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Original Article

Utilization of Recycled Concrete Materials in Concrete Production: Methodology, Characterization, and Performance Evaluation

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Abstract *- The industry produces great volumes of Construction and Demolition Waste (CDW) that pose various environmental issues, such as resource depletion and accumulation of waste. This research focuses on the appropriateness of recycling Construction and Demolition Waste (CDW) in the form of reuse of Recycled Concrete Aggregates (RCA), Recycled Concrete Sand (RCS), and Recycled Concrete Powder (RCP) as green substitutes in concrete production The work provides a full process cycle of recycling CDW wastes ranging from material collection, processing and performance assessment in concrete mixtures. 12 concrete mixtures were prepared with varying percentages of the recycled materials and were evaluated for their workability and compressive and tensile strength. Results show that up to 50% of the replacement of conventional materials with recycled CDW does not significantly affect the strength of concrete and has environmental benefits. The study finds that Mixes containing RCP and RCS at this level have acceptable mechanical properties and enhance sustainability. However, full replacement with recycled materials resulted in lower strength, suggesting their potential for non-structural applications. This study emphasizes the need for improved recycling techniques and the opportunity to use recycled aggregates in concrete to support circular economy initiatives. The results provide a foundation for subsequent investigation on improving the utilization of CDW in construction and promoting sustainable construction.*

Keywords *- Concrete demolition waste, Fresh properties, Recycling Concrete, Strength properties.*

1. Introduction

Natural resource depletion and environmental degradation are caused primarily by the construction industry. Infrastructural development is at an all-time high in many countries, including India, leading to spiralling demand for materials like cement, sand, and aggregates. The growing consumption of goods and services is depleting natural resources and has caused large amounts of waste to be generated, along with increasing environmental problems. Moreover, to address these problems, the use of recycled concrete sustainably addresses them, lowering construction projects' impact on the environment. CDW can be used as an alternative recycle aggregate. It can be recycled back into new construction, processing demolished concrete, saving resources by diverting the materials from landfills and reducing the carbon emissions involved in the supply and transportation of virgin material.

This reduces resource depletion and supports a circular economy by returning materials to the production process. Recycled concrete may be used as a coarse and fine aggregate and a partial replacement for cement. It is often used in pavements, foundations, and structural elements if it is of good quality. However, inconsistencies in quality, contamination, and degraded mechanical properties prevent it from being used broadly.

Although global research has explored CDW applications extensively, most existing literature focuses on specific components like coarse aggregates or emphasizes environmental impact without addressing implementation at scale in developing regions. Notably, there is a clear lack of practical, integrated studies on the use of Recycled Concrete Powder (RCP), Sand (RCS), and Aggregate (RCA) simultaneously, particularly under Indian construction conditions. This represents a significant research gap that this study aims to address.

Due to the rate of urbanization and demolition, construction waste has gone all over India just as effectively as waste management. To alleviate this environmental problem, effective recycling alternatives are required. As reported, the country produces approximately over 700 million tonnes of CDW, which remain largely unrecovered due to highly disorganized recycling strategies, the non-existence of useful options, and the lack of detailed scientific studies in the areas [1]. Globally, over 20 billion tonnes of natural materials are used in making new concrete, and demolished concrete contributes 20% to 40% of total solid waste, often ending up in landfills as the final disposal option [2]. The condition is particularly concerning for fast-developing countries like India. It is interesting to note that concrete waste also gets generated from constructing new structures, although its quantity is less significant [3]. The recycling rate of CDW in India stands below 1% because of insufficient data collection, inadequate infrastructure, and inadequate enforcement of waste management regulations [4].

The potential of waste management remains limited by tracking issues and management challenges of residential CDW. Developing central trading platforms alongside stakeholder participation will solve the current systemic inefficiencies while enabling material exchange and accountability mechanisms [5]. CDW recycling promotes national sustainability and climate goals by reducing emissions and resource consumption compared to landfill disposal [6]. CDW is a natural aggregate replacement in sub-base and base layers, making it an economical and sustainable choice for large-scale reuse in infrastructure [7].

Case studies of CDW generation show that scientific assessments and explorations are needed to decrease demolition waste's environmental implications in addition to laws, strategies, and regulations [8]. A few studies have shown that CDW may be utilized in making new concrete to an extent [9]. However, the practical utilization of CDW remains underexplored regarding the experimental integration of all its forms into functional concrete mixtures. While prior work has investigated aggregates or powders in isolation, very few studies provide a full-cycle analysis from processing to performance evaluation of combined CDW constituents in structural and non-structural applications.

The primary challenges are related to CDW generation and its non-utilization. Studies on waste generation, waste evaluation and utilization approaches, and life cycle assessment indicate that waste recovery from CDW has remained limited. It may be concluded that the reuse of CDW possesses a broader perspective for addressing this issue [10-13]. Environmental penalties for creating and demolishing waste have been studied, and reuse has been promoted.

The most researched CDW component is the aggregate. Recycled concrete aggregate life cycle assessments are detailed [14-16]. Wherein the hazardous impacts have been highlighted. A detailed study suggests a framework and material flow analysis for construction and demolition wastes. Various significant studies have demonstrated that the utilization of construction waste should be supported by national policies, rules, and bylaws, creating effective waste management facilities, using modern methods of waste identification and evaluation, and addressing technical problems hindering the reuse of recycled CDW [17–20]. Overall, it may be summarized that the alternative use of CDW in new construction could effectively solve the problem.

Regarding the technical aspects of making usable material from recycled CDW, especially concrete composites, a few research works are available for reference. Research was carried out on the effects of recycled powder and fine aggregates from CDW in the fresh state behaviour of modified concrete production, providing important insights on the topic [21].

A rigorous analysis of recycled powder for cement replacement found that adequate pre-treatments may improve concrete property reduction and offer the potential for CDW in environmental safety and sustainable material development processes [22, 23].

The authors and their team have also performed pilot studies using CDW in concrete manufacturing. The modification has been evaluated through primary strength investigations. The results have been encouraging, and the team has continued experimenting with extensive mix designs for concrete, as discussed in this article [24-26].

This study builds on such findings but advances the field by conducting a holistic performance evaluation using RCP, RCS, and RCA combined with systematic variation of replacement levels. Unlike previous works, this research does not limit its focus to individual material types or single performance tests—it explores fresh and hardened properties, workability, and mechanical strength, thereby providing a practical framework for implementation.

Despite several research outcomes on the utilization of CDW for making new material, a lack of consistency in the knowledge and information is a missing link between the research works and real utilization in the field. The topic requires a complete understanding of Pre-processing, Conditioning, Separation of the CDW constituents, study of the recycled material properties, and evaluation of different compositions and mixes under standard test conditions. The present study focuses on all these aspects. It consists of stage-wise information and knowledge that can be a ready reference for further development and futuristic work.

The experiments encompass the preparation of a new construction composite using recycled CDW ingredients. As a generalized approach, the recycled CDW ingredients have been utilized to produce concrete separately. The evaluation of preliminary strength properties on the mixes has been presented to provide a scientific understanding of the contribution of recycled material in manufacturing new construction materials.

