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Stress-strain characteristics and energy absorption analysis of Construction and demolition waste recycled aggregate concrete in compression

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Abstract

The stress strain characteristics and mechanical properties of construction and demolition waste recycled aggregate concrete at two different w/c ratios – 0.4 and 0.5 are presented in this study. The mechanical and stress strain characteristics of recycled aggregate concrete are compared to the properties and Stress strain characteristics of the conventional aggregate concrete. The mechanical properties include the cube and cylindrical compressive strength, Modulus of elasticity, flexural strength, split tensile strength and hardened density. Under stress strain characteristics, strain at peak stress and the energy absorbed under compression is included. The study is aimed to correlate and compare the behaviour of recycled aggregate concrete and Conventional aggregate concrete having comparable compressive strength. Finally, the experimental stress strain characteristics of the Recycled aggregate concrete is analysed for its compatibility of the assumed stress strain behaviour of concrete in IS 456. According to the findings, recycled aggregate concrete has similar stress-strain characteristics to conventional aggregate concrete of comparable strength, and existing stress block parameters can be suitably used for the recycled aggregate concrete.

Keywords- Construction and demolition waste aggregate, Recycled aggregate concrete, stress-strain characteristics, energy absorption, RCA concrete mechanical properties.

1. INTRODUCTION

Rapid urbanization in past years has caused a surge in the production of construction and demolition waste (CDW). The proper management and disposal of these waste materials are a serious concern as it adversely affects the environment. One of the promising methods of disposal of these aggregates lies in their use as aggregate in Concrete production. Akhtar and Sarmah[1] presented a global perspective on the generation and properties of recycled aggregate concrete. Their study highlighted the need for proper standards and further research to endorse the application of Recycled aggregate concrete. They also suggested using the CDW recycled aggregates in the range of 30% to 50 % to obtain strength similar to natural aggregate concrete. Silva et al.[2] examined 236 publications from 1997 to 2014 and described numerous aspects impacting the characteristics of recycled aggregates used in concrete manufacturing. The study suggests that certain criteria must be addressed while collecting and using RA (Recycled Aggregate) based on the findings. Wagih et al.,[3] investigated the viability of converting and utilizing concrete debris as recycled aggregate in structural concrete. The study discovered that RA's water absorption and abrasion resistance were lower than the Egyptian standard code. In addition, replacing NA (Natural Aggregate) with RA completely lowered the workability and strength of the concrete. The strength of the concrete is only slightly reduced when NA is replaced with 25% to 50% RA. Rao et al.,[4] give a global overview of building and demolition waste management, the qualities of recycled aggregate and concrete manufactured from it, and several barriers to its widespread application in their study. According to the findings, RA may be used to make conventional structural concrete with the inclusion of fly ash, condensed silica fume, and other additives. Hahladakis et al.,[5] provide insights into the current state of C&D (Construction & Demolition) waste management practice in Qatar and implement a SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis. The study presents strategies to improve the current status of C&D waste utilization in the construction industry.

One of the promising applications of construction and demolition waste lies in Geopolymer concrete production. Panizza et al.,[6] presented an assessment of metakaolin-slag-potassium-silicate geopolymer mixture containing aggregates made from CDW. The study concludes with the promising application of CDW aggregates in geopolymers as the properties of the concrete even with more than 50% of the aggregates showing desirable behavior. Arenas [7] evaluated the applicability of recycled CDW aggregates in the fly ash-based geopolymeric porous concrete for application as road noise barriers. In the study, primarily the physical, mechanical, and acoustic properties of fly-ash-based geopolymer concrete were analyzed. The study found promising properties also the use of fly ash and cdw aggregates don't seem to cause leaching issues in the environment. Also, the application of CDW aggregate in pavement construction is widely studied by researchers. Tavira et al.,[8] studied the functional and structural parameters of a paved road section constructed with mixed recycled construction and demolition waste aggregate and excavation waste with soil. The study concluded an acceptable mechanical performance and surface roughness of the mix. The durability of concrete is a serious concern, particularly in the case of concrete with recycled CDW. Bosque et al.,[9] studied the carbonation of concrete with construction and demolition waste-based recycled aggregates. The study concludes that the mean carbonation depth in the concrete with recycled aggregates was higher than the normal aggregate concrete. Although it was also found that the carbonation coefficient was below 4 mm/year^0.5 suggesting good quality. Along with durability the environmental impact of construction and demolition waste and the recycled aggregates are critical parameters and are studied by Diotti et. al.,[10]. The study presents a data analysis on the environmental behavior of CDW and Recycled aggregates in terms of chemical composition as well as the release of contaminants pertaining to the leaching test. The findings indicated the importance of the demolition process to improve the environmental quality of CDWs and RAs.

