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Shekhar, Darshini
Presidency University

Godihal, Jagdish
Presidency University

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Exploring the Mechanical and Microstructural Characteristics of Recycled Concrete Hollow Blocks: Transforming Waste into Valuable Resources

Darshini Shekhar[1*], Jagdish Godihal[2]
[1]Presidency University, Bengaluru, Karnataka, 560064, India
[2]Presidency University, Bengaluru, Karnataka, 560064, India

* Author to whom correspondence should be addressed:
E-mail: darshinis@presidencyuniversity.in

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Abstract: India has experienced rapid urbanization in recent years, which has increased housing demand and construction activity. This has caused a rise in the use of natural resources and has resulted in a variety of potential pollution. Concrete should be made with additional cementitious materials, such as coal bottom ash (CA) and recycled aggregates, to combat this problem and prevent the earth's surface from degrading. This paper investigates the feasibility of using recycled coarse and fine concrete aggregates (RCA, RCFA) and coal bottom ash to create two different cavity blocks that meet mechanical properties as per American and Indian standards. Percentage variation strength has been illustrated for replacing solely with natural coarse material and combining recycled fine and coarse aggregate. Scanning electron microscope (SEM) and Energy-dispersive X-ray spectroscopy **(**EDX) examination of the materials used in preparing concrete for this study has been conducted to ascertain the variance in attributes of various concrete. The study's outcome says that fine aggregate rather than coarse aggregates plays a significant role in achieving good mechanical strength. Natural aggregates and cement can be supplemented with recycled aggregates up to 90% and coal bottom ash up to 45% respectively in making hollow masonry units and can be used in building envelope as per both American and Indian construction practices. Recycled concrete hollow block's good workability and stability have been hampered by the presence of a surplus of calcium and potassium, a deficiency of silica, built-in fractures in the recycled aggregates, and unburned carbon in coal bottom ash.

Keywords: compressive strength, hollow block, SEM, EDX, recycled aggregates, coal ash