1.1. Research Significance

The research addresses some of the primary challenges of using CDW in new material manufacturing. It explains the essential steps to identify the affordable and simple methodology for recycling the CDW in raw form. The processed materials have been evaluated for mechanical, physical, chemical, and microstructural material properties to check the feasibility of their use. Later, an extensive number of mixes for concrete have been designed and evaluated. The objective was to suggest the optimum replacement ratio of conventional to recycled materials in each mix. The work also suggests the areas of application of the modified mixes. In summary, the authors have made efforts to simplify the overall process of using CDW in construction applications. The significance of this study lies in its comprehensive approach, which goes beyond the scope of most existing research that typically focuses on isolated components like RCA or basic compressive strength evaluation. This research uniquely integrates all three recycled constituents, RCP, RCS, and RCA, into mix design and testing. It further evaluates the material behavior under practical construction scenarios, offering a data-backed pathway for optimized substitution in structural and non-structural applications. This level of integration and real-world relevance makes the study especially novel in the Indian context, where CDW recycling is still in its infancy and standard frameworks are lacking. By combining mechanical testing with practical mix proportions and application-based recommendations, the study provides a replicable reference for stakeholders aiming to scale CDW usage responsibly.

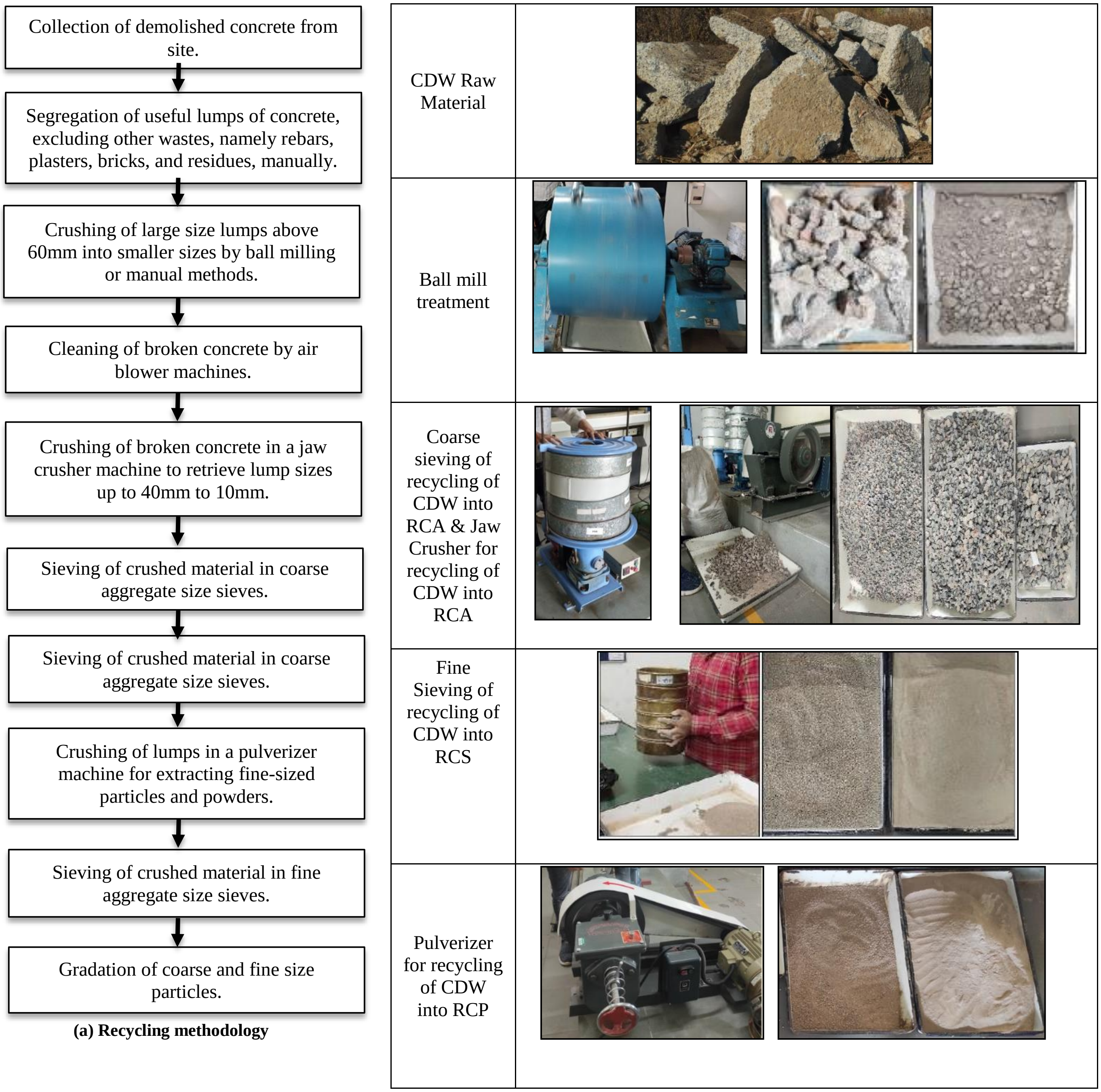
2. Experimental Program

The experimental work was conducted in three major phases: recycling of CDW, materials characterization of CDW, and assessment of the concrete mixes prepared with CDW. Physical tests and microstructural analysis have been exploited for the characterization of CDW in order to assess the prospects of recycled material for construction purposes. The fresh and hardened characteristics of concrete are undertaken to determine the concert of the CDW as a construction material. The materials used in the study were collected from a building demolition site as part of routine site clearance activities, and their use was aligned with the intended research purpose. Only waste concrete debris from structural members was included, while materials such as bricks, plaster, and reinforcement were excluded during collection. This ensured that the recycled products remained representative of concrete-based demolition waste and minimized variability. The materials used in the study were collected from a building demolition site as part of routine site clearance activities, and their use was aligned with the intended research purpose. No hazardous or restricted material was used in any part of the work. The sourcing process complied with applicable norms and followed good environmental and ethical practices.

2.1. Recycling of CDW and Characterization

The CDW was manually collected from a building demolition site in the local area of Rajkot City, Gujarat. The collected waste was segregated and recycled at the university laboratory by adopting the methodology shown in Figure 1(a). Recycling aimed to obtain useful ingredients in varying forms of RCP, RCS, and RCA. The ball mill, jaw crusher and pulverizing machines, as shown in Figure 1(b), have been utilized strategically for the recycling of CDW. At the first recycling stage, the CDW large non-uniform sized boulders were ball milled to obtain lumps of average size of 50mm to 35mm. In the second stage, a jaw crusher was used to break the lumps of CDW into a particle size of 10mm. After jaw crushing, sieving of the material was carried out, and fine and coarse particles were separated. The fine particles were further crushed into the pulverizer machine to obtain a fine powder of CDW. Figure 2 shows all sizes of the particles recycled and graded as per the requirements of the experimental program. The comparative gradation curve shown in Figure 3 indicates the good correlation of the particles obtained from CDW with the conventional primary materials, namely cement, sand and aggregate to prepare concrete composites. IS 383- 2016 code has been referred to as the guidelines for necessary tests on the material obtained from the recycling. The physical characteristics of the coarse and fine aggregates are indicated in Table 1, and the chemical composition of the RCP relative to the conventional cement is indicated in Table 2.