For the structural application of construction and demolition waste aggregate concrete, its mechanical behavior and its stress-strain characteristics need to be evaluated. In terms of the stress-strain characteristics, the strain at peak stress and the ultimate strain is of prime importance. Concrete's stress-strain behavior depends primarily on its compressive strength [11]. Singh et al.[12] investigated the stress-strain characteristics of unconfined high-strength concrete and proposed some significant revisions to the existing Indian standards for the higher strength concrete but for the concrete with strength up to 50MPa existing IS456 provision seems satisfactory for natural aggregate concrete. Recent research work [13] also relates the short-term mechanical characteristics with its compressive strength. Singh et al.,[14], [15] have also reported the parameters, empirical equation, and experimental validation for the shear and flexural design of concrete with varying strength in their research. The present study focuses on the stress-strain characteristics and mechanical properties of the concrete made with 100% replacement of natural coarse aggregate with recycled construction and demolition waste aggregate. In the study mixes with two different w/c ratios are considered whose compressive strength is under 50 MPa. The study will try to highlight the deviation from the standard stress strain curve for the concrete given in IS456, in the case of recycled aggregate concrete.

2. EXPERIMENTAL SETUP

2.1 Compressive strength and hardened density

IS: 516 [16] was used to test the compressive strength of cylindrical and cubical specimens after 28 days of curing. On the date of testing, weight of the specimens has been measured to estimate the hardened density of the concrete. The specimen size of the cylinders used was 150mm Diameter X 300mm Height. The cube size was 150mm X 150mm X 150mm.

2.2 Modulus of Elasticity and Poisson's ratio

On cylindrical samples of 150 mm x 300 mm, the Modulus of Elasticity (MOE) and the Poisson's Ratio was determined according to ASTM C-469 [17].

2.3 Split Tensile strength

At 28 days, the split tensile strength of the cylindrical concrete specimen was assessed using the IS: 516 on the cylindrical specimen. These tests were carried out on a total of three specimens, and the average value was provided.

2.4 Flexural strength

For the concrete mixes, 28-day flexural strength was evaluated using prism specimens of size 150mm X 150mm X 500 mm, according per IS: 516. The flexural strength of the concrete beam was evaluated using the three-point loading method, which involved placing the concrete beam on two rollers and applying the whole weight to its centre. The supporting and loading rollers bearing surfaces were cleaned, and any loose sand or other debris was removed from the surfaces of the specimen that would come into contact with the rollers.

2.5 Stress-Strain Characteristics

Cylindrical Specimens of size 150 mm diameter and 300 mm height were used to obtain the stress –strain characteristics of the concrete mixes. The specimens were sawed at both ends before testing to provide a flat and robust surface. The concrete specimens were put through their paces in a 3000 KN closed-loop servo hydraulic displacement controlled compression testing machine. Two compressometer were utilised to measure strain at the middle half of the height, and two strains were averaged. One LVDT (Linear Variable Differential Transformer) was also used to capture the strain. For the whole compression test, a rate of loading of 0.4μm/s was used.

3. Materials and Mix design

The concrete-making materials used to prepare Recycled Aggregate Concrete (RAC) are described in the present section. Cement, fine aggregates, recycled coarse aggregate, and super plasticizers were used for making the concrete. Cementitious ingredients include OPC 43 grade cement according to IS 269-2015 [18]. Table 1 lists the physical and chemical parameters of the cement utilised. For the production of RAC, crushed sand that conforms to Zone II according to IS: 383-2016[19] was utilised as fine aggregate. Table 2 lists the physical characteristics of fine aggregate. In this investigation, recycled aggregate was collected from building and demolition debris. Table 2 lists the physical parameters of the recycled aggregate. Polycarboxylic group-based superplasticizer was utilised in both mixtures. The recycled coarse aggregates were collected from a plant situated in Delhi, India (as shown Figure-1).

Fig-1: C&D Waste Plant at Delhi, India

Table-1: Properties of cement

Characteristics	**OPC-43**
Physical Tests	
Fineness (m^2/kg)	271.00
Soundness (Autoclave) (%)	00.05
Soundness (Le Chatelier's) (mm)	1.5
Setting Time Initial & Final (min.)	130.00 & 180.00
Specific gravity	3.15

Characteristics		***OPC -43***
Chemical Tests		
Loss of Ignition (LOI) (%)		3.23
Silica (SiO_2) (%)		20.19
Iron Oxide (Fe_2O_3) (%)		4.39
Aluminium Oxide (Al_2O_3)		4.97
Calcium Oxide (CaO) (%)		61.84
Magnesium Oxide (MgO) (%)		1.83
Sulphate (SO_3) (%)		2.08
Alkali (%)	Na_2O & K_2O	0.30 & 0.47
Chloride (Cl) (%)		0.018
IR (%)		1.64

Table-2: Properties of Aggregates

Property		**Recycled Coarse aggregates**		**Fine Aggregate**
		20 mm	**10 mm**	
Specific gravity		2.39	2.37	2.64
Water absorption (%)		4.58	4.75	0.8
Sieve Analysis Cumulative Percentage Passing (%)	40 mm	100	100	100
	20mm	93	100	100
	10 mm	2	74	100
	4.75 mm	1	6	95
	2.36 mm	0	0	87
	1.18 mm	0	0	68
	600 μ	0	0	38
	300 μ	0	0	10
	150 μ	0	0	2
	Pan	0	0	0

