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MECHANICAL PERFORMANCE AND WATER ABSORPTION CHARACTERISTICS OF CEMENT MORTARS INCORPORATING RECYCLED CONCRETE WASTE POWDER AS CEMENT PASTE REPLACEMENT

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Abstract: *The rapid growth of construction and demolition (C&D) waste and the increasing environmental impact associated with cement production have intensified the need for sustainable alternatives in cement-based materials. This study investigates the feasibility of utilizing recycled concrete waste powder (RCWP) as a partial cement paste replacement in MM4 grade cement mortar. Mortar mixtures containing RCWP at replacement levels of 5–50% were prepared with water–cement ratios of 0.70, 0.80, and 0.90. The fresh and hardened properties of the mortars were evaluated through flow table, cone penetration, and compressive strength tests at curing ages of 7, 14, 28, 56, and 90 days. The influence of RCWP on durability was further examined through water absorption analysis. The experimental results showed that the incorporation of RCWP progressively reduced mortar workability because of its higher specific surface area and water absorption characteristics. Nevertheless, moderate replacement levels enhanced the mechanical performance of the mortar. The optimum performance was obtained at 15% RCWP replacement with a water–cement ratio of 0.70, achieving a 28-day compressive strength of 23.43 MPa, which further increased to 24.01 MPa after 90 days. Replacement levels exceeding 25% resulted in a gradual reduction in compressive strength owing to the cement dilution effect and increased pore connectivity. The overall trends indicate an inverse relationship between compressive strength and water absorption, highlighting the role of pore refinement in improving mortar performance. The findings demonstrate that recycled concrete waste powder can be effectively utilized as a sustainable cement paste replacement in masonry mortar at moderate replacement levels. The proposed optimum mix provides a balance between workability, mechanical performance, and durability while contributing to reduced cement consumption, effective utilization of construction waste, and the promotion of environmentally sustainable construction practices.*

Keywords: *Recycled concrete waste powder; Cement mortar; Cement paste replacement; Compressive strength; Workability; Sustainable construction.*

1. Introduction

The rapid expansion of urban development and infrastructure activities has led to a substantial increase in construction and demolition (C&D) waste generation. Concrete constitutes a major fraction of this waste stream, particularly from the demolition of buildings, pavements, and other structural components. In many cases, demolished concrete is either disposed of in landfills or used as low-value filling material, resulting in the inefficient utilization of resources and increased environmental burden. Therefore, the recycling of concrete waste into value-added construction materials has gained significant attention in recent years [1], [2], [3].

Ordinary Portland cement (OPC) is one of the principal binding materials used in mortar and concrete; however, its production involves considerable energy consumption and carbon dioxide emissions. The cement sector remains a major source of industrial CO_2 emissions, primarily due to clinker production and limestone calcination processes[4]. Consequently, partial replacement of cementitious constituents with recycled materials has become an important approach for reducing the environmental impact of cement-based construction materials.

Recycled concrete waste powder (RCWP), produced by crushing and grinding demolished concrete, consists of residual hydrated cement paste, partially hydrated cement particles, fine aggregate particles, and mineral phases originating from the parent concrete. Depending on its particle size distribution, source characteristics, and replacement level, RCWP may influence the packing density, hydration process, pore structure, and mechanical performance of cementitious composites [1], [2], [5]. The presence of fine particles in recycled concrete powder may provide a filler effect and act as nucleation sites for the formation of hydration products. However, higher replacement levels may also reduce the available cement content and increase the porosity of the matrix, thereby affecting strength and durability performance.

Several researchers have investigated the use of recycled concrete powder in cement-based composites. Horsakulthai [3] evaluated recycled concrete powder as a partial replacement for ordinary Portland cement in self-compacting mortar and reported that the compressive strength decreased with increasing recycled concrete powder content. The study also observed an increase in water absorption and porosity at higher replacement levels. Similarly, Gao et al.[1] reported that the incorporation of recycled concrete powder influenced the mechanical and durability properties of recycled mortar, with strength reduction becoming more pronounced at increased replacement levels. Jiang et al. [2] investigated the role of recycled concrete powder as a fine material in cement mortar and highlighted that particle characteristics and replacement proportion significantly affect mortar workability, strength development, and pore structure.