1. Introduction

The building industry consumes the majority of extracted natural resources, and the products it creates are the largest consumers of energy and generate a great deal of trash. Ever-increasing construction projects in India had a tremendous impact on natural habitats by exploring natural resources[1)]. Concrete is made up of cement, water, fine aggregate, and coarse aggregate. The aggregate, which forms about 60-65% of concrete, is obtained from natural stone exposures or river bottoms. Both of these sources have been exhausted as a result of the continual mining of finite resources for a long period. To lessen the industry's negative environmental impacts, it is critical to seek out novel environmental management methods that strive for more sustainable manufacturing[2)]. After freshwater, the second most utilized natural resource is river sand[3)]. River sand's construction use vastly outpaces natural renewal rates[4)]. River sand consumer demand is much higher than artificial sand demand because river sand is naturally categorized by grain size and is freely available[5)]. The 2018 sand mining framework mandates that states evaluate the demand-supply gap and then explore their alternatives for River sand[6)]. A different resource supply will reduce reliance on and demand for river sand[7)]. Perhaps there are less expensive alternatives to river sand, which could aid in resource conservation[8)]. Conventional solid clay bricks have been formally expelled in building construction to address this condition and focus on boosting building energy efficiency and stimulating the study and usage of novel wall block materials[9)].The sources of natural aggregates have been dwindling wherein disposal of construction demolition waste has been a problem due to space constraints in urban areas[10)]. On the other hand, the building industry has long been viewed as one of the most significant causes of negative environmental effects due to the massive quantity of trash generated by construction, demolition, rehabilitation, and construction-related activities. Concerns about the environmental impact of natural aggregate consumption have generated interest in more conservative and cost-effective concrete materials like recycled concrete aggregate (RA), which is obtained by recycling CDW[11]. One proposed answer to the increasing volumes of construction demolition waste (CDW) dumped is the circular economy, which might drastically reduce or eliminate the quantity of CDW dumped. The circular economy is a business-based economic system that replaces the concept of waste with the principles of reducing, reusing, recycling, and restoring materials. Frameworks for the circular economy (CE), more notably resource restoration and manufacture centered on CDW reuse, recycling, and remodeling into new construction solutions. Pulverized fuel ash is a byproduct of the burning of bituminous or sub-bituminous coal that has been ground, powdered, or crushed (lignite). Around 80% of total ash is finely split and exits the boiler along with the flue gases. The remaining ash, which amounts to around 20%, is collected in the bottom of the boiler and is referred to as bottom ash. Indian powdered coal ashes have shown a larger potential for usage as a building material, according to research. Increasing the usage of pulverized fuel ash will not only conserve rare construction resources but will also aid in the resolution of the waste disposal problem [12]. Experimental research on M25 grade concrete in which river sand was combined with copper slag, quarry dust, foundry sand, and sawdust in proportions ranging from 10% to 60% revealed that the water absorption of river sand is comparable to that of other alternative fine aggregates. Quarry Dust can be used as a substitute for river sand, just as copper slag, foundry sand, and sawdust can be used to replace 40%, 30%, and 35% of river sand, respectively [13]. In test results on the properties of recycled aggregates (RA) impurities such as crushed clay brick, crushed ceramic materials, and gypsum were detected. Some physical-mechanical qualities, such as particle density and water absorption, were directly influenced by the ceramic material and mortar attached to recycled aggregates[14]. The strength behavior of concrete constructed with a processed recycled aggregate of 20 mm, replacing coarse aggregates with subsistence levels of 30%, 50%, and 100% recycled aggregates was investigated experimentally. When 100% processed recycled aggregates are used in place of natural coarse aggregates in concrete, the workability and strength of M20-grade concrete can be maintained[15]. To evaluate the compressive and flexural characteristics of recycled concrete (RC) hollow blocks, four different replacement rates—0%, 30%, 60%, and 100% recycled fine aggregate (RFA) are utilized as variable parameters. The compressive strength index of RC blocks MU10 and MU7.5 reduces by around 10% when the replacement rate of the RFA is 30%. Flexural strength for 100% RFA and recycled coarse aggregate (RCA) replacement rate is almost 50% lower than for natural concrete blocks[16]. The optimum way to utilize these RFA features to create high-quality concrete with the same or less cement content is still unknown, and no rules or recommendations are in place. As a reason, RFA's widespread use and best application in new concrete are hindered[17]. Contrary to its behavior in virgin aggregate concrete, the effect of 30% coal fly ash on RAC yielded subpar results when compared to RAC built wholly of OPC. In particular for long-term compressive strength and sustained RAC, the data justified the replacement of OPC with 50% GGBS[18]. CDW was characterized to discover fresh uses for recycled aggregates from Mexico City. The characterization was performed using chemical microanalysis (EDS), X-ray fluorescence (XRF), pH measurement, and sieve analysis. Feldspars, cristobalite, and pyroxene, which matched the natural aggregates, as well as varying amounts of calcite, a byproduct of the carbonation of the cement paste, and smaller amounts of calcium hemicarbo aluminate, rosenhanite, and tobermorite, were among the minerals discovered in the materials under investigation[19]. Also, the impact of blended ground coal bottom ash and coal fly ash on pozzolanic properties was investigated. Similar pozzolanic, physical, and chemical characteristics are shared by all of the coal ash combinations. Because of this, Portland cement clinker can be safely substituted with pulverized coal bottom ash in proportions ranging from 10% to 35%, leading to better pozzolanic properties[20]. Urban waste like CDW must incorporate waste reduction and recycling concepts and aim toward an integrated processing and disposal facility[21]. The addition of fly ash to cement has ideal applications in the natural gas industry, where fly ash cement with chemical additives is used to repair natural gas pipelines.A mixture of sodium silicic acid, cement, and fly ash can achieve the sealing property[22]. Policies and measures for mitigating global warming should be harmonized internationally across vast regions. Particularly in large populations, waste management and resource recycling are crucial policies for reducing greenhouse gas emissions[23]. Since stakeholders have begun requesting disclosure of corporations' environmental information in light of the potential cost and liability connected with environmental issues, environmental reporting has arisen as an important facet of reporting practices. Ultra Tech Cement Ltd was the only company in the cement sector of the building industry to take an active role in minimizing its impact on the natural world[24]. The cost-benefit analysis of ready-mixed self-consolidating concrete manufacturing prepared with recycled concrete aggregate was investigated using an inductive qualitative technique. The investigation’s results show that irrespective of the production plants employed, the RCA price cannot drop under that of natural concrete aggregate (NCA). The key takeaway of this article is that RCA production sites can be employed for large-scale manufacture of recycled aggregate concretes at reasonable prices[25]. An investigation on the impact of recycled aggregate size on the percentage of adhered mortar and the characteristics of recycled aggregate using the image analysis approach. The recycled aggregate with a particle size of 10.0-16.0 mm exhibited the highest concentration of adhered mortar, hitting 39.39%. To enhance the quality of the mix proportion, it is recommended to increase the proportion of recycled aggregates with a particle size between 16.0 and 20.0 mm, as this fraction contains less adhered mortar and higher quality recycled aggregate[26]. The scanning electron microscopy (SEM) analysis reveals the presence of a compact interfacial transition zone (ITZ) within the layer between the recycled aggregate and the cement matrix. The formation of a strong link between the fresh cement paste and the aggregate is facilitated by the coarse texture and significant porosity of recycled concrete aggregate, enabling the infiltration into the aggregate matrix. The presence of limited ettringite was found which aids in the development of cracks in hardened concrete as a consequence of its expansive behavior during the hydration process[27]. The EDS results of concrete prepared with RCA and fly ash and RCA/coal bottom ash demonstrate that the amount of calcium/silicate ratio is increased after 120 days of curing as compared to the 28-day cured samples. The decreased calcium/silica ratio in RCA/fly ash concrete showed that a smaller amount of hydration product developed[28]. The study on microstructural characteristics of mortar comprised of high-quality recycled aggregate (HRA) and high-quality recycled powder (HRP), both obtained from waste of high-performance concrete (HPC) demonstrated that the HRP microparticles mostly comprise hydration products, silica fume, and quartz particles. The scanning electron microscopy (SEM) photos depict the comparison between HRP and ORP (ordinary recycled powder) and is observed that the aggregate phenomena in ORP are comparatively less pronounced than in HRP. Additionally, the microparticles of ORP primarily comprise a smaller amount of calcium silicate hydrate (C-S-H) gel, along with substantial quartz particles and $CaCO_3$ particles[29].

