive strength but also do satisfy the requirement of chloride ion penetration as their properties were closer to those of normal aggregates.

VIII. Drying Shrinkage Test

Aggregates have a restraining effect on shrinkage. There is a reasonable direct relationship between the shrinkage of an aggregate and its absorption capacity, i.e., aggregates of good quality with low shrinkage are known for low absorption. If the volume of such aggregates is increased, the concrete shrinkage will also decrease as the aggregates will restrain the shrinkage [17]. However, in case of recycled aggregates, this will be required to be established. On the basis of the results obtained, by researchers Hasaba et al. [18], Zagurskij and Zhadanovskij [19], Limbachiya et al. [20], it is observed that drying shrinkage of recycled aggregate concrete made with coarse recycled aggregate and natural sand is approximately 50% higher than the shrinkage of corresponding control concretes made with normal aggregate. When both coarse and fine aggregates are used, drying shrinkage of recycled aggregate concrete is 70% higher than that of control concrete. The drying shrinkage also adversely affects the compressive strength of concrete on account of removal of water of hydration. Thus, it was found necessary to test recycled aggregate concrete for drying shrinkage.

The drying shrinkage test was conducted by using the length comparator apparatus that meets the requirements of IS:4031-(Part X) [21]. 30 concrete specimens of size 100×100×300 mm made with recycled aggregate samples from all 10 identified places were subjected to drying shrinkage test. The concrete specimen cured at 27±2 °C was removed from water and its initial length was measured at 6 days using a length comparator apparatus. The specimen was further cured and the final readings at 35 days were noted. The average of difference in length of three specimens to the nearest 0.01% of the effective gauge length is reported as the drying shrinkage.

The test results of all ten samples consisting of average of three specimens tested in the present work and those of various other researchers for percentage replacement and compressive strength in the similar range are shown in Fig. 8.

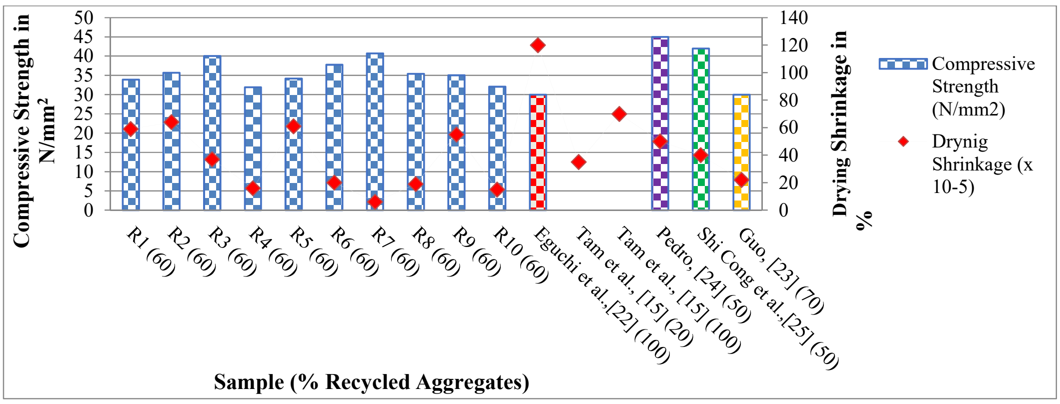

Fig. 8 Comparison of Drying Shrinkage Values

It is observed from the experimental results that R_7 sample has been subjected to the least drying shrinkage of 6×10^{-5}, whereas R_2 showed the highest value of drying shrinkage strain of 64×10^{-5}. It was found that R_7 sample provided the highest compressive strength of 40.74 N/mm^2 and R_2 the least compressive strength 35.69 N/mm^2 of all samples tested in the present work. Thus, from this work, it can be concluded that the samples namely R_3, R_6 and R_7 with higher compressive strength have lower drying shrinkage, whereas those with relatively lower compressive strength such as R_1, R_2, R_5, and R_9 have showed higher drying shrinkage strain. Moreover, it could be inferred that the concretes made with recycled aggregates in the present work having water absorption in the range of 2.61 to 5.55% as shown in Table I are in the same range as reported by other researchers i.e. from 6×10^{-5} to 64×10^{-5}.