Two distinct w/c ratios were used to make two separate mixtures. Table 3 lists the investigated blends. The concrete containing 100% recycled coarse aggregate is represented by the mix ID 0.4 RAC. A similar name convention was used for 0.5 RAC, which had a w/c ratio of 0.5. Ojha et al.,[20] studied concrete mixes with conventional aggregate of similar strength range which is shown in table 4 . The results of the study were utilised to compare the mechanical properties and stress strain characteristics of natural and recycled aggregates. The mix ID 0.47 CAC and 0.36 CAC, denotes Conventional aggregate (Granite Coarse aggregate) Concrete mixes from the literature.

Table-3: Mix design for recycled aggregate concrete

S.No.	**Mix _ID**	**W/C**	**Mix Constituents (Kg/m^3)**		**Coarse aggregate as % of total aggregate by Volume**
			Cement	**Water**	
1.	0.4 RAC	0.40	380	152	65%
2.	0.5 RAC	0.50	350	175	62%

Table-4: Mix design for natural aggregate [20]

S.No.	**Mix _ID**	**W/C**	**Mix Constituents (Kg/m^3)**		**Coarse aggregate as % of total aggregate by Volume**
			Cementetious content (Cement + fly ash)	**Water**	
1.	0.47 CAC[20]	0.47	362 (290+72)	152	65%
2.	0.36 CAC[20]	0.36	417(334+83)	150	61%

4. EXPERIMENTAL RESULTS AND ANALYSIS

4.1. Mechanical Properties

The present section details the observed mechanical properties of the recycled aggregate concrete and compares it to the conventional aggregate concrete of similar strength range. The results are given in Table 5.

Table-5: Mechanical properties of Recycled aggregate concrete and Conventional Aggregate concrete

Ids	MOE (GPa)	Poisson's ratio	28 days Cylindrical Compressive strength (MPa)	28 days Cube Compressive strength (MPa)	Flexural strength (MPa)	Split tensile strength (MPa)	Density
0.40 RAC	34.29	0.16	40.5	48.00	4.30	3.25	2384.74
0.36 CAC	36.90	0.16	39.3	54.10	6.61	4.04	2517.13
0.50 RAC	31.87	0.15	29.00	36.50	4.05	2.80	2382.02
0.47 CAC	30.69	0.15	27.62	36.90	4.42	3.37	2515.35

Density of the mix with recycled aggregate were lower than the density of the conventional aggregate concrete. This can be attributed to the higher density of the conventional aggregate which is granite for the CAC mixes. Figure 2 shows a comparative analysis on the density and the compressive strength of the mixes.

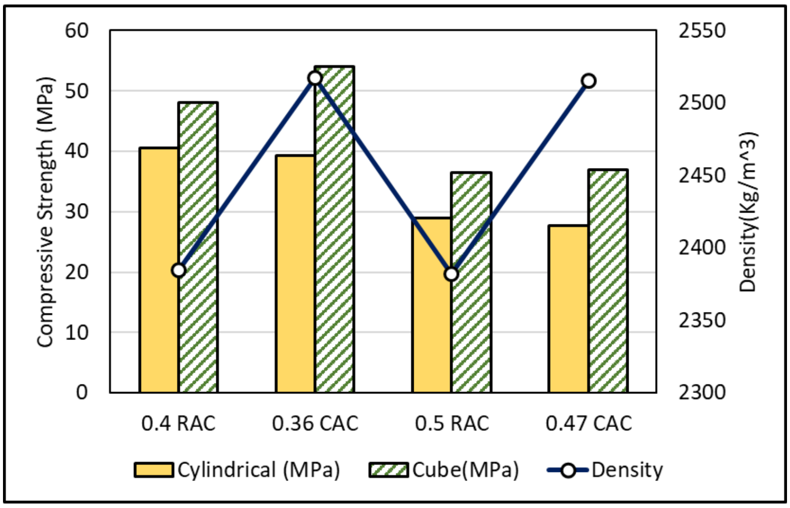

Fig-2: 28-day cylindrical and cube strength and Hardened density of the mix

The stiffness of the material is represented by its modulus of elasticity (MOE). The MOE values for the recycled aggregate concrete with a w/c ratio of 0.4 and 0.5 are 34.30 Mpa and 37.87 Mpa respectively. Comparing the value to the corresponding natural aggregate concrete of similar strength, it is found that both the natural and recycled aggregate concrete shows a similar modulus of elasticity. The MOE values for Conventional aggregate concrete of w/c ratio 0.47 and 0.36 is 30690 and 36900 respectively. The Poisson's ratio, defined as the ratio of transverse strain and the longitudinal strain is also comparable between the RAC and CAC. The values of the Poisson's ratio vary between 0.150 to 0.160 for all the mixes considered. The MOE and the Poisson's ratio of the mixes are shown in figure 3.