The collected waste from a site was transported to the laboratory. The ball milling did not show any loss of material during the breaking of lumps. All treated materials were collected for further processing, and nothing was discarded. Similarly, the jaw crushing was done without noticeable loss of material being recycled. However, the pulverizer showed a loss of material due to significant dusting induced during the process. The quantities required to prepare specimens, namely cubes and cylinders for the concrete, were estimated as per the target strength of the mixes. The entire set of concrete mixes was formulated to meet the specifications of the grade; M15 to M25 were the acceptance limits. This way, the optimum utilization of CDW may be obtained to qualify the composite for its intended usage and applications. It is to be noted that water was not used at any stage of recycling throughout the process. Cleaning by water washing or soaking the recycled materials may restrict the ingredients in providing actual response and behavior. However, normal air blowing was done to remove adhered dust and other impurities on the large to medium-sized boulders and 20 mm-sized aggregates. Moreover, cleaning recycled material with water increases unwanted water demand and is found uncapable of removing hardened paste from the aggregates and sand particles. It would be more practical to utilize the ball milling methods if the hydrated slurry is to be removed from the aggregates. Pre-treatment of CDW ingredients is one of the major aspects of utilizing waste in construction activities [23].



(a) Recycling methodology

(b) Recycling of CDW using machines

Fig. 1 Recycling methodology and machines for CDW

Fig. 2 Recycled CDW transformed into varying particle size

2.2. Characterization of Recycled Ingredients of CDW

2.2.1. Particle Size

Physical investigations were performed on all three ingredients, namely RCP, RCS, and RCA. It was required to establish the feasibility of the CDW for preparing concrete mixes. The research gap in the literature was the deficiency of the adequacy check of the recycled material in various sizes and forms. Therefore, tests for chemical components of RCP and RCS, particle size distribution, and comparative study with conventional sand were performed during the present study and presented in the discussion. The fine and coarse aggregates of conventional concrete have been compared with CDW ingredients. Following is a particle size distribution curve for recycled and conventional materials shown in Figure 3. The legends, namely NCA and NFA, indicate normal coarse and normal fine aggregates, respectively, and OPC indicates conventional cement. The graph shows the mapping of the particle sizes with the conventional materials. The comparison of the particle sizes showed that the recycled ingredients fulfill the grain size requirements of the concrete mixture. The recycling methodology adopted was also found appropriate by this comparison. However, the RCP particles showed a deviation of 2%,10%, and 6% from the reference particle sizes of the conventional cement for the sieve sizes of 300-micron,150–micron and 90-micron, respectively. This is an important observation and must be noticed because the fineness of the binder particles is responsible for the bond formation and intermolecular structures [24, 25].

The visual inspection suggested that, unlike the normal aggregate, the CDW aggregate consisted of adhered mortar layers, as shown in Figure 4. Such layers are difficult to delaminate with water-washing treatments. Conversely, it contributes to additional friction and better adhesion of the cement gel. However, careful selection of the waste material from the recycling process is essential. There are lumps formed with the mortars only, which also look like the CDW aggregates but are not appropriate for use owing to limited strength. They are basically hardened mortar pastes consisting of sand and binder particles only and do not offer any structural property for application in concrete.

2.2.2. Chemical and Physical Properties of Recycled CDW Ingredients

Along with the particle sizes, the CDW ingredients have also been evaluated for their physical properties. As per the code guidelines, the preliminary tests to obtain physical properties have been carried out. The results of the test are presented in Table 1. A number of research studies have been performed on the use of CDW in the preparation of new composites, but a detailed study of the unique features of ingredients derived from recycling needs to be considered. Serving to the requirement, the ingredients of CDW in powder, fine, and coarse sizes have been assessed for their preliminary properties. The Recycled Concrete Powder (RCP) has been evaluated as per the guidelines of IS codes 4031-1 to 4031-4 as per the latest codal provisions reaffirmed. The RCP samples have been assessed for their material residue by sieve test, soundness, and consistency exclusively employed for binder material quality. The fine aggregates and coarse aggregates as RCS and RCA, respectively, have been evaluated for their properties, namely specific gravity, water absorption, crushing value, abrasion, flakiness index and alkali reactivity.

The physical properties of the RCA of varying sizes showed that, except for the water absorption, the strength values were better than the normal aggregates. This is due to the strong adhesion of the other matrix materials to the surface of the aggregates of the CDW samples. The composition of cement and RCP is presented in Table 2. This was a crucial achievement achieved in the course of employing the recycled CDW in the production of new concrete composites. The chemical composition of RCP shows a larger content of silicon oxides. This has been reconfirmed by the X-ray diffraction analysis (EDX) of the samples of RCP, as shown in Figure 5.

The presence of silica is excessively high, which might result in the activation of alkali-silica reaction reactions in the matrix since concrete composites. This may lead to the formation of the unwanted expansion of the hydrated cementitious gel and binder constituents. Moreover, the inter-transitional zone (ITZ) may also be affected due to this phenomenon. The literature suggests similar responses where the recycled aggregates have been used to prepare and test the concrete using CDW.

This work aimed to uncover the main causes of this anticipated decrease in strength and other properties of the modified concrete with CDW constituents. This observation of the microstructural and chemical analysis of the samples of the recycled CDW provided important information regarding the loss of properties and the influence of the recycled material on the performance of the composite. This assumption has been checked in the tests on the hardened specimens with different ingredients of the mixes of the concrete.

3. Mix Design Proportions

3.1. Mix Design for Concrete Mixes

12 combinations of mixes were carried out and evaluated as a function of three replacement ratios of original material (cement, sand and aggregate) by RCP, RCS and RCA. However, the acceptance limit of the concrete was targeted at a minimum of M15; it may be worth checking the feasibility of the use of CDW in preparing lean concrete for secondary construction applications. The mix design has been carried out as per the guidelines of the IS:10262-2019 code. Table 3 shows the Percentage Composition of Concrete Mixes Incorporating Natural and Recycled Material for all 12 mixes.