Shrinkage strain may be detrimental to the concrete prepared on account of the water of hydration being removed from the structure of concrete; however, in the present work, it is observed that the recycled aggregate concrete is not subjected to shrinkage strain that is adversely affecting the compressive strength of concrete. This may be attributed to the lower water absorption of the recycled aggregates. Comparing these results with other researchers, it is observed that Eguchi et al. [22] in their studies on recycled aggregate concrete with 100% replacement of recycled aggregates having water absorption of 7.3% for a target compressive strength of 30 MPa reported the shrinkage strain of around 120×10^{-5} at the age of 26 weeks. Tam et al. [15] however noticed that the value was around 70×10^{-5} at 28 days with 100% recycled aggregates which was found to be reduced to 35×10^{-5} with the reduction in volume of recycled aggregates at 20% with water absorption of aggregates above 5%. Guo [23] observed that with 70% of recycled aggregates replacement, the shrinkage strain was 22×10^{-5} for a compressive strength of 30 MPa at 6.51% water absorption where Pedro [24] observed the shrinkage strain of 50 $\times10^{-5}$ with 50% replacement with water absorption of 6.10% for a desired compressive strength of 45 N/mm^2. Shi Cong et al. [25] in their work on durability of recycled aggregates with 50% replacement have similarly arrived at shrinkage strain value of 40×10^{-5} with w/c ratio of 0.45 for a compressive strength obtained as 42 N/mm^2 and water absorption of 3.52%. Thus, it can be summarised that recycled aggregate concrete as designed in this work does not cause drying shrinkage that can be detrimental to the structure of concrete. However, it is noticed that concrete with higher compressive strength results in lower drying shrinkage strains.

IX. Water Permeability Test

Water permeability in concrete is primarily on account of the connected pores present in concrete. Aggregates contain pores which are generally discontinuous and are also enveloped by highly porous cement paste which may contribute towards the permeability of concrete in a large way. Khan [26], BCSJ [12], Abou-Zeid et al. [11] and Konin [27] noticed that highly porous recycled aggregates may act as paths; increasing the permeability in concrete. These may contribute to additional water in the cement paste and thus produce a highly permeable concrete. Thus, it is necessary to evaluate water permeability of recycled aggregate concrete in order to assess its performance.

Depth of penetration of water was obtained in accordance with German Standard DIN:1048 [28]. The air dried concrete specimens are mounted on the table with suitable rubber gaskets below the cubes after being cured for 28 days. The pressure of 5 bars is maintained for 72 hours on the specimens. After the specified time period all the specimens are split using compression testing machine with the help of splitting device provided with equipment and the maximum and minimum water penetration level is observed.

Recycled aggregate concrete samples of size 150×150×150 mm cured for 28 days from all ten places R_1, R_2, R_3, R_4, R_5, R_6, R_7, R_8, R_9 and R_{10} were subjected to water permeability test for 72 hrs. The average results of three specimens for each of the ten samples are shown in Table VI along with other researchers for a similar range of compressive strength with corresponding percentage replacement.

TABLE VI
Comparison of Water Permeability Results

Reference		Recycled Aggregates Replacement (%)	Compressive Strength N/mm^2	Water Permeability mm
Present Work	R_1	60	33.92	6.67
	R_2	60	35.69	30.00
	R_3	60	40.07	7.67
	R_4	60	31.92	14.67
	R_5	60	34.21	15.00
	R_6	60	37.78	12.00
	R_7	60	40.74	16.00
	R_8	60	35.45	10.00
	R_9	60	35.06	9.00
	R_{10}	60	32.07	12.00
Fung [16]		50	30.00	120.00
Fung [16]		100	30.00	120.00
Caggiano *et al*. [29]		60	24.08	15.78
Caggiano*et al*. [29]		100	10.69	116.93

Water permeability studies indicate that for concrete to satisfy the permeability criteria, water should not permeate the concrete cube specimens of depth 150 mm. All the samples tested for water permeability were compared with the DIN:1048 [28] as shown in Table VII.

TABLE VII
Permeability Ranges as per Standard DIN: 1048 (Part 5)-2006

Permeability as per DIN 1048 standard	Low	Medium	High
Penetration depth	Less than 30mm	30-60 mm	Greater than 60 mm

The results as obtained from the experimental programme infer readings of all samples in the low permeability range (6.67 to 30.00 mm) as shown in Table VI. It is observed from the experimental results that sample R_1 having a compressive strength of 33.92 N/mm^2 was least permeable to water wherein an average depth of 6.67 mm was noted and sample R_2 having a compressive strength of 35.69 N/mm^2 had an average depth of penetration of 30.00 mm. It was observed that both these values were lying in the low water permeability range.