The presence of walls is of paramount importance in ensuring the holistic structural stability and operational efficacy of a building. The aforementioned roles serve to enhance the stability, safety, and performance of the structure. To the best of our knowledge, however, there hasn't been any research on the application of recycled aggregates (coarse and fine) and coal bottom ash in hollow masonry blocks addressing the significance of replacing natural coarse aggregate and fine aggregates corresponding to the mechanical performance ensuing the microstructural characterization. The purpose of this research is to undertake a thorough microstructural examination of recycled aggregate concrete (RAC) to acquire a better understanding of its internal composition, interfacial transition zones, and overall microstructure. This study intends to determine the impact of integrating recycled aggregates on the mechanical characteristics of concrete by analyzing the microstructure of RAC and comparing it to those of conventional concrete. The study intends to uncover important microstructural factors that govern RAC behavior and provide insights into optimizing its mix design and boosting its sustainable use using sophisticated microscopy techniques and image analysis. The primary goal of this research is to use new forms of aggregate called recycled concrete aggregate (coarse and fine) obtained from processing construction and demolition debris with supplementary cementitious material (coal bottom ash) in constructing the building envelope. The building envelope is projected to be built of hollow blocks with different cutouts (circular and rectangular). Two distinct hollow blocks compressive strength, density, and water absorption are evaluated for an average of five specimens for approximately nine various concrete mix proportions, like the conventional mix, RCA+CA mix, and RCA+RFA+CA mix. This experimental study's inclusion of increasing amounts of coal bottom ash (up to 45%) and RA (up to 90%) raises its appeal in the research domain. The significance of this study is to reveal the complex links between microstructure and mechanical properties. Using sophisticated analytical procedures. The fine detailed image and elemental composition of concrete materials used for cavity blocks provide useful insights into the possible benefits and limitations of using recycled aggregates and coal ash in concrete.

2. Experiment Design and Fabrication

Ordinary Portland cement (53 grade), coal bottom ash, manufactured sand (conventional fine aggregate), recycled fine aggregate, conventional coarse aggregate, and recycled coarse aggregate were employed as test materials in this work. Traditional aggregates are obtained through rock quarrying, whereas recycled aggregates are obtained from the CDW recycling factory in Yelahanka, Bengaluru. Coal bottom ash (light brown), a bottom residue of the brick manufacturing boiler, is collected and sieved. Older concrete components that have been crushed and processed make up the majority of recycled aggregates. Materials can range in aggregate particle size from small sand-like particles to bigger crushed stone fragments. The aggregates remain glued by cement paste and mortar. Other impurities, such as residual paint, adhesives, and wood were discovered. For the investigation, the coarse aggregate of 10mm down and fine aggregate of less than 4.75mm was sieved and collected. The basic property test of concrete composites and mix design of concrete is followed as per IS10262 (2019). The production method, density, water absorption, compressive strength, and quality replacement ratio of concrete hollow blocks with 0-45% coal bottom ash and 0%-90% recycled aggregates are investigated adhering to IS2185 (2005) guidelines. The sequence of the study is shown in Fig 1.

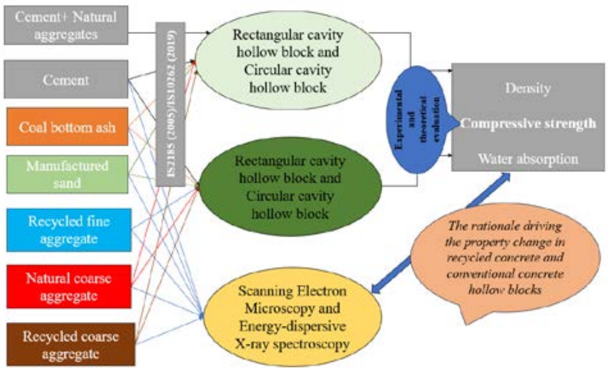

Fig 1. Sequence of the study

2.1 RC block manufacturing technology

A combination of hand moulding, concrete vibration ramming, and mass manufacturing is used to create the RC hollow block. Fig 2 depicts the production process, which is divided into three stages. 1) concrete mixing technique; 2) concrete hollow block-making method; 3) maintenance technique. Since there is no exclusive codal provision for the mix design of recycled concrete aggregates, a hollow block is cast as per IS10262 (2019) with the addition of extra water to the concrete mix based on water absorption values of the RA. The hollow block size is (500*100*100 mm) with rectangular and circular cutouts. Each block's web/flange thicknesses of 25mm/50mm in rectangular cutout and 25mm/60mm in circular cutout are given. The concrete is mixed in the laboratory following 24 hours, the recycled concrete hollow blocks are de-molded and stored in a tank for 28 days for curing. The casted blocks are immersed in a clean open water tank as part of the standard curing operation. The curing condition's temperature and humidity are restricted to atmospheric variation. The temperature and humidity vary in the curing period from 19-28 degrees Celsius and humidity from 25% to 80%. Regardless of the addition of chemicals or membrane coverage, the curing state remains consistent over time. For the loading test, seven days and 28 days of cured hollow blocks of an average of 5 units are evaluated.

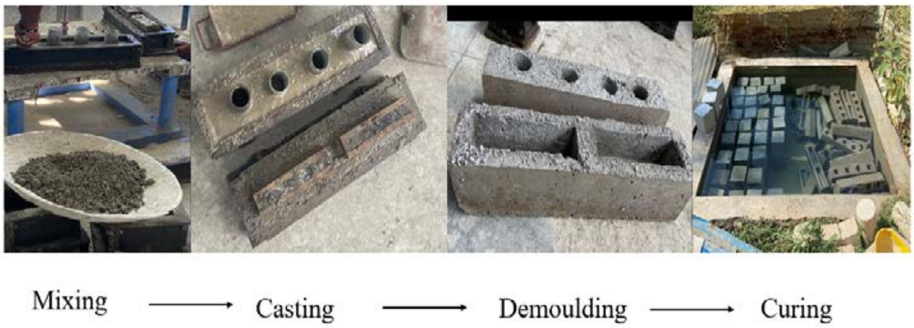

Fig 2. Recycled concrete block manufacturing technology

The difference between recycled concrete (RC) with varied aggregate replacement rates is that the doses of fine aggregate, coarse aggregate, and cement are adjusted in a specific proportion. The substitution of RA ranges from 30%-90% and the CA substitution ranges from 15%-45%, with the ideal mix proportion determined for a hollow block with a minimum compressive strength of 5MPa. The initial concrete mix ratio was only taken into account when substituting recycled coarse aggregate. The following samples were combined with both recycled coarse and fine aggregate, with coal bottom ash used as supplemental cement material. The concrete mix proportion considered in the study is shown in Table 1.