The workability of mortar is an important parameter because it influences mixing, placing, finishing, and bonding behaviour in masonry applications. RCWP may alter workability due to its fine particle size, irregular shape, residual cement paste, and relatively higher water demand. Previous studies have generally reported reductions in mortar flowability with increasing recycled concrete powder content [6], [7]. However, most investigations have assessed workability using a single test method. In mortar applications, both flow table and cone penetration tests are commonly used to evaluate consistency and fresh-state behaviour. Therefore, a comparative assessment using both methods can provide a more reliable understanding of the influence of recycled concrete waste powder on mortar workability.

The compressive strength of cement mortar containing recycled concrete powder is influenced by several factors, including replacement level, fineness of the powder, water–cement ratio, curing duration, and the composition of the parent concrete. Low replacement levels may maintain satisfactory strength due to improved particle packing and filler effects. However, excessive replacement may result in strength reduction because of cement dilution and increased pore volume[7], [8]. Zhang et al.[1] reported that recycled concrete powder content below 10% had a limited effect on the compressive strength of cement mortar, whereas higher replacement levels resulted in more noticeable strength reduction.

Water absorption is an important durability-related property of mortar because it reflects the pore structure and permeability characteristics of the hardened matrix. The incorporation of RCWP may either refine the pore structure at low replacement levels (RL) or increase water absorption at higher replacement levels due to the porous nature of residual cement paste particles [1], [9]. Hence, the combined evaluation of workability, compressive strength, and water absorption is essential to identify suitable replacement levels for practical mortar applications.

Although previous studies have examined RCWP in cementitious materials, limited information is available regarding its application as a cement paste replacement material in masonry-grade mortars prepared at higher water–cement ratios. In addition, there is limited research comparing flow table and cone penetration measurements for evaluating the consistency of mortars containing RCWP. Therefore, the present study investigates the feasibility of using recycled concrete waste powder as a partial cement paste replacement material in MM4 grade cement mortar.

The study evaluates the effect of RCWP on mortar workability through flow table and cone penetration tests. The hardened properties are assessed through compressive strength and water absorption measurements. The objective is to identify suitable RL that satisfy the strength requirements of MM4 grade mortar while promoting the beneficial utilization of recycled concrete waste in sustainable construction applications.

2. Literature Review

The recycling of C&D waste has become an important research area due to increasing environmental concerns, depletion of natural resources, and the growing demand for sustainable construction materials. Among various recycled materials, RCWP has received considerable attention because it can be processed into fine particles and utilized as a partial replacement for cementitious constituents in mortar and concrete. The use of RCWP not only reduces landfill disposal but also minimizes the consumption of virgin raw materials and lowers the environmental impact associated with cement production[10], [11].

Previous investigations have demonstrated that the physical characteristics of recycled concrete powder, including particle size distribution, fineness, residual cement paste content, and mineralogical composition, play a significant role in determining its performance in cementitious systems. Fine recycled concrete particles improve particle packing and may provide additional nucleation sites for hydration products, resulting in a denser microstructure at lower replacement levels. However, excessive incorporation generally leads to cement dilution, increased porosity, and deterioration of mechanical properties [12], [13].

Several researchers have evaluated the influence of recycled concrete powder on the fresh properties of mortar. Horsakulthai [3] reported that increasing the recycled concrete powder content reduced mortar flow because of the higher water demand associated with recycled particles. Jiang et al. [2] similarly observed that the irregular particle morphology and residual hydrated cement paste significantly affected mortar consistency. Comparable findings have also been reported by Gao et al. [1], who attributed the reduction in workability to the porous nature and greater specific surface area of recycled powders. Although these studies provide valuable information, most investigations have relied on a single workability assessment method. Comparative evaluation using both flow table and cone penetration tests remains limited, particularly for masonry mortars.

The effect of RCWP on compressive strength has also been widely investigated. Low RL generally maintain satisfactory strength because of the filler effect and improved particle packing, whereas higher RL reduce strength due to the lower availability of reactive cement

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and the increased volume of porous recycled particles. Horsakulthai [3] reported that mortar containing RCWP exhibited a gradual reduction in compressive strength with increasing replacement percentage, although lower RL remained suitable for practical applications. Gao et al. [1] observed similar behaviour in recycled mortars and concluded that optimum RL should be selected to balance sustainability and mechanical performance. Zhang et al.[10] further reported that replacement levels below approximately 10–15% had only a limited influence on compressive strength, while higher dosages produced more significant reductions.