By comparing these results with those of other researchers, it is observed that the research undertaken by Fung [16] with

50% and 100% replacement of normal aggregate by recycled aggregate with a water cement ratio of 0.45, indicate water permeability to be around 120 mm for a target compressive strength of 30 MPa. Caggiano et al. [29] in their research work on recycled aggregate with 60% replacement level of recycled aggregate at water cement ratio of 0.50 obtained a water permeability of 15.78 mm at 28 days; however, the same was observed to be 116.93 mm with 100% replacement. This concrete with recycled aggregates though provided low permeability was not able to satisfy the requirement of compressive strength.

It can be concluded from the present work that since recycled aggregate samples provided desirable compressive strength in the range of 31.92 to 40.74 N/mm^2, the water permeability was lower. Since all the samples lie in the low range of water permeability, the behaviour of recycled aggregate could be considered as satisfactory.

X. Modulus of Elasticity Test

BCSJ [12], Zagurskij and Zhadanovskij [19], Hansen and Hedegaard [30], Xiao et al. [31] and Parekh and Modhera [32] reported that recycled aggregate concretes have lower modulus of elasticity and may lead to cracking on loading. This property of concrete is important to the designer as it would be essential to understand the elastic deformation that the concrete with recycled aggregates may undergo without large strains (cracking). Further, it is also seen that in case of recycled aggregates, the recycled material itself consists of adhered mortar with low modulus of elasticity. Thus, the impact of the attached mortar on the properties of recycled aggregate concrete would essentially be important to be studied.

The modulus of elasticity in the present study was evaluated by using a test apparatus as per ASTM:C469 [33] consisting of hydraulically operated machine capable of imposing a load at a constant rate of 0.25±0.05 MPa per second. Samples that provided the maximum, average and minimum compressive strength at 28 days, i.e. R3, R8, and R4 respectively satisfying the requirement of desired compressive strength were tested for the modulus of elasticity. Results of the cylindrical specimens of size 150 mm diameter and 300 mm length are shown in Fig. 9 along with the results of other researchers.

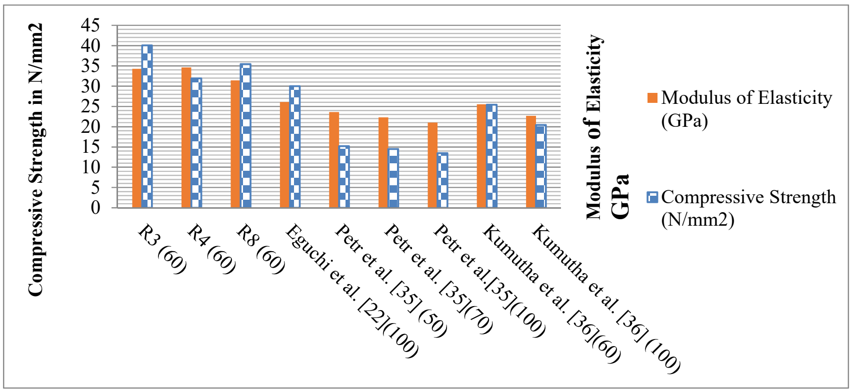

Fig. 9 Modulus of elasticity readings

Higher modulus of elasticity is an indication of more load carrying capacity of the concrete member without any deformation or cracking. IS:456 [34] signifies that the modulus of elasticity is related to compressive strength and defines an equation for calculating the same for normal aggregate concrete. Since ASTM standards do not specify the range, the same correlation as specified by IS:456 [34] has been used for recycled aggregate concrete.

It is observed that the modulus of elasticity values obtained experimentally from the average of three specimens of each recycled aggregate sample are in the similar range as those calculated by using the equation given in IS:456 [34] which are 31.65 GPa, 29.77GPa and 28.25GPa for R_3, R_8, R_4 samples respectively. Thus, signifying that recycled aggregate concrete produced after removal of adhered mortar content behaves almost similar to normal aggregate concrete and provides comparable modulus of elasticity. From the comparison of results with compressive strength it is seen that the concrete samples which provided the desired compressive strength in the range of 31.40 MPa to 40.07 MPa the modulus of elasticity also was in the acceptable range. Thus, the modulus of elasticity of recycled aggregate concrete tested in the present work indicates a direct relation with compressive strength.