Table 1. Concrete mix proportion considered in the study

Mix no	Description	Cement kg/m^3	Coal bottom ash kg/m^3	NCA kg/m^3	RCA kg/m^3	M sand kg/m^3	RFA kg/m^3
1	CA_0RCA_0	472	-	863.76	-	703.28	-
2	$CA_{15}RCA_{30}$	401.2	70.8	604.1	258.9	703.28	-
3	$CA_{25}RCA_{50}$	354	118	302	302	703.28	-
4	$CA_{35}RCA_{70}$	330.4	141.6	259.66	604.1	703.28	-
5	$CA_{45}RCA_{90}$	221.4	259.6	87.06	776.7	703.28	-
6	$CA_{15}RCFA_{30}$	401.2	70.8	604.1	258.9	492.8	210.98
7	$CA_{25}RCFA_{50}$	354	118	302	302	351.64	351.64
8	$CA_{35}RCFA_{70}$	330.4	141.6	259.66	604.1	211	492.3
9	$CA_{45}RCFA_{90}$	221.4	259.6	87.06	776.7	70.28	633.0

2.3 Loading device and procedure of testing.

Fresh property test of concrete and workability test is carried out on slump cone. Based on the obtained slump concrete workable range is specified. Two methods of testing the compressive strength are followed in this study. 1: Experimental test results and 2: Analytical model equation. The universal testing machine (UTM) serves as the test's loading device, as indicated in Fig 3. The specimens are loaded onto the testing machine's bearing plate following the requirements of the test method for concrete hollow blocks until the specimens are destroyed. For the compression test, the number of specimens in each group is five blocks to assure test accuracy. The procedure specified in IS 2185 (2005) has been followed in terms of block density and water absorption (annexures C and E) calculation. Farooq et.al[30] created an analytical model that takes into account the ratio of fine to coarse aggregates, the percentage of cement by weight of all aggregates, and the casting pressure. The equation suggested is given below.

$$fc = \frac{-0.4x + 0.811y + 1.004z - 1.8721}{0.67}$$

where x is the ratio of recovered fine to coarse aggregates, y is the cement content (%) by weight of the total aggregate in the mix, and z is the casting pressure (MPa), fc is the theoretical compressive strength.

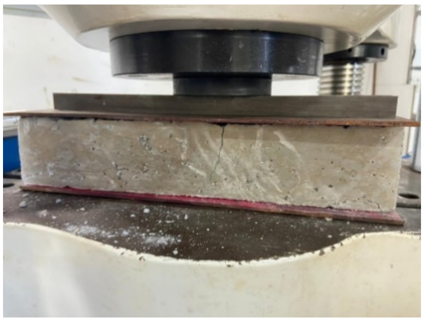

Fig 3. Hollow block sample testing in the universal testing machine

2.3 Comparison of application of the study block according to Indian and American standards.

Based on the results obtained on a hollow block of compressive strength, the density of block and water absorption capacity application of these considered different mix proportion block types has been discussed for Indian and American standard construction practice. ASTM C90-14 (2016) and ASTM C129 (2017) is the code referred to for America and IS2185 (2005) is the codal provision for India.

2.4 Microstructural analysis of materials used in the study

The SEM is an instrument that generates a highly magnified image using electrons as opposed to light. Electromagnetic lenses focus on electron beams that are accelerated by a potential difference between an electron cannon (cathode) and another cap-like system (anode). Electrons interact in many ways, producing secondary electrons, back scattered electrons, and x-rays. Different accelerating velocity is required to image the samples. To obtain a good representative image of the sample, 25 voltage is applied to concrete materials.

An EDX detector produces more details about a sample's chemical composition, including the elements present as well as their distribution and concentration, when used in conjunction with a scanning electron microscope (SEM). when SEM and an EDX detector are combined, X-rays reveal chemical information. EDX operates on the principle that the electron beam strikes the interior shell of an atom, knocking off an electron and leaving a positively charged electron-hole. When an electron is displaced, it attracts an outer-shell electron to replace the vacancy. As the electron moves from the outer, higher-energy shell of the atom to the interior, lower-energy shell, this energy difference can be released as an X-ray to identify each element present in a sample.

3.0 DATA COMPILATION AND OUTCOME ANALYSIS

3.1 Basic property test and sieve analysis of concrete composites

When compared to natural aggregates, recycled aggregates have a more angular shape and a larger range of particle sizes. The irregular shape and varying particle sizes produce holes and gaps between the particles, which contributes to recycled aggregate's lower specific gravity. The specific gravity and water absorption are inversely proportional as witnessed in recycled aggregates and natural aggregates. Because of the existence of pores, fissures, stuck mortar, and other foreign particles in RA, the overall fundamental property difference between natural and recycled aggregates is distinct. While coal bottom ash is a finer material than cement and is formed by coal combustion, it has varying mineral concentrations and leftover carbon, which influences the lower specific gravity. Specific gravity and water absorption of concrete constituents are shown in Table 2.

Table 2. Basic properties of materials used in the study

Concrete Materials	Specific Gravity	Water Absorption
M Sand	2.72	7.9%
RA (Fine)	2.56	5.8%
Natural Coarse (NCA)	2.64	<1%
RA (Coarse)	2.32	6.12%
OPC 53 Grade Cement	2.89	NA
Coal Ash	2.61	NA

Fig 4 and Table 3 demonstrate the particle size distribution and grading curves of the aggregate. Despite their comparable nature, both natural and recycled aggregates could not have hampered the workability of fresh concrete. The RA gradation is determined by the source of the demolished concrete and the manner of recycling. The RA used in the study had a higher percentage of finer particles than the ordinary aggregate. According to article 6.3 of IS 383 (2016), RA (fine) falls into Zone 1 and M sand falls into Zone 2. The 300-75 micron filter in RA (fine) and the 4.75mm micron sieve in RA (coarse) have the highest percentage fraction fluctuation.