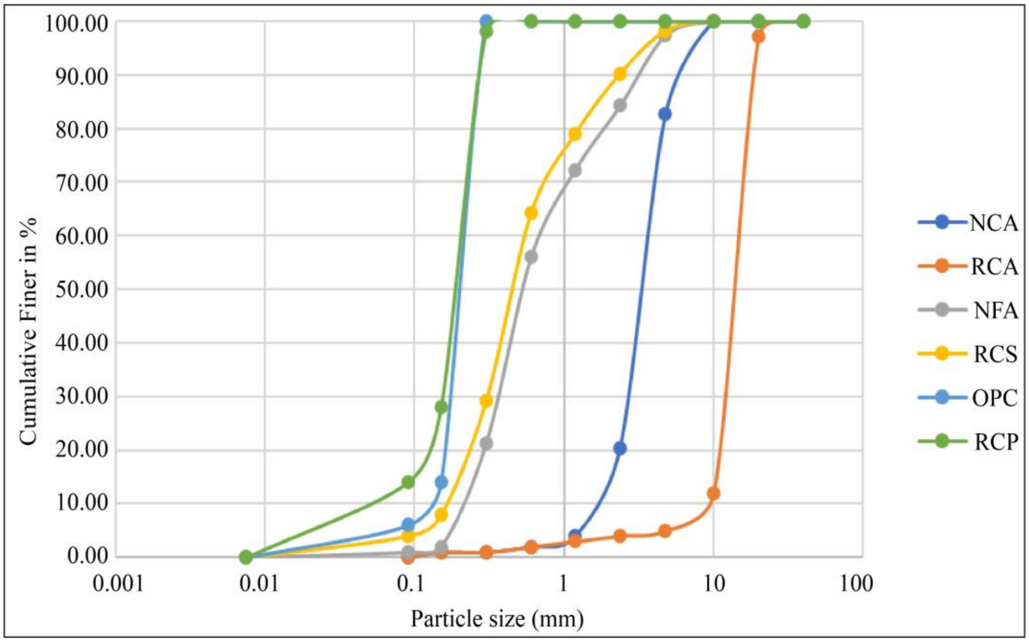


Fig. 3 Particle gradation curve

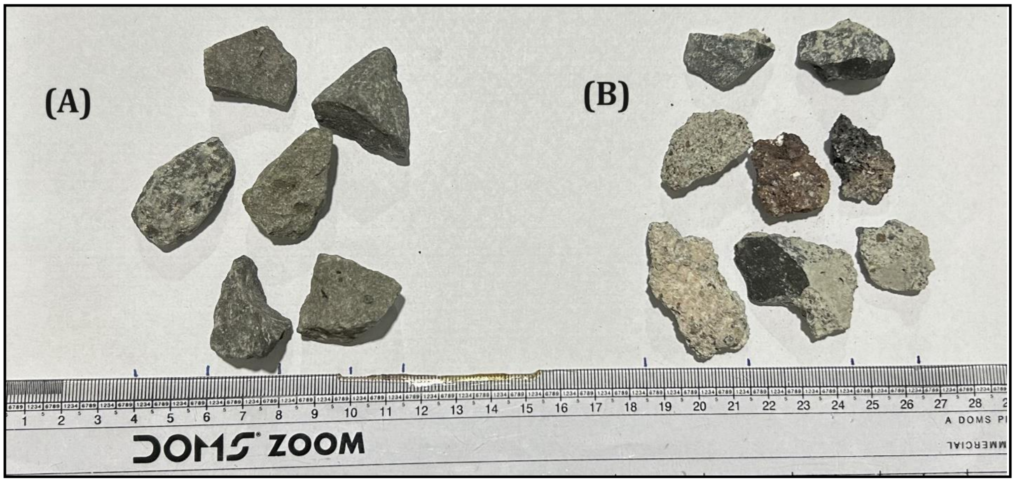


Fig. 4 A closer look at the (a) Normal aggregate, and (b) Recycled CDW aggregate.

Table 1. Physical properties of CDW ingredients and normal constituent

Property	Fine Aggregate	Coarse Aggregate	Recycled Concrete Sand	Recycled Concrete Aggregate
Specific Gravity	2.64	2.72	2.48	2.63
Aggregate Crushing Value (%)	-	17.11	-	20.54
Aggregate Impact Value (%)	-	14.44	-	24.22
Los Angeles Abrasion Value (%)	-	13.38	-	18.3
Flakiness Index (%)	-	14.60	-	19.25
Elongation Index (%)	-	17.32	-	21.7
Water Absorption (%)	1	1.01	2.8	1.68
FM	2.94	6.84	3.18	6.96
Bulk density (Kg/m^3)	1655	1590	1423	1363

For M25 grade concrete mix per 1 m³, the quantities of materials used are 373 kg cement, 736 kg fine aggregate, 1216 kg coarse aggregate, 167 kg water, and 3.73 kg superplasticizer. While working with the RCP and RCS, it was observed that both wastes increased the water demand to maintain the workability, and therefore, appropriate admixture as water reducing agent has been used. When water was added to the concrete that had been prepared as a reference or control mix, the concrete displayed appropriate workability and consistency, for example. Nevertheless, the water demand for the paste increased due to the higher content of CDW constituents, mainly RCP, from 25% to 100%.

Table 2. Chemical composition of normal cement and RCP sample

Chemical Constituent	Normal cement (%)	RCP (%)
CaO	62.01	41.33
SiO_2	20.05	39.12
$Al2O_3$	5.19	7.61
Fe_2O_3	3.41	4.10
MgO	1.82	2.61
Na_2O	0.25	1.03
SO_3	2.70	0.66
K_2O	0.61	1.45

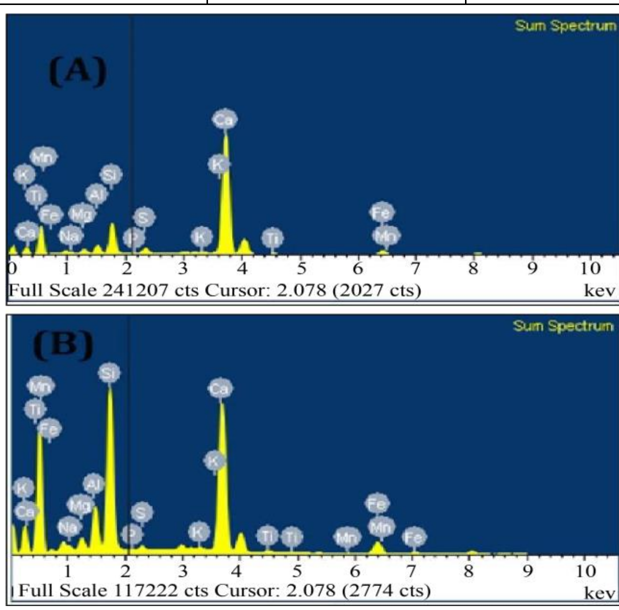


Fig. 5 EDX analysis of (a) Normal cement, and (b) RCP sample.

4. Methods of Evaluation of Properties of Mixes

4.1. Evaluation of Concrete Consisting of Recycled CDW

Ingredients The concrete prepared with varying replacement ratios from 0% to 100% for cement, sand, and aggregates with recycled CDW ingredients have been evaluated for workability, flow table value fresh density, compressive and splitting tensile strength properties as per the procedures of IS 516-2021 code. Figure 6 shows the test arrangements carried out on the concrete specimens.