When compared with other researchers it is seen that Eguchi et al. [22] in their research work on recycled aggregate as shown in Fig. 9 noticed that with 100% replacement of recycled aggregates, the modulus of elasticity of concrete was around 26.1 GPa wherein the compressive strength achieved was 30 MPa. The results however as observed by Petr and Kohoutkova [35] revealed that the modulus of elasticity decreases from 23.60 GPa to 21.00 GPa, as compressive strength reduced from 15.20 MPa to 13.50 MPa respectively with increase in the replacement level of recycled aggregate from 50 to 100%. Similarly, Kumutha and Vijay [36] also observed the modulus of elasticity to be 25.52 GPa with 60% replacement which decreased to 22.68 GPa at 100% replacement. The compressive strength was also found to reduce from 25.42 MPa to 20.43 MPa at 28 days for the same replacement amounts. Thus, it can be inferred from various researchers' works that modulus of elasticity of recycled aggregate concrete depends mainly upon compressive strength of concrete rather than percentage replacement of recycled aggregate.

The modulus of elasticity results in the present work show that the recycled aggregate concrete prepared after removal of adhered mortar content has modulus of elasticity in the range of 31.40 to 34.64 GPa for a compressive strength range 31.92 to 40.07 N/mm^2. Therefore, modulus of elasticity is found to be adequate for such proportioned recycled aggregate concrete as in the present study which is certainly at par with normal concrete.

XI. Creep Test

Creep occurs in concrete on account of the hydrated cement paste, the role of the aggregate in concrete being primarily that of restrain. However, in case of recycled aggregates it would be necessary to understand the implications of recycled aggregates on creep of such concrete. There is no fundamental difference between normal and recycled aggregates as far as the creep properties are concerned, however higher creep of concretes reflects lower modulus of elasticity of that aggregate. Thus, it can be concluded that aggregates which exhibit lower modulus of elasticity may show a greater sign of creep. Since recycled aggregates have adhered mortar content with lower modulus of elasticity and may absorb moisture from cement paste, the property of creep was evaluated in the present work for those recycled aggregate concrete samples which were tested for modulus of elasticity.

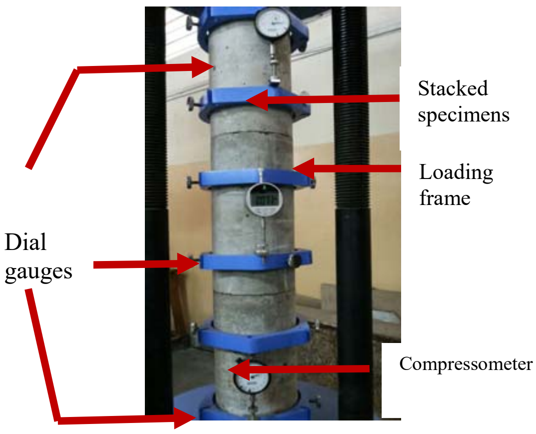

Fig. 10 Creep apparatus

Creep test on recycled aggregate concrete of M25 grade was conducted as per ASTM:C512 [37]. The apparatus includes a loading frame consisting of springs such as railroad car springs capable of applying and maintaining the required load on the specimen, despite any change in the dimension of the specimen as shown in Fig. 10. The specimens were loaded at an intensity of not more than 40% of the compressive strength at the age of loading and compressometers were provided for measuring the applied load. The strain readings were recorded immediately before and after loading, 2 to 6 h later, then daily for 1 week, weekly until the end of 1 month.

Creep is quantified in terms of the strain that occurs in addition to the elastic strain due to the applied loads. Creep coefficient is calculated on the basis of this measured strain which is the ratio of the ultimate creep strain to the elastic strain.

The typical samples of recycled aggregate concrete tested for modulus of elasticity studies were also tested for creep. The creep coefficients of the average of two concrete specimens of size 150 mm diameter and 300 mm length for each of the samples are shown in Table VIII.