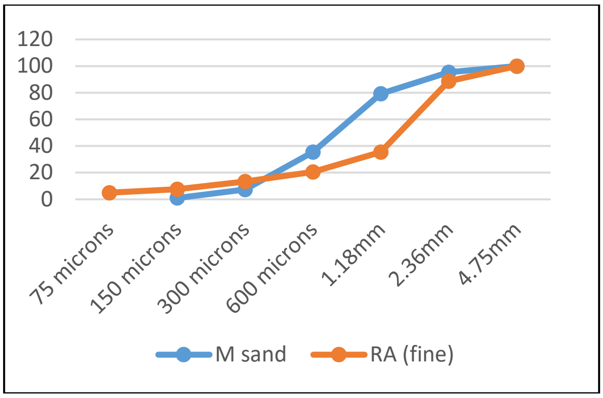

Fig. 4 Grading curve of fine aggregate

Table 3. Particle size distribution of coarse RA and NA

IS Sieve	% passing NCA	% passing RA (coarse)
20mm	100	100
12.5mm	100	99.7
10mm	93.4	89.4
4.75mm	2.2	4.1

3.1 Compressive Strength Test Data of the Recycled Concrete Hollow Block: Reporting and Computation

The measured data from the UTM testing is used to determine the peak load value of the RC hollow block. The following equation determines the compressive strength (fck) of each set of RC hollow blocks.

fck= F/ SA

where the peak load of the block is F and SA is the surface area

SA= length x breadth – (hollow cut-out area)

The average fck of all nine mixes is plotted in Fig 5. From the below graph observation, it has been noted that the cutouts given in the block are responsible for lowered compressive strength for the design mix. In a comparison of circular cutout block (C_CB) and rectangular cutout block (R_CB), the strength achieved for the same mix proportion is lower in R_CB. This is due to the large cut out area and less web and flange thickness provided.

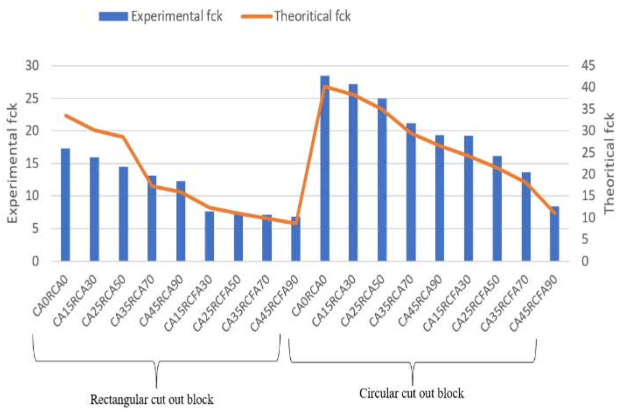

Fig 5. Experimental and Analytical results of 28days compressive strength

The C_CB and R_CB blocks of mix CBA_0RCA_0 have achieved 28.45 MPa and 17.29 MPa respectively. The decremental ratio of the conventional block to recycled coarse aggregate-coal bottom ash block to recycled coarse and fine aggregate-coal bottom ash block is given below.

CA_0RCA_0:$CA_{45}RCA_{90}$:$CA_{45}RCFA_{90}$=1:0.7:0.39------ R_CB case

CA_0RCA_0: $CA_{45}RCA_{90}$: $CA_{45}RCFA_{90}$=1:0.68:0.29----- C_CB case

The analytical model equation considered is for the concrete made of both recycled coarse and fine aggregates. The analytical model that was made correctly projected the compressive strength, with an average absolute error (AAE) of 8.48% for R_CB and 14% for C_CB hollow concrete blocks. The bar graph shows the 28 days of experimented compressive strengths (MPa) of RC blocks, while the lines on these graphs show the values expected by using the equation. In comparison to ordinary concrete, the substitution of recovered coarse aggregate and coal

bottom ash has only slightly reduced fck. Nonetheless, it

is noticeable that the quality of concrete where M sand and natural coarse aggregate have been substituted has declined significantly. Fig 6 illustrates that fine aggregates play an important role in gaining concrete strength. Using recycled fine aggregate as a replacement for M sand would decrease more than 50% of concrete strength made with recycled coarse aggregate. The larger surface area of

fine aggregates gives more cement paste contact sites, improving bonding and concrete strength. When aggregate becomes too fine, it increases water demand, which can lead to workability concerns and a decrease in strength.