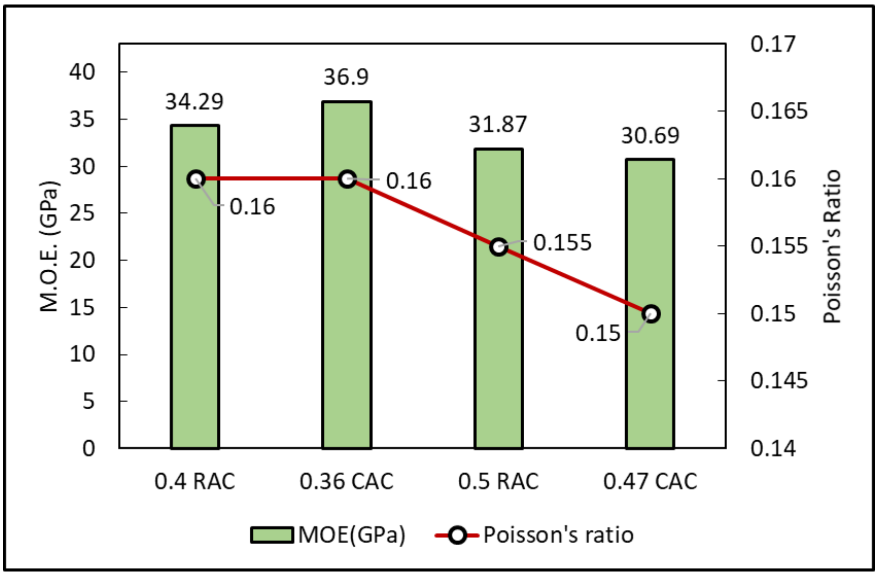

Fig-3: MOE and Poisson's ratio

The split tensile strength and flexural strength of the concrete is evaluated for the mixes and analysed to observe the relative trend between CAC and RAC. Figure 4 shows a comparative trend of the flexural and split tensile strength along with the compressive strength of the mixes. Based on the experimental finding it is observed that CAC with w/c ratio of 0.36 shows the highest split tensile strength whereas the RAC with w/c ratio of 0.5 shows the least tensile strength. As seen from the past studies also, the old adhered mortar in C&D based aggregates causes reduction in compressive strength which is due to weak interfacial transition zone resulting from relatively higher porosity and water absorption properties, resulting in poorer workability and lower mechanical strength when used in new concrete. Micro-cracking that happens during demolition and crushing processes could further cause reduction in flexural and split tensile strength of concrete. Tensile and flexural strength shows a trend with the observed compressive strength of mix which agrees with the established literature and codal provisions [25, 26, 27, 28].

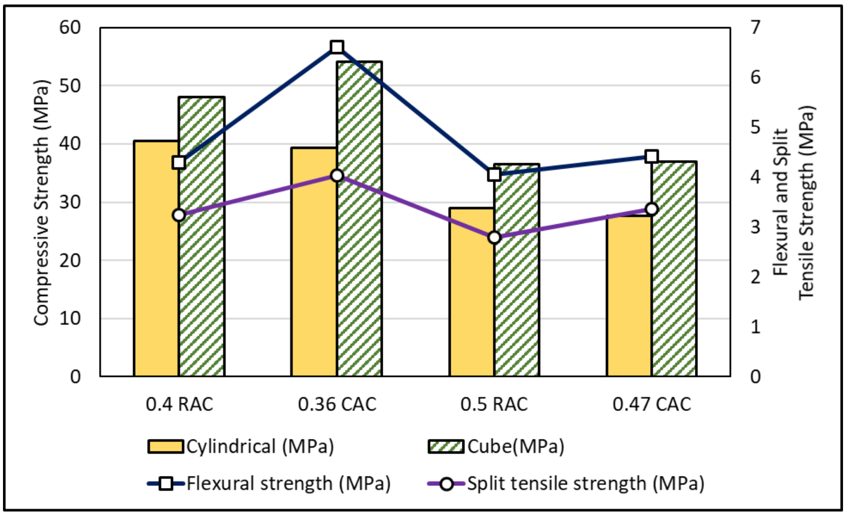

Fig-4: Flexural and Split Tensile strength

4.2 Stress-strain Characteristics

The results of the stress-strain behaviour study is explained in the present section, and the curves produced are shown in Figure 5 (a-f) and Figure 6. The graphs depict stress-strain behaviour of the samples of recycled aggregate concrete in figure 5 (a-f), as well one curve for conventional concrete of similar grade from the literature [21, 23, 24] in figure 6 for comparison. Each curve is made up of two plots: (i.) LVDT strain vs stress (ii.) compressometer strain vs stress. The caption in the upper right corner of each plot contains information about the colour code of the curves. Strain at maximum stress is given in brackets along with the legends.