TABLE VIII
Creep Coefficient of Concrete

Sr. No	Sample	Avg. Creep Coefficient at 28 days age of loading
1.	R_3	1.283
2.	R_8	1.210
3.	R_4	1.190

Creep coefficient was evaluated by using the standard procedure as per the ASTM:C512 [37]. The standard only elaborates the procedure for conducting the creep test. There are no threshold values defined in the standards for satisfactory performance of concrete. However, while designing the concrete mixes, it would be essential to understand the creep strain the concrete may be subjected to due to loading. Thus, comparison of creep coefficient in the present work is undertaken with IS:456 [34] which gives guidelines on the range of the ultimate creep coefficient in case of normal aggregate concrete. It is a simplified estimate where the age of loading is the only factor considered. Creep studies conducted on recycled aggregate concrete in the present work after removal of adhered mortar content show that the creep coefficient is well within the specified range of 1.190 to 1.283 and thus satisfies the criteria defined in IS:456 [34] for 28 days. Therefore, it can be summarised that this concrete performs similar to normal aggregate concrete. Since creep strain is also related to the modulus of elasticity; the comparison of the same is shown in Table IX.

TABLE IX
Comparison of Creep Coefficient with Modulus of Elasticity

Sample	Creep Coefficient (θ)	Modulus of Elasticity (GPa)
R_3	1.283	34.25
R_8	1.210	34.64
R_4	1.190	31.40

From Table IX, it is observed that all the samples of recycled aggregates provided a very high modulus of elasticity and thus all have shown a lower creep strain which is even lower than 1.6 as specified in IS:456 [34] for normal aggregate concrete. Fig. 11 represents the creep coefficient v/s time results of the present work with those obtained by other researchers.

From Fig. 11, it is seen that Mendes et al. [38] in their study on recycled aggregates with 100% replacement have found creep value to be 1.60 at 22 days age for M25 grade concrete. Tam et al. [15] found the value to be 3.2 at 20% replacement and around 6.69 at 100% replacement at 28 days.

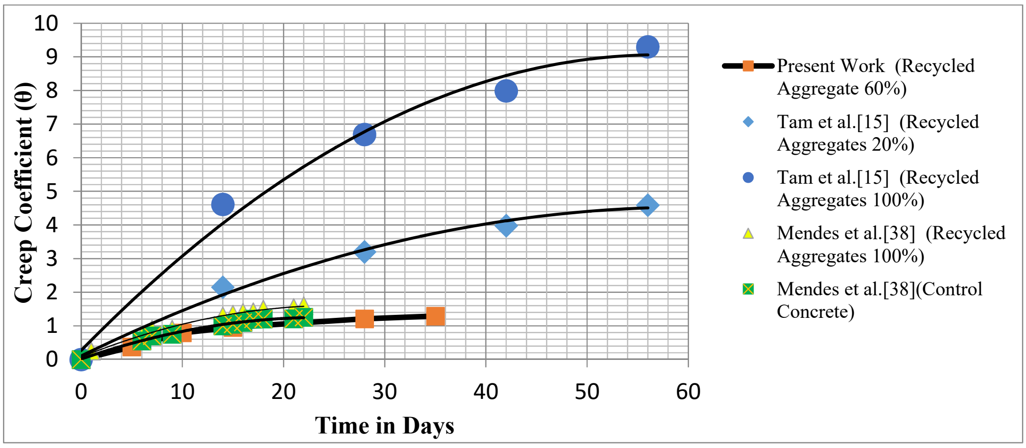

Fig. 11 Creep v/s time

Creep studies conducted on recycled aggregate concrete in the present work after the removal of adhered mortar content show that the creep coefficient is lower than the values obtained by Mendes et al. [38] and Tam et al. [15]. Moreover, it is also found to be lower than the value defined in IS: 456 [34] and also lower than the reference concrete tested by Mendes et al. [38]. Thus, in the present work the lower value of creep coefficient for M25 grade indicates that recycled aggregate concrete will not lead to cracking on loading. The creep coefficient thus is found to be in the satisfactory range and this is on account of the higher modulus of elasticity observed in case of concrete prepared with recycled aggregate in the present work. Thus, it can be concluded that this concrete prepared with 60% recycled aggregates of 20 mm size and the remaining 40% with normal aggregates of same size performs similar to normal aggregate concrete when adhered mortar is effectively removed.