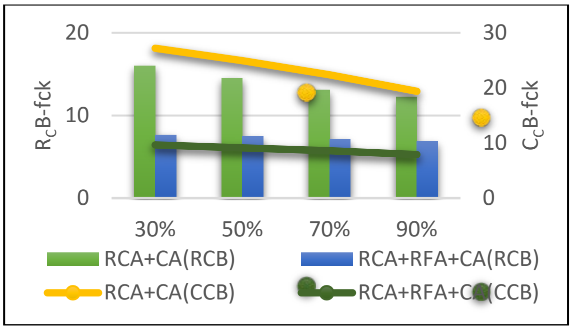

Fig 6. fck comparison between RCA +CA and RCA+RFA +CA mix

3.2 Recording of workability, density, and water absorption

The slump value of concrete determines its workability of concrete. The slump value diminishes as the recycled aggregate quantity increases and hence the poor workability of RC is observed. However the slump range is within the acceptable range as prescribed in IS 1199 (2018) standards. The block density of recycled aggregate hollow concrete block is 0.1 times lower than a conventional concrete hollow block. This is due to the porosity and low specific gravity. Water absorption of both R_cB and C_cB- conventional concrete and recycled aggregate concrete are below 10% which is acceptable in practice as per both Indian and American standards. The density of the considered blocks in the study ranges from 1442- 1940 kg/m3 wherein R_cB is less dense compared to C_cB due to the high content of concrete mixtures. There is a slight decrease in water absorption of concrete block types when a superplasticizer is used. When recycled aggregates are used in place of coal bottom ash, the concrete's water absorbability rises. This is because the porosity is increased by the use of recycled aggregate with aged mortar. Table 4 presents the density and water absorption of each block type made of different concrete mixes and water absorption of each block type made of different concrete mix.

Table 4. Density, slump and water absorption of different block

Block type	Slump (mm)	Density(Kg/ m3) R_cB / C_cB	Water absorption (%)
CA_0RCA_0	65	1633/1940	4.39%
$CA_{15}RCA_{30}$	60	1599/1910	5.78%
$CA_{25}RCA_{50}$	53	1550/1870	6.56%
$CA_{35}RCA_{70}$	42	1505/1751	7.3%
$CA_{45}RCA_{90}$	39	1470/1763	8.4%
$CA_{15}RCFA_{30}$	45	1590/1905	6.17%
$CA_{25}RCFA_{50}$	37	1578/1850	6.9%
$CA_{35}RCFA_{70}$	35	1565/1715	7.68%
$CA_{45}RCFA_{90}$	30	1442/1672	8.59%

3.3 Differential construction application of hollow block

A comparison of the application of the considered hollow block in the study is shown in Table 5. ASTM C90-14 (ASTM 2016)-Load bearing hollow block; ASTM C129 (ASTM 2017)- Non-load bearing hollow block; IS2185 (2005)- concrete masonry block are the code books considered for interpreting the application of hollow block for being load and non-load bearing units. In the case of rectangular hollow block $CA_{35}RCA_{70}$ can be used as load bearing (>13MPa) as per both ASTM and IS standards(>5MPa) and the addition of recycled fine aggregate as a replacement to m sand has failed to meet ASTM standards for being load-bearing element. The circular hollow block in $CA_{25}RCFA_{50}$ and $CA_{35}RCA_{70}$ behaves as load bearing unit in both ASTM and IS cases.

Table 5. Comparison of application of hollow block based on American and Indian standards

Rectangular hollow block	ASTM Load bearing	IS2185 (2005)	ASTM Non-Load bearing	Circular hollow block	ASTM load bearing	IS2185 (2005)	ASTM Non-Load bearing
CA_0RCA_0	✓	✓		CA_0RCA_0	✓	✓	
$CA_{15}RCA_{30}$	✓	✓		$CA_{15}RCA_{30}$	✓	✓	
$CA_{25}RCA_{50}$	✓	✓		$CA_{25}RCA_{50}$	✓	✓	
$CA_{35}RCA_{70}$	✓	✓		$CA_{35}RCA_{70}$	✓	✓	
$CA_{45}RCA_{90}$		✓	✓	$CA_{45}RCA_{90}$	✓	✓	
CA_0RCFA_0		✓	✓	CA_0RCFA_0	✓	✓	
$CA_{15}RCFA_{30}$		✓	✓	$CA_{15}RCFA_{30}$	✓	✓	
$CA_{25}RCFA_{50}$		✓	✓	$CA_{25}RCFA_{50}$	✓	✓	
$CA_{35}RCFA_{70}$		✓	✓	$CA_{35}RCFA_{70}$		✓	✓
$CA_{45}RCFA_{90}$		✓	✓	$CA_{45}RCFA_{90}$		✓	✓

3.4 Material Characterization and its Impact on Strength

3.4.1 Coal ash

Table 6 presents the chemical composition of CA, where the percentages of the chemical composition are expressed by mass.

Table 6. Chemical composition of coal bottom

Element	Weight %	Element	Weight %
C	3.9	Ca	5.1
O	43.0	Ti	1.1
Mg	1.1	Fe	6.1
Al	13.3	Mo	2.1
Si	20.0	Ba	2.7
K	1.7		

Silicon dioxide (SiO2), aluminum oxide (Al2O3), (Fe2O3) ferric oxide, and calcium oxide (CaO) are the primary mineral compounds in coal rock. The table below shows that coal bottom ash contains high amounts of SiO2, Al2O3, and Fe2O3 that improve pozzolanic effects, mixture interlock, and properties such as strength[31]. SEM and EDX image of the CBA taken in the study is shown in Fig 7 and Fig 8.