The stress strain curves for the samples suggests strain at peak stress to be 2000 to 2500 microns for concrete with strength 20 to 40 MPa in most of the cases. Some of the samples behaves as outliers as for the specimen with compressive strength of 24.73 MPa. One of the trend in most of these curves is the increase in the strain at peak stress with increase in the compressive strength. Comparing the curves in figure 5 (a-f) with the curves in figure 6, which shows the stress strain behaviour of conventional aggregate concrete it can be concluded that for similar strength range the stress strain characterises of the concrete is similar in case of both the Recycled aggregate concrete and Conventional aggregate concrete.

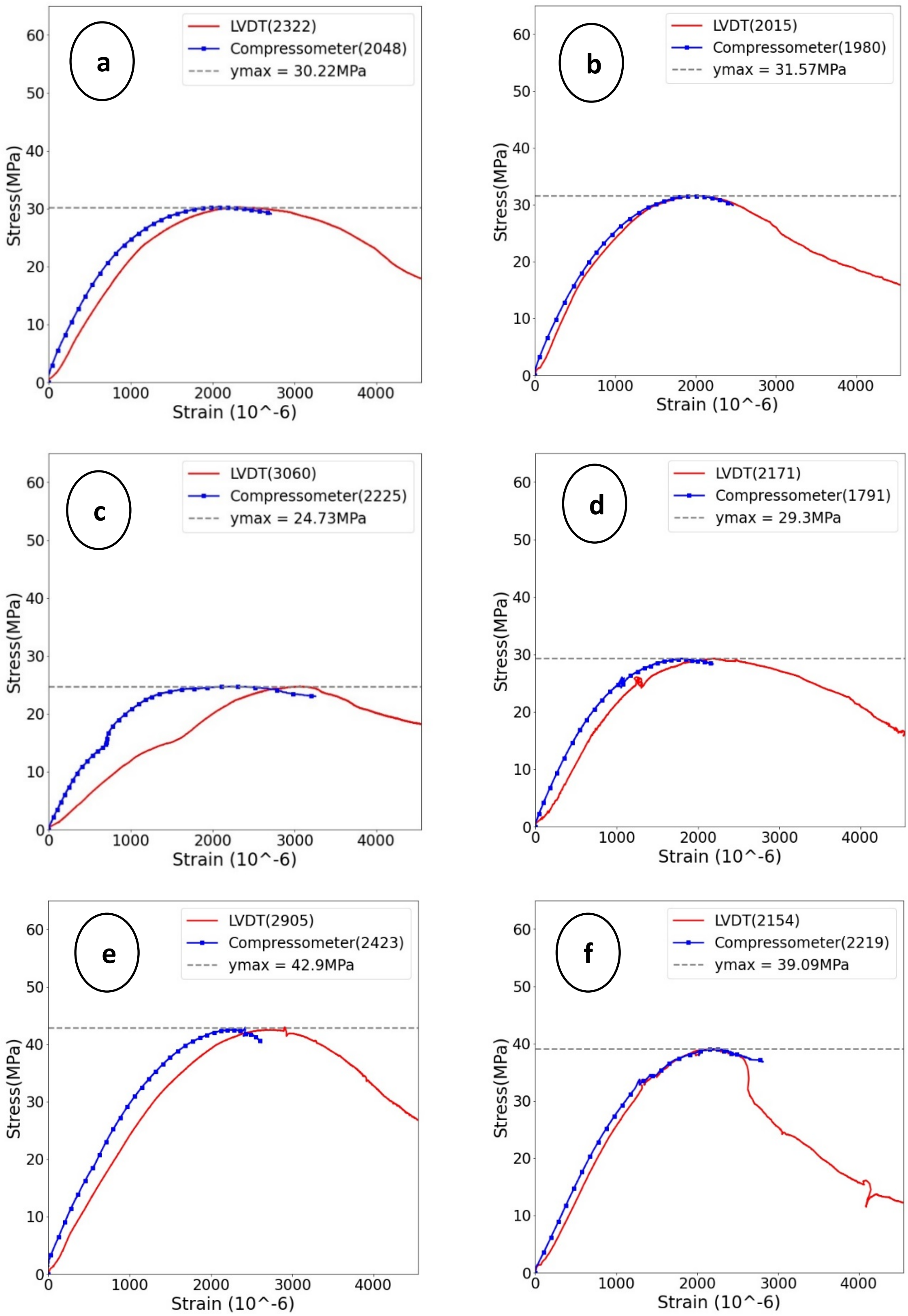

Fig-5: Stress-strain characteristics of recycled aggregate concrete mix

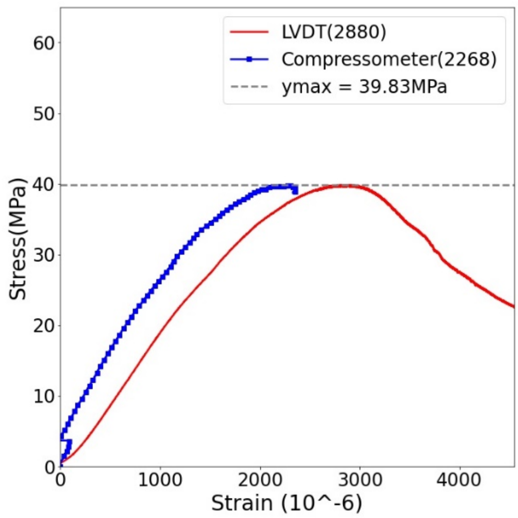

Fig-6: Stress-strain characteristics of natural aggregate concrete mix (w/c = 0.47) [21]