The concrete cubes were water-cured for 28 days for each mixture type, namely M1 to M12. The mixes include the reference mixtures, with a 0% addition of the CDW ingredients. The experimental work focused on the generation of data and information that is essential to understanding the response and performance of the CDW ingredients in the form of concrete. Obtaining explicit information on CDW ingredients, namely RCP, RCS, and RCA, provided clarity on their usage in the synthesis of concrete composites. The responses and behavior of the CDW ingredients have been recorded, analyzed, and discussed in detail by comparing them with the characteristics of the conventional primary materials, namely cement, sand, and aggregates.

5. Results and Discussion

5.1. Freh Properties of Concrete Mixes

The workability of the concrete mixtures was checked using the slump and the flow table test. The recycled materials demand excess water owing to the high absorption tendency, as observed during the experimental work. However, to overcome the challenges, appropriate dosage and type of admixture can result in the desired workability. The tests were conducted for all 12 mixes containing varying replacements of RCP, RCS, and RCA with and without the use of admixture. The slump and flow table test outcomes are shown in Figures 7 and 8 in Table 4. The visual inspection of the fresh material provided important information on the consistency and uniformity of the mixes, as shown in Figure 9. The concrete tested on the flow table remained uniform within the center of the circle formed during the demolding process. However, the peripheral concrete showed material segregation to an extent. This led to a better suitability for lightly reinforced structural members. The concrete prepared with CDW ingredients showed more stiffness than the conventional concrete in the fresh state. With increased CDW ingredients, the mixture tends to absorb more water. However, the modified mixes, namely M2 to M12, were found to be denser than the M1 reference mixes. The particle formation of RCP supported varying particle sizes in the mix and encouraged the gap-filling within the matrix with fewer voids. This observation was also supported by the micro-structural investigation of the RCP samples. The slump result showed a steep reduction in values up to 80%, resulting in nearly zero slump conditions of the mixes with increased RCP and other CDW ingredients. Table 4 indicates the relative variation that occurred in fresh properties of recycled concrete mixes to the control mix. The findings show a constant decrement of slump and flow values with increasing use of recycled material, which provided that the material has high water absorption, an angular shape, and a rough texture. The incorporation of RCP, RCS, and RCA led to stiffer mixes with reduced flowability, highlighting the need for proper water management and admixture use. Overall, increased recycled content adversely impacts workability, confirming the importance of optimized mix design for achieving desired fresh properties.

Table 3. Percentage Composition of Concrete Mixes Incorporating Natural and Recycled Material

Mix	Cement (%)	Sand (%)	Aggregates (%)	RCP (%)	RCS (%)	RCA (%)
M1	100	100	100	0	0	0
M2	75	75	75	25	25	25
M3	50	50	50	50	50	50
M4	25	25	25	75	75	75
M5	75	75	100	25	25	0
M6	50	50	100	50	50	0
M7	25	25	100	75	75	0
M8	0	0	100	100	100	0
M9	75	100	75	25	0	25
M10	50	100	50	50	0	50
M11	25	100	25	75	0	75
M12	0	100	0	100	0	100

(a) Slump test **(b) Flow Table test** **(c) Compression test** **(d) Splitting tensile strength test**

Fig. 6 Tests on modified concrete composite with CDW ingredients

Table 4. Relative Change in Fresh and Mechanical Properties of Recycled Concrete Mixes with Reference to Control Mix

Mix	Slump Value (mm)	Flow Table Value (%)	Compressive Strength at 28 Days (N/mm^2)	Tensile Strength at 28 Days (N/mm^2)
M1	114	43.73	34.92	3.48
M2	94 (-17.54%)	39.26 (-10.22%)	28.43 (-18.59%)	2.59 (-25.57%)
M3	58 (-49.12%)	32.68 (-25.27%)	14.18 (-59.39%)	2.07 (-40.52%)
M4	22 (-80.7%)	24.39 (-44.23%)	9.56 (-72.62%)	1.44 (-58.62%)
M5	64 (-43.86%)	37.34 (-14.61%)	32.23 (-7.7%)	2.9 (-16.67%)
M6	41 (-64.04%)	33.74 (-22.84%)	19.8 (-43.3%)	2.42 (-30.46%)
M7	17 (-85.09%)	21.38 (-51.11%)	12.28 (-64.83%)	2.15 (-38.22%)
M8	6 (-94.74%)	17.22 (-60.62%)	8.28 (-76.29%)	1.36 (-60.92%)
M9	78 (-31.58%)	40.42 (-7.57%)	34.85 (-0.2%)	2.96 (-14.94%)
M10	52 (-54.39%)	38.08 (-12.92%)	14.86 (-57.45%)	2.28 (-34.48%)
M11	14 (-87.72%)	26.22 (-40.04%)	8.55 (-75.52%)	1.32 (-62.07%)
M12	4 (-96.49%)	19.23 (-56.03%)	7.56 (-78.35%)	0.65 (-81.32%)

5.2. Strength Properties of the Hardened Concrete Mixes

5.2.1. Compressive Strength

The cube specimens prepared with M1 to M12 mixes were evaluated for the compressive strength assessment. It is well established that resistance to compression for the concrete depends on the strength of aggregates and hardened binder and its adhesion with the constituents [26-28]. The hypothesis in this regard was to receive better strength from the modified concrete with CDW for a given replacement of the conventional ingredients. The reason was the presence of RCS and RCA being more uniform in particle sizes. The CDW waste materials were found capable of producing the all-in aggregate scenario for the given mixture, resulting in less voided microstructure [29]. The hypothesis was found to be fair enough while performing the strength tests. For every mix starting from M1 to M12, three cube specimens were tested at 7-28 days curing durations. The observations on the test results are in Figure 10. The strength values of modified concrete were observed to decrease as the CDW replacement ratio increased.