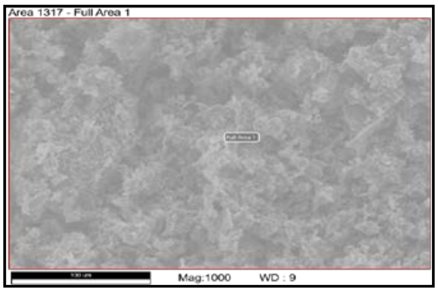

Fig 7. SEM image Coal ash

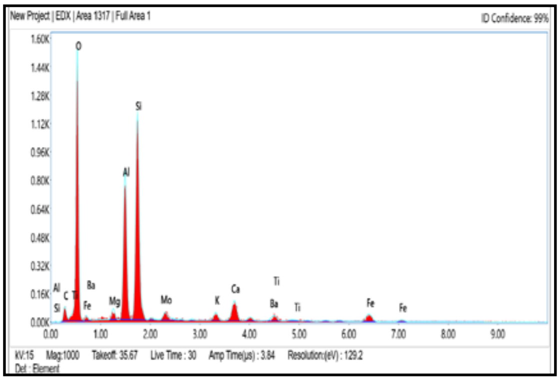

Fig 8. EDX result of coal ash

Due to its low pozzolanic activity, calcium oxide could be a barrier to its application in cementitious systems. CA used in the study is classified as class C ash because the sum of SiO2+ Al2O3 + Fe2O3 is below 70 % [32]. Bottom ash is easier to compact under loading since it has a more porous and vesicular structure due to its larger proportion of unburned carbon. The presence of Mo and Ba indicated the presence of alkali compounds which react with siliceous content in the aggregate to form alkali-silica gel in the hydration process which imbibes the pore fluid and causes cracking thereby reducing the compressive strength.

3.4.2 Comparison of recycled concrete aggregates and natural aggregates

The surface-saturated M Sand following IS: 383 (2016) is utilized to avoid further water absorption and achieve optimum strength. The study makes use of recycled demolished concrete waste from CDW produced in local Bengaluru as Fuel. The crushed recycled aggregate from the recycling plant is utilized in the project as fine aggregate. M sand is the homogeneous dense structure wherein RFA is porous and has calcium silicate hydrate (C-S-H) gel over it, as shown in Fig 9 and Fig 10.

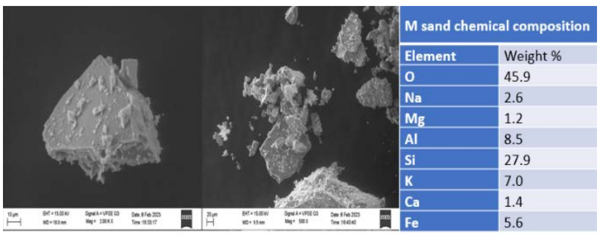

Fig 9. SEM image EDX result of M sand

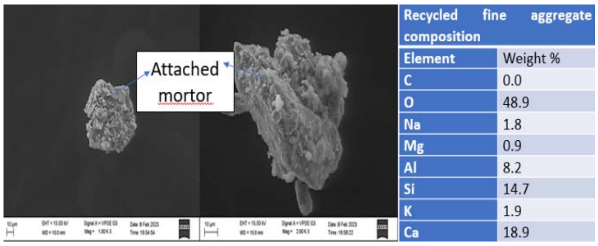

Fig 10. SEM image EDX result of recycled fine aggregate

Natural coarse aggregate under IS: 383 (1987) is utilized. The coarse aggregate utilized is less than 10 mm in size. Fig 11 and Fig 12 depict an angularly structured NCA and an irregularly shaped RCA with an attached motor on the surface and the presence of built-in microcracks and mortar around it. The variation in aggregate morphology is influenced by the source, technique of excavation, and treatment system.

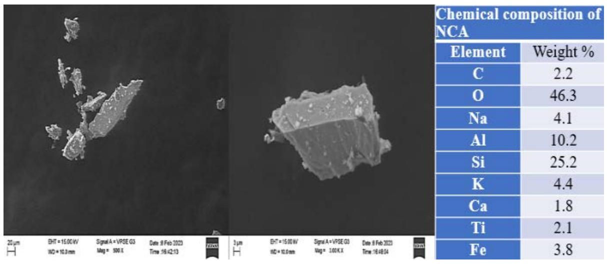

Fig 11. SEM EDX result of natural coarse aggregate

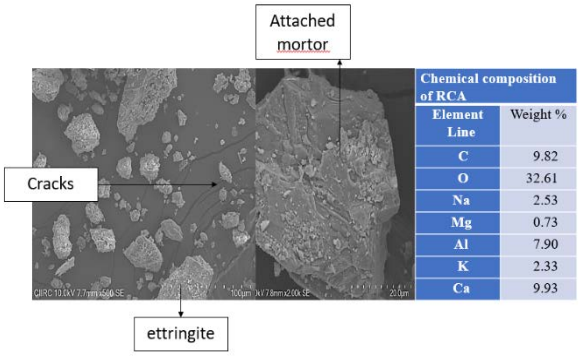

Fig 12. SEM image EDX result of recycled coarse aggregate

The calcium content in recycled concrete aggregate is too high, which can lead to aggregate deterioration and a decrease in the strength and durability of the concrete. Excess calcium can cause concrete to become weak and powdery, which reduces its strength and can also lead to increased shrinkage, cracking, and other issues[34].When the potassium content is too low, it can cause a decrease in the workability, plasticity, and cohesion of concrete. It can also lead to a decrease in abrasion and erosion resistance, as well as an increase in the permeability of concrete. The amount of silica present in RFA is half the quantity of M sand. This is when the hydration does not occur properly due to a deficiency in the silica to form calcium silicate hydrate gel.

3.4.3 SEM elucidation of Recycled aggregate concrete

The physical and chemical connection between RA and cement paste is poor as a result of the faults in the microstructure of RA. While the failure of conventional concrete is caused by the growth of cracks along the interfacial transition zone (ITZ), the failure of RAC is caused by the combined action of ITZ failure and internal RCA cracking[36)]. ITZ thickness for RAC typically falls between 30 and 60 micron meter[37,38)]. Fig 13 and Fig 14 depict the micro-morphology images of ITZ, calcium silicate hydrate (C-S-H), ettringite, pores, and calcium hydroxide ($CaOH_2$) in the RAC ($CA_{45}RCA_{90}$ and $CA_{45}RCFA_{90}$). RA will develop additional $CaOH_2$ and ettringite crystals at the early hydration stage when the calcium silicate and calcium aluminate concentration of the binder is quite high. This procedure alters the RAC characteristics by making its microstructure loose and porous[39)]. Compared to RCA, RCFA concrete has numerous fractures and tiny holes due to the loosening ITZ in the parent concrete and the damage sustained during the production of RA[40)]. A key aspect in achieving the best possible mechanical performance of concrete structures is the denser C-S-H matrix exhibited in RCA as compared to RCFA.