XII. Conclusions

1. Recycled aggregate concrete designed in the present work since adopts low water cement ratio and has been observed to attain the desired compressive strength for M25 grade resists chloride ion penetration and water permeation.
2. The experimental results show lower drying shrinkage strains thus implying that recycled aggregate concrete does not cause drying shrinkage that can be detrimental to the structure of concrete and is attributed to lower water absorption achieved by processing recycled aggregates for removal of adhered mortar with good compressive strength.
3. The modulus of elasticity of concrete prepared with recycled aggregates is dependent upon compressive strength of recycled aggregate concrete. Recycled aggregate concrete provided high modulus of elasticity value which in turn ultimately resulted into lower creep strains.
4. Recycled aggregate concrete performs at par with normal aggregate concrete when characteristics of recycled aggregate are in specific range and when recycled aggregate is in composition of 60% with mix proportions as specified in the present study have been used.

References

[1] Ghosh, Sadhan (2011). Rebuilding C&D Waste Recycling Efforts in India-Waste Recycling, *International Society of Waste Management, Air and Water (ISWMAW)*, October.
[2] Rao, Chakradhara M., Bhattacharyya, S. K. and Barai, S. V. (2011). Recycled Aggregate and its Use in Concrete, *Journal of Indian Concrete Institute*, Vol. 11(4), 55-77.
[3] IS:8112-(1989). 43 Grade Ordinary Portland Cement – Specification.
[4] IS:4031, Part VI-(1988). Reaffirmed (2005). Methods of Physical Tests for Hydraulic Cement, Determination of Compressive Strength of Hydraulic Cement other than Masonry Cement.
[5] IS:383-(1970) reaffirmed (1997). Specification for Coarse and Fine Aggregates from Natural Sources for Concrete.
[6] Pathak, S.R. and Yadav, S. R. (2011) Removal of Adhered Mortar from Recycled Aggregate, *Journal of Construction Engineering, Technology & Management Volume 1*, Issue 1, May, 23-31.
[7] Tavakoli Mostafa and Soroushian Parviz (1996). "Strengths of Recycled Aggregate Concrete made Using Filed Demolished Concrete as Aggregate", *ACI Materials Journal*, Vol. 93(2), 182-194.
[8] Pathak, S. R. and Yadav, S. R. (2012). "Mix Design Methodology for Concrete Made with Recycled Aggregates", *International Journal of 3R's*.Vol.3, No.4, 482-490 Oct- Dec.
[9] IS: 516- reaffirmed (1999). "Testing of Compressive Strength of Concrete".
[10] Hansen, T. C. (1986) Recycled Aggregates and Recycled Aggregate Concrete Second State-of-the-Art Report Developments 1945-1985, *Demolition and Recycling of Concrete, RILEM Technical Committee-37-DRC*, 201-246.
[11] Abou-Zeid, M. N., Shenouda, M. N., McCabe S. and El-Tawil, F. A. (2005). Reincarnation of Concrete, *Concrete International*, Vol. 27(2), 53-59.
[12] BCSJ. (1978) Study on Recycled Aggregate and Recycled Aggregate Concrete, *Building Contractors Society of Japan, Committee on Disposal and Reuse of Concrete Construction Waste, Summary in Concrete in Japan*, Japan, Vol. 16(7), 18 -31.
[13] ASTM:C1202-(1997) reaffirmed (2012). Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride ion Penetration.