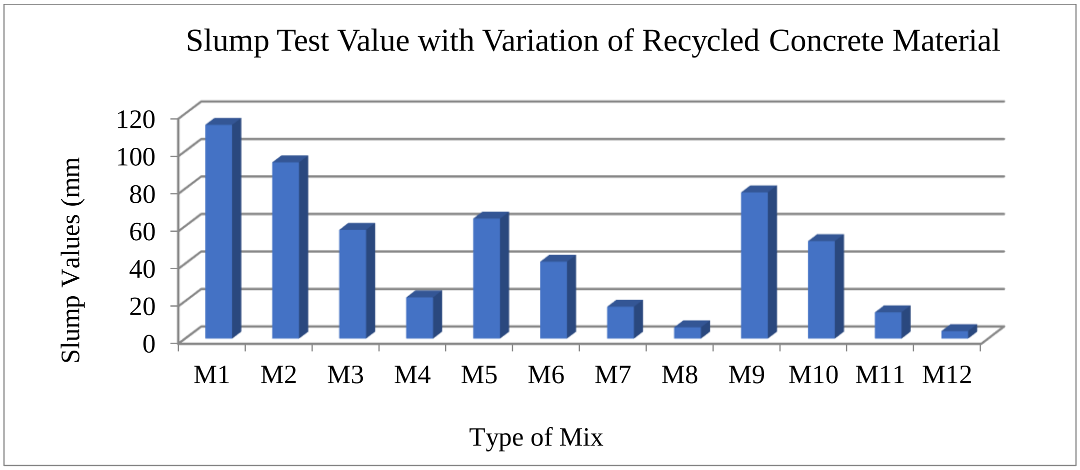


Fig. 7 Slump test results of concrete consisting of CDW wastes

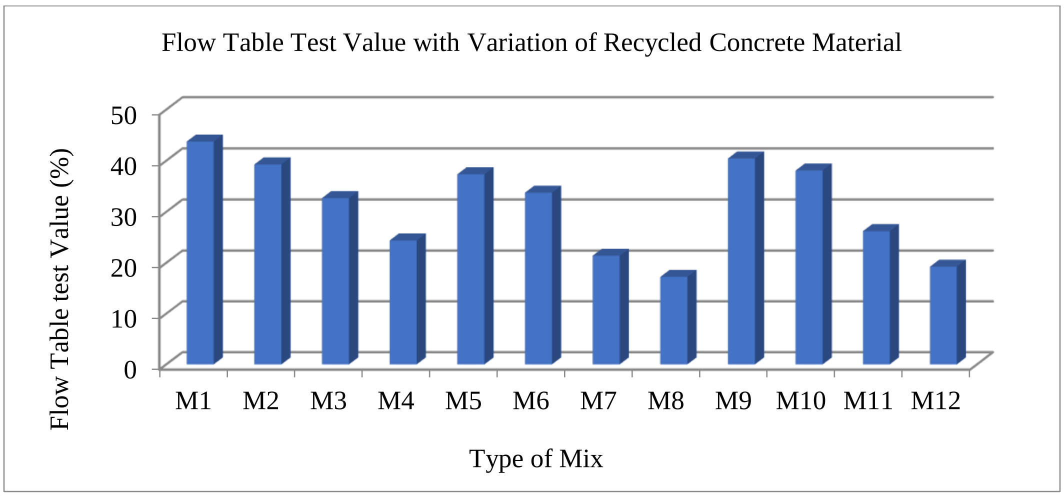
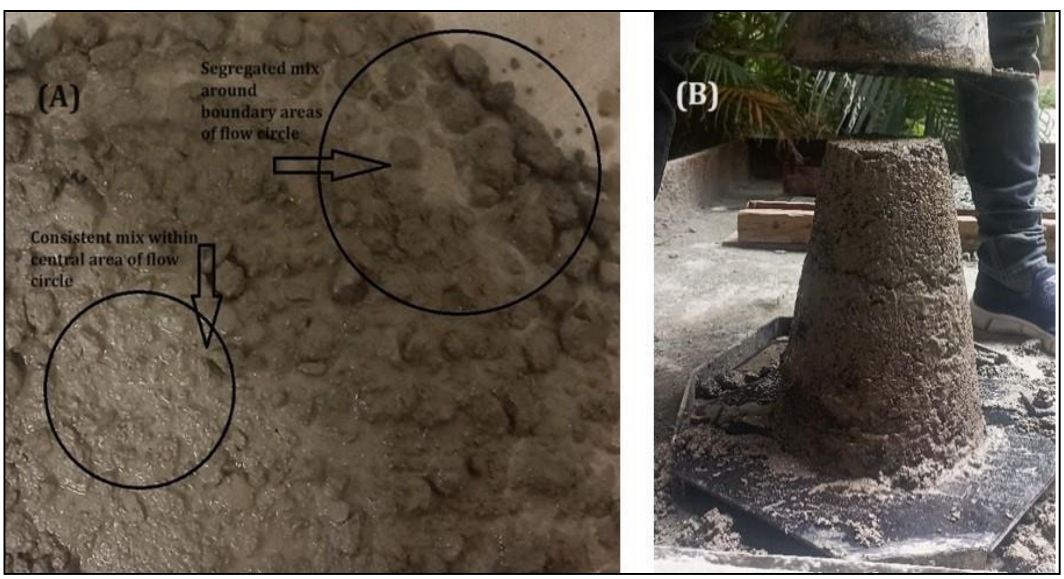