Figure 5(a) shows the LVDT strain reading as 2322 microstrains and Compressometer strain reading as 2048 microstrains for the specimen with compressive strength of 30.22 MPa. The LVDT shows a slightly higher strain value than the compressometer due to its larger gauge length ratios as discussed later. Also the LVDT is attached between the platens of the compression testing machine rather than directly attached to the sample, therefore the comparison of the strain values among the samples has been performed on the compressometer strain values in present section. With increase in compressive strength the strain values increase for both the compressometer and LVDT except for figure 5(c) which can be considered as an outlier in experimental investigation. The corresponding Compressometer readings in figure 5(b) ,5(c), 5(d), 5(e), and 5 (f) are 1980, 2225, 1791, 2423, and 2219 respectively. The increase in the peak strain values with increase in compressive strength for C&D waste recycled aggregate well agrees with the past studies on the conventional concrete [21]. Figure 6 shows the compressometer reading for the conventional Natural aggregate concrete sample with compressive strength of 39.83 MPa. At the achieved strength level, the Natural aggregate concrete shows the compressometer strain of 2268 macrostrain which lies in the similar range as the C&D waste recycled aggregate concrete (figure 5e and 5f).

The combined curves for the recorded strain using the compressometer and the LVDT has been shown in the figure 7 and figure 8. As shown in the figure, with increase in the compressive strain the strain at the peak stress increases with minor deviations from the trend for few samples. The difference in the two strain recording devices- LVDT and The compressometer can also be explained from the stress strain curves. As can be observed, that the strain values recorded in the compressometer are lower that the strain values recorded by LVDT. The reason for the variation can be attributed to the variation in gauge length ratio as well as the method of attachment of the instrument. An LVDT has a gauge length ratio of 1.0 and measures the strain based on the decrease in spacing between the platen. Since the variation in entire sample is recorded in the LVDT it gives a slightly higher value. Also due to minor adjustments in the platens just after the beginning of the loading, the initial rising limb of LVDT is not as accurate as compressometer. But the LVDT attached between the platens does not get affected by the specimen failure therefore is capable of capturing the Post peak behaviour. On contrary the compressometer used in the study was attached directly to the sample in the middle half. It had a gauge length ratio of 0.5. It is capable of accurately estimating the rising limb of the stress-strain curve but fails with the initiation of initial crack in the specimen. Therefore a compressometer is not capable of capturing the post peak behaviour.