Durability performance has become an equally important consideration in evaluating recycled cementitious materials. Water absorption is commonly used as an indicator of pore structure and permeability, which directly influence the long-term performance of mortar. Previous studies have shown that finely ground RCWP can improve matrix densification at lower RL through the filler effect, thereby reducing water transport. However, at higher RL, the porous residual cement paste associated with RCWP tends to increase capillary porosity and water absorption [1], [3]. These observations indicate that the durability of recycled mortars depends strongly on the RL and the characteristics of the RCWP.

Although substantial research has been carried out on recycled concrete aggregates and RCWP in structural concrete, comparatively fewer studies have focused on masonry-grade cement mortars. Furthermore, many published investigations have employed relatively low water–cement ratios (W/C) and have primarily evaluated compressive strength. Limited information is available regarding the combined assessment of workability through both flow table and cone penetration methods together with compressive strength and water absorption for mortars prepared at higher W/C. Such information is important because masonry mortars require adequate consistency for placement while simultaneously satisfying the prescribed strength and durability requirements.

Based on the existing literature, it is evident that RCWP possesses considerable potential as a sustainable cementitious material. However, further experimental studies are required to establish suitable RL for masonry mortars and to understand the relationship between fresh properties, mechanical performance, and durability under practical mix conditions.

Research Gap

A critical review of the published literature reveals the following research gaps:

- Most previous studies have focused on recycled concrete aggregates rather than recycled concrete waste powder used as a cement paste replacement.
- Limited investigations have examined RCWP in MM4 grade masonry mortar, where higher water–cement ratios are commonly adopted.
- The majority of published studies evaluate workability using only one consistency test, whereas a comparative assessment using both flow table and cone penetration tests has rarely been reported.
- Few studies simultaneously correlate fresh properties, compressive strength, and water absorption to identify practical replacement levels suitable for masonry applications.

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- Experimental evidence supporting the utilization of RCWP as a sustainable cement paste replacement material for masonry mortar remains limited.

Accordingly, the present study investigates the influence of RCWP on the workability, compressive strength, and water absorption characteristics of MM4 grade cement mortar prepared at higher W/C. The study aims to establish the feasibility of RCWP as a sustainable cement paste replacement material while satisfying the engineering requirements of masonry mortar.

3. Materials and Methods

3.1 Materials

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 [14]was used as the primary binding material throughout the investigation. The cement possessed a specific gravity of 3.15 and satisfied the physical and mechanical requirements specified in the relevant Indian Standards. Manufactured sand (M-sand) conforming to Zone II grading as per IS 383:2016 was used as the fine aggregate. The sand was free from organic impurities and was maintained in a saturated surface dry (SSD) condition prior to mixing.

RCWP was obtained from demolished concrete collected from local construction and demolition sites. The demolished concrete was manually cleaned to remove impurities such as steel reinforcement, wood fragments, plaster, bricks, and other foreign materials. The cleaned concrete was crushed using a laboratory jaw crusher and subsequently ground in a ball mill until the desired fineness was achieved. The ground material was sieved through a 75 µm sieve to obtain a uniformly fine powder suitable for use as a partial cement paste replacement.

The physical properties of OPC and RCWP were determined in accordance with relevant Indian Standards. The RCWP exhibited a lower specific gravity than cement because of the presence of residual hydrated cement paste and fine aggregate particles. The finer particle size of RCWP contributes to improved particle packing while also increasing water demand because of its larger specific surface area.

The chemical composition of recycled concrete waste powder primarily consisted of silica (SiO_2), calcium oxide (CaO), alumina (Al_2O_3), and ferric oxide (Fe_2O_3), originating from the parent concrete and residual cement paste.

Table 1. Physical properties of cement and recycled concrete waste powder

Property	OPC	RCWP
Specific gravity	3.15	2.51
Blaine fineness (m^2/kg)	318	156
Particles passing 75 µm (%)	-	66.42
Water absorption (%)	—	1.2

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3.2 Mix Proportions

Mortar specimens were prepared using a cement-to-sand ratio of 1:4 corresponding to MM4 grade mortar. RCWP was incorporated as a partial replacement for cement paste at different RL to evaluate its influence on mortar performance.