[14] Hwang, Jun Phil, Hyun, Bo Shim, Sooyoung, Lim and Ki Yong, Ann (2013). Enhancing the Durability Properties of Concrete Containing Recycled Aggregate by the Use of Pozzolanic Materials, *KSCE Journal of Civil Engineering*, Vol. 17(1), 155-163.
[15] Tam, Vivian W. Y., Tam, C. M. (2007). Assessment of Durability of Recycled Aggregate Concrete Produced by Two- Stage Mixing Approach, *Journal of Material Sciences*, Vol. 42(10), 3592-3602.
[16] Fung, W. K. (2005). Durability of Concrete using Recycled Aggregates, *Standing Committee on Concrete Technology -Annual Concrete Seminar*, 2-8.
[17] Neville, A. M. (2013). Properties of Concrete, Fifth edition, Amazon.co.uk.
[18] Hasaba, S., Kawamura, M., Torik, K. and Takemoto, K. (1981). Drying Shrinkage And Durability of Concrete Made of Recycled Aggregate, *Transactions of the Japan Concrete Institute*, Vol. 3, 55- 60.
[19] Zagurskij, V. A. and Zhadanovskij, B. V. (1985). Breaking Reinforced Concrete and Recycling Crushed Materials*, Special Technical Report, Research Institute for Concrete and Reinforced Concrete (GOSSTROY)*, Moscow, 80-90.
[20] Limbachiya, M. C., Koulouris, A., Roberts, J. J. and Fried, A. N. (2004). Performance of Recycled Aggregate Concrete, *Proceedings of RILEM International Symposium of Environmental – Conscious Materials and System for Sustainable Development, RILEM Publications*, 127-136.
[21] IS:4031, Part X-(1988). Reaffirmed (1995) Methods of Physical Tests for Hydraulic Cement, Determination of Drying Shrinkage.
[22] Eguchi, Kiyoshi, Kohji, Teranishi, Akira, Nakagome, Hitoshi, Kishimoto, Kimihiko, Shinozaki and Masafumi, Narikawa (2007). Application of Recycled Coarse Aggregate by Mixture to Concrete Construction, *Construction and Building Materials*, Vol. 21, 1542-1551.
[23] Guo, Yuanchen (2012). Experimental Study on Forecasting Mathematical Model of Drying Shrinkage of Recycled Aggregate Concrete, *Mathematical Problems in Engineering,* Hindawi Publications. Article ID 567812, 1-14.
[24] Pedro, Amorim (2012). Concrete Made with Coarse Concrete Aggregate Influence of Curing on Durability, *ACI Materials Journal*, Vol. 109, 195-204.
[25] Shi Cong, Kou, Chi Sun, Poon and Dixon, Chan (2008). Influence of Fly Ash as a Cement Addition on the Hardened Properties of Recycled Aggregate Concrete, *Materials and Structures*, Vol. 41(7), 1191-1201.
[26] Khan, Rasheeduzzafar A. (1984). Recycled Concrete - a Source of New Aggregate*, Cement, Concrete and Aggregates(ASTM)*, Vol. 6(1), 17-27.
[27] Konin, Athanas (2011). Influence of Cement Content on Recycled Aggregate Concrete Properties, *Modern Applied Science*, Vol. 5(1), 23-31.
[28] German Standard DIN 1048-Part 5. (1991) reaffirmed (2006). Testing Concrete for Water Permeability.
[29] Caggiano, A., Faella, C., Lima, C., Martinelli, E., Mele, M., Pasqualini, A., Realfonzo, R. and Valente, M. (2011). Mechanical Behaviour of Concrete with Recycled Aggregate, *2nd workshop on the new Boundaries of Structural Concrete, Italy*, 55-62.
[30] Hansen, T. C. and Hedegaard, S. E. (1984). Properties of Recycled Aggregate Concrete as affected by Admixtures in Original Concrete, *ACI Journal,* Vol. 5(7), pp. 21-26.
[31] Xiao, Jianzhuang, Li, Jiabin and Zhang, Ch. (2005). Mechanical Properties of Recycled Aggregate Concrete under Uniaxial Loading, *Cement and Concrete Research,* Vol. 35, 1187 -1194.
[32] Parekh, D. N. and Modhera, C. D. (2011). Characterization of Recycled Aggregate Concrete, *International Journal of Advanced Engineering Technology*, IJAET, Vol. 2(4), 321-330.
[33] ASTM:C469-(2002). Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression.
[34] IS: 456-(2000). “Plain and Reinforced Concrete Code of Practice”.
[35] Petr, Stemberk and Kohoutkova, Alena. (2007). Method for Assessment of Mechanical Behaviour of Structures made of Recycled Concrete,*In: SB07 New Zealand,*Branz, Vol. 11, 2-10.
[36] Kumutha, R. and Vijai, K. (2010). Strength of Concrete Incorporating Aggregates Recycled from Demolition Waste, *Asian Research Publishing Network, Journal of Engineering and Applied Sciences*, Vol. 5(5), 64-71.
[37] ASTM:C512-(1994) reaffirmed (2002). Standard Test Method for Creep of Concrete in Compression.
[38] Mendes, Thiago Melanda, Morales, Gilson and Carbonari, Gilberto (2004). Study on ARC's Aggregate Utilization Recycled of Concrete, *International RILEM Conference on the Use of Recycled Materials in Building and Structures,* 629-635.