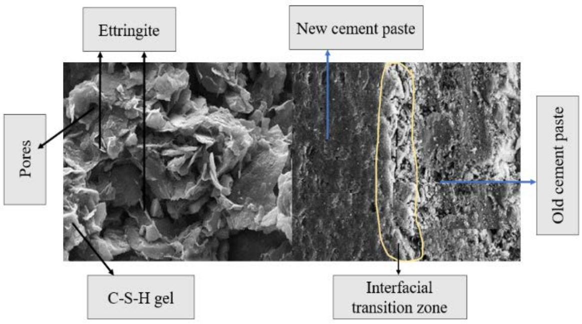

Fig 13. SEM image of $CA_{45}RCA_{90}$ mix concrete

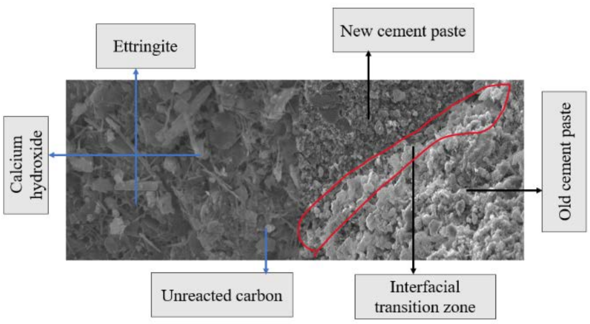

Fig 14. SEM image of $CA_{45}RCFA_{90}$ mix concrete

4. Discussion

The Bureau of Indian Standards has authorised the use of recycled concrete coarse and fine aggregate materials under IS-383 based on the substantiation of the concrete strength results at various research centers. Featuring the use of recycled aggregate concrete and coal ash, the current study went one step further by conducting a thorough investigation of hollow masonry units with different cavity cut out. The study has attempted to close the gap between microstructural changes and mechanical behavior through the use of modern imaging techniques and mechanical testing, offering a comprehensive understanding that has been noticeably underexplored Supplementing RCA, RFA,CA for conventional materials and increasing the hollow area of masonry unit declines the mechanical performance being building envelope. The microstructure faults of RA are reflected in the weak physical and chemical bonding between aggregate and cement paste, as well as the existence of cracks and pores and attached mortar in recycled concrete, consequently losing out the mechanical performance. The failure of the interfacial transition zone (ITZ) and the internal breaking of RCA are both accountable for the failure of RC. Since the recycled aggregates have tiny cracks when it is poured into the new cement paste, the old ITZ mixes with the new ITZ. This weakens the bond between the cement base and the RA, making the RC fail to deliver the design characteristic strength[35)]. Coal bottom ash and recycled aggregates consume lesser energy in manufacturing than conventional materials[33)]. Furthermore, the wellbeing of the community is improved by the decrease of industrial waste and its accompanying harmful effects on the environment and human health.

5. Conclusion

This work presents a novel contribution to the realm of sustainable construction materials by investigating the mechanical and microstructural attributes of concrete blocks manufactured using a blend of recycled concrete aggregates and coal ash. This research uniquely combines these two eco-friendly materials to create a hybrid construction product-building envelope. Research aids in the development of greener construction practices and paves the way for the utilization of unconventional materials in the production of high-performance hollow concrete blocks.

- Due to the low potassium content, lack of fineness, level of contaminants present, and variability in gradation, the workability decreases as the number of recycled aggregates increases in the concrete mix. For the maximum replacement of recycled aggregates and coal bottom ash, the lowest slump value measured is 30mm.
- In the case of rectangular hollow block $CA_{35}RCA_{70}$ can be used as load bearing (>13MPa) as per both ASTM and IS standards(>5MPa) and the addition of recycled fine aggregate as a replacement to m sand has failed to meet ASTM standards for being load-bearing element. In both ASTM and IS cases, circular hollow block- $CA_{25}RCFA_{50}$ and $CA_{35}RCA_{70}$ behaves as load-bearing units.
- The compressive strength of recycled coarse aggregate blocks was lowered by 30%, and recycled coarse-fine aggregate blocks were weakened by 60%-70% when compared to normal concrete blocks.

- The $CA_{45}RCFA_{90}$ concrete mix proportion is recognized as the ideal mix for achieving the required characteristic strength according to American and Indian standards, irrespective of building loading type with the lowest percentage of error between experimented and adaptive equation determined compressive strength.
- Due to the material's porous nature and irregular shapes, which can be seen in SEM analysis, the density of recycled concrete hollow blocks falls as the RA content and CA levels rise. The existence of inherent fissures and the various morphology of the cement patches on the surface of the recycled aggregate grains cause this concrete to absorb more water than regular concrete. As a result, the water absorption and density of recycled concrete blocks vary in inverse proportion to the density of conventional concrete blocks.
- According to this study, recycled concrete aggregate composition and potential contamination can be controlled in the first place by determining the chemical composition. Because the amount and quality of cement paste adhering to these aggregates will vary based on their size.
- The presence of calcium, silica, and carbon in an undesirable proportion in coal bottom ash interferes with the chemical reactions that take place during the hydration process. The presence of reactive silica produces alkali-silica gel, which can rupture and crush concrete, lowering its strength.

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