Fig. 8 Flow table test results of concrete consisting of CDW wastes



(a) Varying consistency of fresh concrete(M12) **(b) Siff concrete slump (M12)**

Fig. 9 Fresh behavior of concrete prepared with CDW ingredients

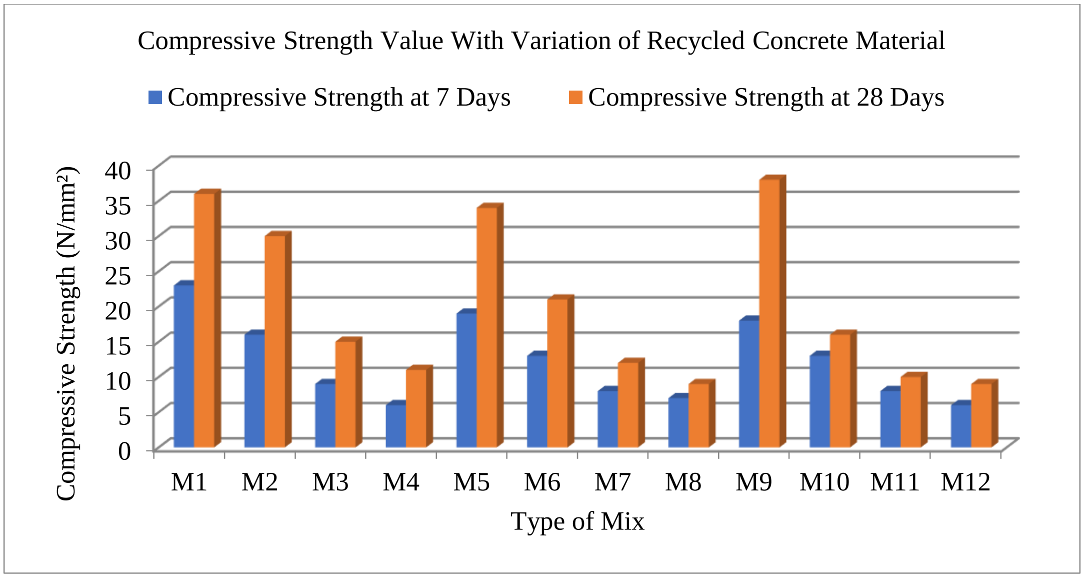


Fig. 10 Results of compressive strength test of concrete with CDW wastes

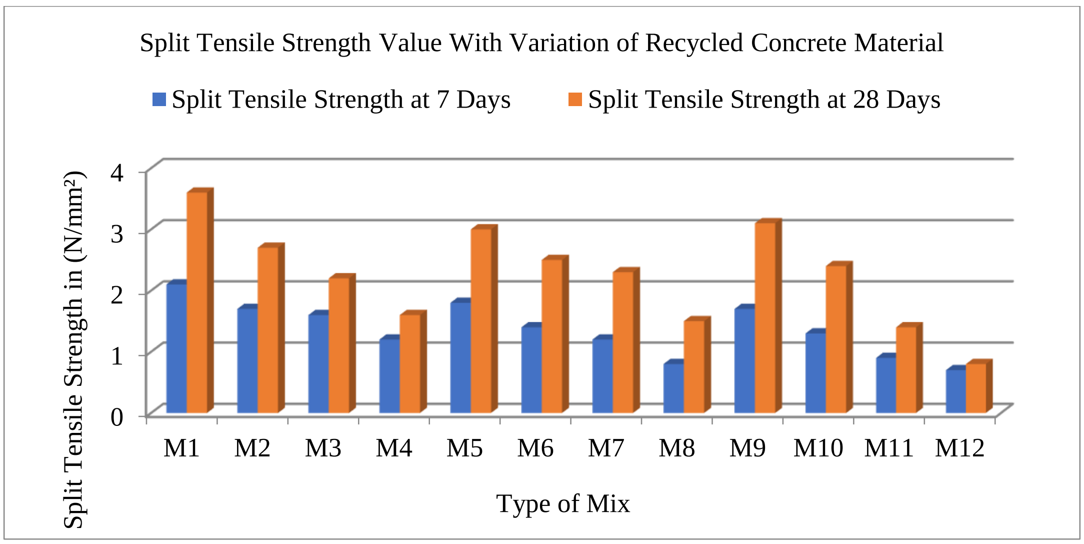


Fig. 11 Results of spit tensile strength test of concrete with CDW wastes

However, mixes M5 and M9 exhibited excellent resistance to the compressive forces as in the case of the reference mixtures. The mixes were formulated with a 25% substitution of conventional cement using RCP, alongside a complete 100% replacement of sand and aggregates with RCS and RCA. This provided an important observation that sand and aggregates may be significantly replaced by the CDW recycled as sand and aggregates. The microstructural images of natural and RCS samples reflected that the RCS consisted of non-uniform microparticles, unlike the natural sand. The altered concrete's internal void structure was thus discovered to be denser. One of the challenges of concrete is the air voids and empty spaces left by the release of the entrapped air in the matrix. This condition leads to reduced load and stress transfer with the mass. In the case of the concrete modified with the CDW, especially with respect to RCS, it showed a more coherent mixture [30]. However, the reduction of cement content and addition of RCP showed a reduction of values up to 70% linked to the reference concrete. The lowest strength value of hardened concrete in compression was measured to be 7.56 MPa at full replacement of all conventional ingredients with CDW RCP, RCS and RCA. It may be useful to note that such mixes consisting of zero natural, conventional concrete ingredients may be useful in producing lean concretes for levelling and filling purposes in construction activities. The concrete prepared with full replacement of natural ingredients with 100% replacement with CDW is suitable for plain concrete applications. However, the replacement of conventional cement, particularly by RCS up to 50%, provided strength in compression just closer to M15 grade concrete, irrespective of the replacement dosage of sand and aggregates. The sand and aggregates rendered from CDW performed better than the third form, namely recycled concrete powder, comparatively

[31]. Table 4 shows the trend of the compressive strength of the concrete. Mixes decreased with the increase in the use of natural materials with recycled CDW constituents. This reduction is primarily attributed to the reduced cementitious content and higher porosity introduced by recycled components such as RCP, RCS, and RCA. While strength loss was significant in fully replaced mixes, several mixes with partial substitution maintained compressive strength within acceptable limits, indicating the feasibility of using recycled materials up to certain thresholds. These findings establish the fact that recycled CDW is suitable for structural and non-structural application provided it is proportioned properly and aligned with the desired strength provided in the target.

5.2.2. Split Tensile Strength

Intermolecular bonding capacity, the strength of hydrated binder gel against cracking, and tension resisting capacity of the hardened concrete constituents may be evaluated by performing the Splitting tensile strength tests. The mixes modified with CDW constituents were evaluated for actions under splitting actions on the cylinder specimens. The experiments revealed important observations, namely, that the cracking patterns due to splitting actions were nearly linear in nature, resembling conventional concrete. As shown in the figure, the modified concrete has good intermolecular adhesion, though the materials were of different sizes, shapes and textures compared to the conventional concrete ingredients, namely sand, cement, and aggregate. These responses exhibited the strength mechanism of the modified concrete with CDW and established the feasibility of the use of CDW for structural concrete applications. Concrete mixes modified with CDW constituents showed acceptable performance under the splitting actions of compressive forces. Though the overall values of splitting tensile strength showed a reduction in the values as per Figure 11, and the trend showed declination, the percentage of reduction values remained within the range of 20% to 40% for the given mix. Out of all the specimens, the mixes consisting of the replacement of conventional cement with RCP between 25% to 50%, namely M2, M5, M6 and M9, showed acceptable values of splitting tensile strength. This is a similar response in the case of the specimens prepared with the replacement of the cement up to 50% tested under axial compression. The visual examination of the failed cylinder samples showed that both the RCS and RCP developed highly coherent and partially void-free microstructural mechanisms. The adhesion of the RCA and the hydrated gel was significantly uniform in the M2 and M9 specimens especially. The resistance against the splitting action indirectly manifests the internal void and cracking of the hardened concrete. For the specimens prepared with the CDW constituents, the overall concrete quality was found acceptable for the construction in secondary applications of the material. However, with the appropriate use of polymer-based chemical admixtures for inter-molecular bond enhancement, the given mixture may be upgraded for better performance in splitting actions and improved resistance to cracking. The data presented in Table 4 indicate that the tensile strength of concrete mixes exhibited a constant decline as the proportion of recycled material replacement increased. This reduction is primarily due to decreased binder integrity and increased porosity introduced by components like RCP and RCS. However, mixes incorporating up to 50% replacement demonstrated reasonably good tensile strength, indicating adequate internal bonding. These findings demonstrate the possibility of utilizing recycled materials on concrete, if adequate, provided that the mix design is well-optimized to enhance structural integrity.

6. Observations on the Recycling Process of CDW and Test Results

6.1. Recycling of CDW

CDW commonly consists of a mixture of several materials of different types and nature. One of the reasons for this is the demolition process. Common practice is to demolish the structure as a gross entity. Instead, it may be carried out stage-wise and material-wise with specific demolition tasks largely oriented towards the material type. Though it may be difficult to implement on an instant basis, with gradual practice, the objective of receiving classified and categorized waste may be obtained as the current study was concerned with the use of decomposed concrete virtually, the choice of the CDW was carefully chosen to choose and collect only the lumps of concrete sections only namely from structural members and plain cement concrete parts only. For a study on CDW, the following points may be taken care of while recycling.