The RL considered in the investigation were 0, 5, 10, 15, 20, 25, 30, 40, and 50% by weight of cement paste. The W/C was selected based on the workability requirements of masonry mortar. A control mix without recycled concrete powder was prepared for comparison.

Table 2. Mortar mix proportions

MIX ID	RCWP REPLACEMENT (%)	CEMENT (KG)	RCWP (KG)	SAND (KG)	WATER–CEMENT RATIO*
CM	0	1.00	0.00	4.00	0.70
RC5	5	0.95	0.05	4.00	0.70
RC10	10	0.90	0.10	4.00	0.70
RC15	15	0.85	0.15	4.00	0.70
RC20	20	0.80	0.20	4.00	0.70
RC25	25	0.75	0.25	4.00	0.70
RC30	30	0.70	0.30	4.00	0.70
RC40	40	0.60	0.40	4.00	0.70
RC50	50	0.50	0.50	4.00	0.70

3.3 Preparation of Mortar Specimens

The dry materials, comprising cement, RCWP, and M-sand, were first mixed until a uniform colour was obtained. Water was then gradually added while mixing continued to produce a homogeneous mortar. Fresh mortar was immediately tested for workability using the flow table and cone penetration methods.

Cube specimens of dimensions 50 × 50 × 50 mm were cast for compressive strength determination. The specimens were compacted in two layers and finished with a steel trowel. After casting, all specimens were covered to prevent moisture loss and demoulded after 24 h. Subsequently, the specimens were cured in potable water until the specified testing ages of 7, 14, and 28 days. Separate specimens were prepared for the water absorption test after completion of the curing period.

3.4 Experimental Programme

The experimental programme consisted of evaluating both fresh and hardened properties of mortar containing RCWP. The experimental sequence adopted in the study includes:

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Fresh Properties

- Flow table test
- Cone penetration test

Hardened Properties

- Compressive strength
- Water absorption

3.5 Workability Tests

3.5.1 Flow Table Test

The workability of fresh mortar was evaluated using the flow table apparatus in accordance with IS 2250:1981 [15]. Fresh mortar was placed inside the standard mould located at the centre of the flow table and compacted uniformly. After lifting the mould, the table was dropped 25 times within approximately 15 s. The average diameter of the spread mortar was measured along two perpendicular directions, and the average flow value was recorded.

3.5.2 Cone Penetration Test

The consistency of fresh mortar was further evaluated using the cone penetration apparatus in accordance with IS 2250:1981[15]. The penetration depth of the standard cone into freshly prepared mortar was measured immediately after mixing. The average penetration value obtained from repeated measurements was reported for each mix.

3.6 Compressive Strength Test

Compressive strength was determined using 50 mm mortar cubes following the procedures specified in IS 4031 (Part 6):1988 [16]. The specimens were tested after curing periods of 7, 14, and 28 days using a calibrated compression testing machine. The maximum failure load was recorded, and the compressive strength was calculated as the ratio of the ultimate load to the loaded area. The reported values represent the average of three specimens.

3.7 Water Absorption Test

Water absorption was determined after 28 days of curing following the procedure specified in ASTM C642. The specimens were oven dried to constant mass at 105 ± 5°C and allowed to cool to room temperature before recording the dry mass. Subsequently, the specimens were immersed in water for 24 h, surface dried using a damp cloth, and weighed again. Water absorption was calculated as the percentage increase in mass relative to the oven-dry mass. The test provides an indirect measure of the pore structure and permeability of the mortar and was used to evaluate the influence of recycled concrete waste powder on durability performance.

4. Results and Discussion

4.1 Workability Characteristics of Mortar Incorporating Recycled Concrete Waste Powder

The workability of mortar is a critical property that governs its ease of mixing, transportation, placement, and finishing during masonry construction. In the present study, the workability of

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fresh mortar was evaluated using the flow table test and cone penetration test in accordance with IS 2250:1981. These two methods provide complementary information regarding the consistency and plasticity of fresh mortar. While the flow table test measures the deformation characteristics of mortar under dynamic loading, the cone penetration test evaluates its resistance to penetration under static conditions. The combined use of both tests provides a comprehensive assessment of the influence of RCWP on fresh mortar behaviour.