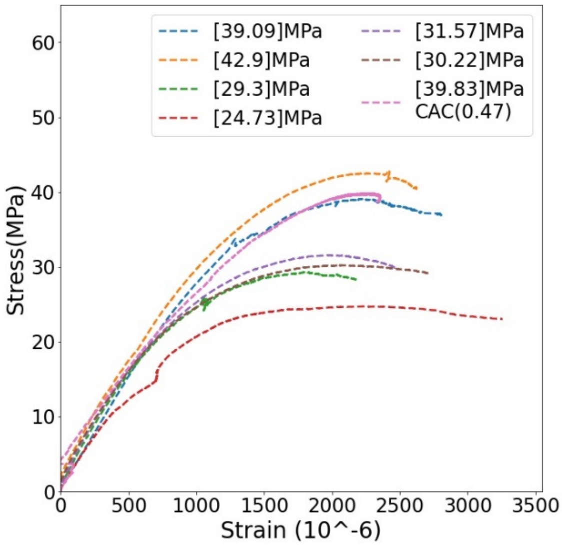

Fig-7: Combined Curve for Compressometer

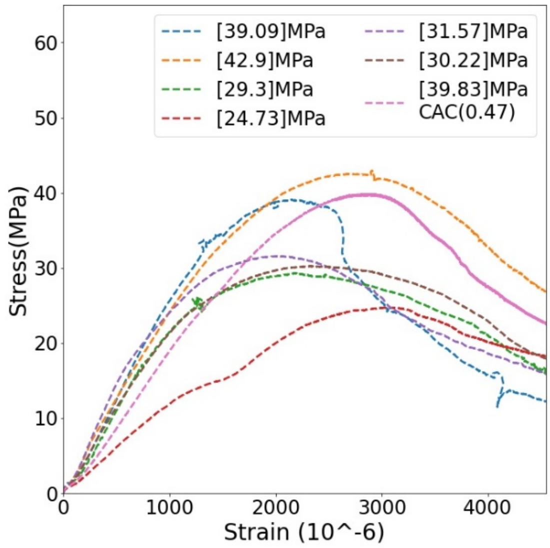

Fig-8: Combined Curves for LVDT

4.3 Energy absorption analysis and comparison with IS 456

Area under the stress-strain diagram gives the amount of strain energy taken by the specimen before failure. Table 6 shows the energy absorption analysis done on the tested specimens. The table shows three parameters. First the energy absorption till failure, this is evaluated by calculating the area under the stress-strain diagram corresponding to the compressometer reading. The second parameter is the energy absorbed per unit volume of the sample, which can be calculated by dividing the energy absorbed by the volume of specimen. The third parameter is the energy absolved per unit mass of the samples. Since the density of recycled aggregate concrete is lower than the conventional aggregate concrete the energy absorbed per unit mass becomes a comparable factor for different mixes.

Table-6: Energy absorption analysis

Sl.No.	Compressive Strength (Mpa)	Energy Absorption in compression till failure (Based on Compressometer) (KJ)	Energy absorbed per unit volume (KJ/m^3)	Energy absorbed per unit mass (KJ/Kg)
1	39.09	43.94	8288.32	3.48
2	42.9	62.02	11698.71	4.91
3	29.3	42.85	8082.71	3.39
4	24.73	36.16	6820.79	2.86
5	31.57	42.93	8097.80	3.40
6	30.22	45.16	8518.44	3.58
7	39.83 -CAC	48.63	9172.98	3.64

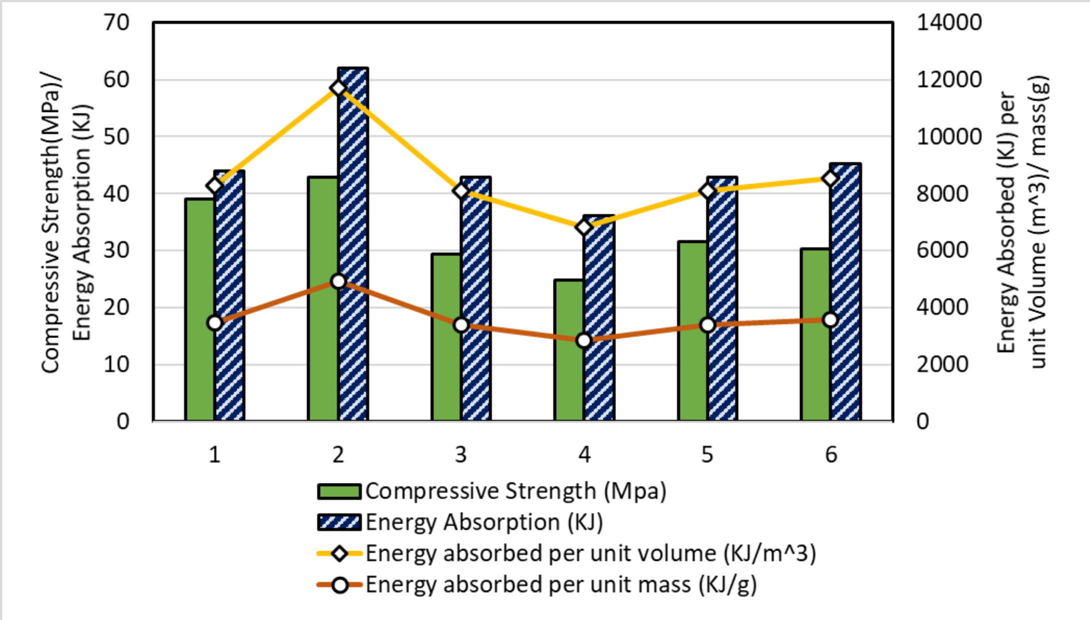

Fig-9: Energy absorption analysis

Figure 9 shows the comparison between various terms as discussed above in energy absorption analysis. As, can be observed from the figure the total amount of energy absorbed by the samples were in proportion with the compressive strength of the samples. Since the samples were of same size the energy absorbed per unit volume follows the similar trend. Although there lies difference in the density of the mixes, the difference is not much significant to have any considerable variation in the energy absorbed per unit mass value for the mixes. The comparison of the recorded strain values with the standard stress-strain curve in IS 456 [22] is given in table 7. The observed strain values approximately agree with the standard values presented in IS 456. Also similar to the standard curve, the experimental curve also has a parabolic raising limb. This suggests that for similar strength range the existing stress block parameter for the normal aggregate concrete can suitably be applied for recycled aggregate concrete. Figure 10 shows the standard stress strain curve assumed in IS 456 and figure 11 shows the Comparison of experimental and standard strain value assumed in IS 456.