- Select only the waste, which consists of concrete from structural members and plasters.
- Wash and sundry the waste before recycling to avoid excessive dust and unwanted or non-contributing materials.
- Keep control of the size of CDW raw forms. The jaw crushing should produce recycled particles in the range of 30mm to 20mm in overall size at the first stage.
- The second stage of recycling should crush the particles up to powder form. The use of a pulverizer is highly encouraged.
- It is essential to carry out preliminary tests on all samples of recycled CDW of all sizes. This stage will eventually be advantageous in making the desired concrete grade.
- Avoid sharp, extra flaky, and porous or lightweight recycled particles if the aim is to use concrete in structural applications.
- A water absorption test is the prime requirement in characterising the CDW raw materials. Such an evaluation will guide users in deciding on appropriate water-reducing chemical agents for the mixes. The dosage of such admixtures should be fixed by conducting the pilot studies.

6.2. Test Results and Behavioral Responses of the Mixes

6.2.1. Influence of RCP, RCS, and RCA on Fresh Behavior

The fresh behavior of mixes was studied for all mixtures prepared with the varying replacement ratio of conventional materials with recycled CDW ingredients. The workability and flow ability of the mixes were significantly impacted by the presence of recycled CDW Powder (RCP) and Sand (RCS). The following are the important outcomes.

The chemical analysis of RCP and RCS showed the presence of silica content more than conventional cement. This resulted in less viscous fresh matrix in concrete samples. Up to 25% and 50% replacement of cement with RCS did not adversely affect the slump and flow values; however, beyond 50% replacement of cement, the workability was reduced significantly. The RCS showed water absorption without producing chemical bonding capacity in the hydrated products. This impacted the loss of adherence within the matrix and, eventually, the strength of the hardened specimens.

Both types of recycled fine particles consisted of dust and crushed fine particles of brick residues and other impurities that were difficult to separate. This impacted the mix design quantities and proportions. Moreover, the concrete, namely M4 and M5, as well as concrete mixtures M8 and M12, performed with a low response to the fresh and hardened concrete Compared to traditional concrete mixtures. The RCA particles did not affect the overall concrete response in a fresh state. However, the loss of stiffness of the fresh mix was observed owing to the excess water absorption by the RCA particles. The thin films of hardened mortars and hydrated gel absorbed extra water compared to the normal aggregates. This response suggested a ball milling process for the RCA before use. The ball milling process removes most of the laminated impurities from the surfaces of the aggregates.

6.2.2. Impact of RCP, RCS, and RCA on Strength Properties

Specimens, namely cubes and cylinders, were prepared and evaluated for strength measurement for all concrete mixes. The strength in compression and splitting action in the concrete case showed a decline in the range of 20% to 60% for a given mix design. The following points were observed during the experimental studies. The RCA resembled conventional aggregates during the specimens' resistance to axial compression and splitting actions. The concrete specimens showed linear cracking under sustained loading conditions. Although the bonding capacity of bound material in a hydrated state has a straight effect on the resistance capacity of a concrete specimen, the failure patterns stem from the void structure, microstructural cracks and inert material dispersion in the mixture.

On the other hand, the surface of the RCA was occupied by the hardened mortars, as observed during the recycling process. The presence of such products indirectly contributed to better inter-molecular bonding of the gel with the constituents. An important observation on the recycling method can be related to this response. The RCA was developed using a jaw crusher and ball mill for CDW lumps. The Ball milling provided a cleaner and smoother surface of RCA compared to the Jaw Crusher. Therefore, the choice of recycling should be made based on the performance requirements of the mixture.

RCS performed nearly like natural or conventional sand in concrete mixes. The microstructural investigations suggested more silica content in the RCS samples. The availability of silica in the mortar and concrete contributes to a better strength-gaining mechanism, filling the air voids and improving the hydration process of the binder gel. However, the silica component possessed by the RCS samples was not freely available to interact with water for chemical processing. This led to a decline in the strength of concrete specimens, but the reduction was insignificant, up to the replacement ratio of 50% with the natural sand in the mixes. Even the mixes and concrete prepared with full replacement of the natural sand sustained 50% of the strength as that of the control mixes.

Strength properties in varying fractions in concrete mixes decreased when cement was replaced with RCP. The cumulative effect of higher water absorption by RCP, reduced cement content, thereby reducing inter-molecular bonding, and the development of useful ettringite for early strengthening contributed to this behavior. However, the strength reduction was recorded up to 40% in concrete. Moreover, the appropriate use of chemical admixtures may improve such deficiencies in the mixes. The concrete mixes, namely M5 and M9, showed relatively improved strength when compared to the other mixes prepared without the use of admixtures. Nevertheless, it may be summarized that the concrete prepared with recycled materials can be used for non-structural applications with full replacement of all the natural ingredients.

The overall observations of the recycling process, characterization and experimental evaluation of concrete consisting of the CDW ingredients in various forms, namely RCP, RCS and RCA, revealed that with an appropriate mix design and according to the intended purpose of the use, the CDW can be effectively utilized in construction applications.

7. Conclusion

Three phases of studies on the use of CDW in construction have been explored, and three possible recycled forms have been obtained from the present study. The investigations revealed the following important attributes of using CDW in varying recycled forms.

The CDW should be selected strategically, consisting of concrete and, to an extent, bricks and plaster wastes. It is possible to pre-process the CDW into different forms suitable for the replacement of all three major forms of concrete-making materials, namely cement, sand, and aggregates. The devices, namely Jaw crushers and Abrasion Ball mills, can provide satisfactory output without significant loss of the material during and after processing, except the Pulverizer machine. However, any desired standard particle size is possible to obtain using the appropriate recycling method.

Compared to the Jaw crusher, the ball milling by the Abrasion mechanism provides better results in the form of useful recycled CDW materials for aggregates. The metal charge of the abrasive machine effectively removes the hydrated cement gel from the surfaces of the aggregates of the CDW, and a simple washing can further enhance the quality of the RCA.

The partial replacement of RCP and RCS up to 50% of the natural cement and sand, respectively, could prove strength up to 40% of the control mixes. The complete substitution of cement and sand with RCP and RCS correspondingly markedly diminished the strength; however, the concrete prepared can be utilized in non-structural applications. The particle size comparison and the microstructural investigations of the RCP and RCS samples revealed that the recycled material can contribute to the micro-voids effectively. Though the water absorption is comparatively more in such cases, the same can be controlled using admixtures. The CDW can be recycled into powder, sand and aggregate forms and can contribute to the making of new concrete. Up to 50% replacement of cement, 75% of natural sand and natural aggregates can be replaced in concrete mixes to obtain satisfactory results. However, appropriate admixtures should be used to maintain fresh behavior, strength-gaining mechanism and hardened strength properties. Including RCP and RCS contributes to the improved microstructure of the concrete mixes and reduces micro-cracks and micro-air-voids.

This area presents meaningful opportunities for further research, particularly in understanding the durability and permeability characteristics of the mixes. As this study was carried out under controlled laboratory conditions, future investigations could explore how recycled CDW materials perform over the long term when exposed to real-world environmental factors, field curing conditions, and larger-scale applications. This will also help to reinforce the practical use of recycled CDW in sustainable construction endeavors by analyzing how regional material variations and construction practices affect performance.

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