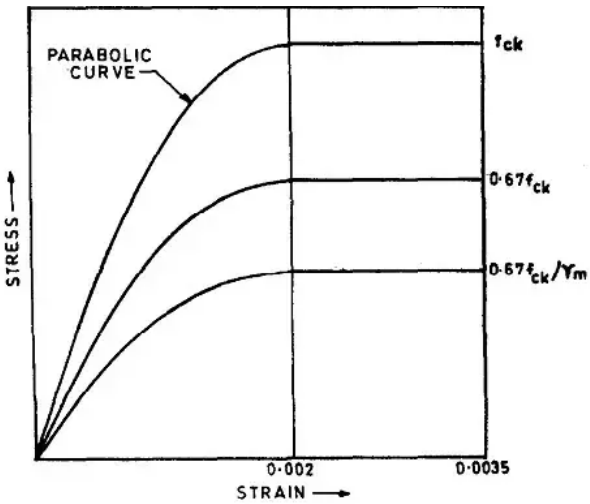

Fig-10: Standard Stress-Strain characteristics of concrete assumed in IS 456

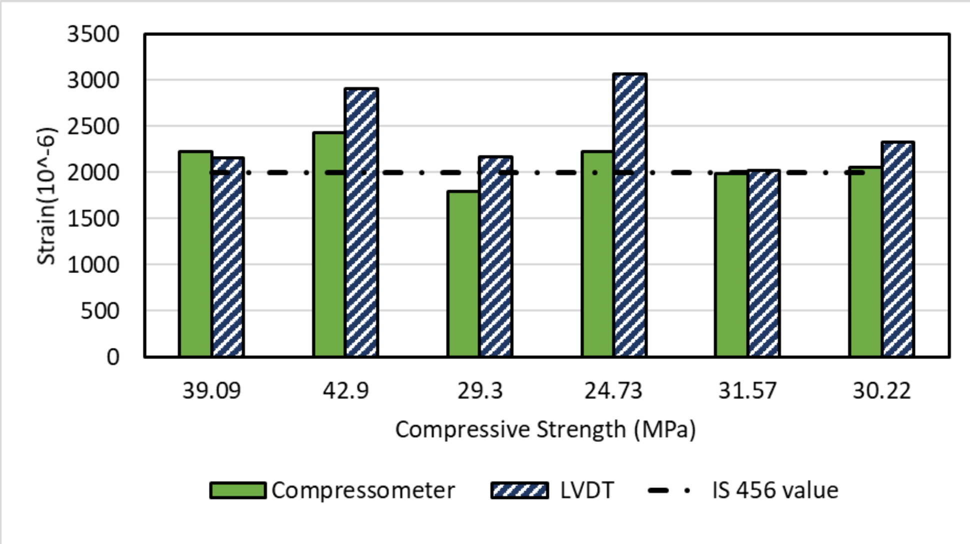

Fig-11: Comparison of experimental and standard strain value assumed in IS 456

Table-7: Comparison of experimental and standard strain value assumed in IS 456

S.No.	Compressive Strength (MPa)	Strain at peak Stress (Experimental)		IS 456
		Compressometer	LVDT	
1	39.09-RAC	2219	2154	2000
2	42.90-RAC	2423	2905	
3	29.30-RAC	1791	2171	
4	24.73-RAC	2225	3060	
5	31.57-RAC	1980	2015	
6	30.22-RAC	2048	2322	
7	39.83-CAC	2268	2880	

5. CONCLUSIONS

Aging buildings, not meeting structural requirements needs to be demolished which produces huge amount of construction and demolition waste. Natural and manmade disasters also contribute to generation of Construction and demolition waste in large quantities. These waste materials are a concern to the environment in terms of contamination of surrounding, wastage of resources, and space occupied by the waste. Therefore, the scientific community is actively looking for suitable methods to re-utilize these waste materials in order to get circular economy. One of the popular method is land filling but it is not the optimum use of the resource. In recent time a number of research work is being done to use the construction and demolition waste as aggregate in the structural concrete. The present study gives the stress strain characteristic and mechanical properties of the construction and demolition aggregate concrete at two different w/c ratios– i.e. 0.4 and 0.5. The mechanical and stress strain characteristics of the recycle aggregate concrete is compared with the characteristics and properties of conventional aggregate concrete. Following Findings concluded from the study are here under –

- The density of the recycled aggregate concrete are marginally lower than the conventional aggregate concrete. This can be attributed to the presence of wide variety of aggregate which may have overall lower density of CDW recycled aggregates in comparison to conventional aggregate which is granite in this case.

- In case of RAC, the properties like flexural strength, split tensile strength and modulus of elasticity are following the constitutive relationship with respect to compressive strength of the mix, depicting a similarity with the conventional aggregate concrete.
- The stress strain characteristics of the Recycled aggregate concrete were comparable with the conventional aggregate concrete of similar strength. Also the assumed stress-strain behaviour in Indian Standard IS 456 for concrete holds good for the recycled aggregate concrete considered in the study. Based on the findings it can be concluded that for similar strength the existing stress block parameters for conventional aggregate concrete can suitably be applied to the recycled aggregate concrete mixes.
- The energy absorption analysis suggests a proportionate relation between the compressive strength and the amount of energy absorbed in compression irrespective of the mix type considered in this study.

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