The experimental results obtained for different RL and W/C are summarized in Table 3, while the variations in flow value and cone penetration are presented in Figures 2 and 3, respectively.

Table 3. Workability characteristics of mortar containing recycled concrete waste powder

W/C RATIO	RCWP (%)	FLOW VALUE (MM)	CONE PENETRATION (MM)
0.70	5	121	17.0
	10	119	15.0
	15	115	14.5
	20	112	11.0
	25	109	9.5
	30	106	8.0
	40	104	7.5
	50	101	6.0
0.80	5	124	28.0
	10	123	20.0
	15	121	15.0
	20	115	13.0
	25	110	11.0
	30	108	10.5
	40	106	9.0
	50	105	7.0
0.90	5	128	26.0
	10	121	20.0
	15	119	19.0
	20	112	15.0
	25	110	12.0
	30	108	11.0
	40	105	9.0
	50	104	9.0

4.1.1 Flow Table Test

Figure 2 illustrates the variation in flow value of mortar incorporating RCWP at different W/C. Irrespective of the W/C, the flow value exhibited a gradual decline with increasing RCWP replacement. At a W/C of 0.70, the flow value decreased from 121 mm at 5% replacement to 101 mm at 50% replacement, corresponding to an overall reduction of approximately 16.5%. Similar reductions of 15.3% and 18.8% were observed for W/C of 0.80 and 0.90, respectively.

The reduction in flowability is primarily attributed to the physical characteristics of RCWP. The RCWP particles possess an irregular and angular morphology together with a relatively high specific surface area, which increases the water demand of the mortar. In addition, the

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presence of residual hydrated cement paste attached to recycled particles contributes to greater water absorption during mixing. Consequently, a smaller quantity of free water remains available for lubrication between particles, leading to reduced mortar mobility and lower flow values.

Although workability decreased progressively with increasing RCWP content, the reduction was relatively small up to 15–20% replacement, indicating that the mortar retained adequate consistency for practical masonry applications. At these lower replacement levels, the fine RCWP particles contributed to improved particle packing, partially compensating for the increased water demand. Beyond 25% replacement, the reduction became more pronounced, suggesting that the filler effect was outweighed by the dilution of cementitious material and the higher water absorption capacity of recycled particles.

The influence of the W/C was also evident. Increasing the W/C from 0.70 to 0.90 improved the overall flow values because additional mixing water enhanced particle lubrication and reduced interparticle friction. However, even at higher W/C, increasing RCWP content consistently reduced mortar workability, indicating that RL remained the dominant factor governing fresh mortar consistency.

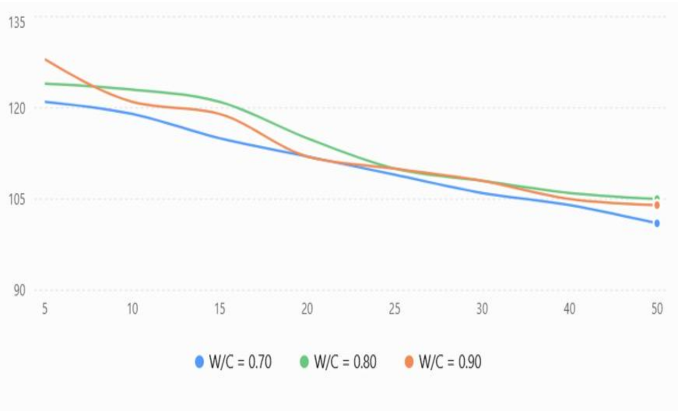

Figure 2. Variation of flow value with RCWP replacement at different water–cement ratios

These findings are consistent with the observations reported by Horsakulthai (2021), Jiang et al. (2022), and Gao et al. (2022), who reported that finely ground RCWP decreases mortar flow because of its porous texture, irregular particle shape, and increased specific surface area. Similar reductions in workability have also been reported for recycled cementitious materials containing construction and demolition waste powder, where the higher water demand of recycled particles was identified as the principal cause of reduced flowability.

Overall, the results demonstrate that recycled concrete waste powder can be incorporated up to approximately 20% replacement without significantly affecting the workability requirements of MM4 grade masonry mortar. Beyond this level, additional water or the use of chemical admixtures may be required to maintain the desired consistency.

4.1.2 Cone Penetration Test

The cone penetration results presented in Figure 3 exhibited trends similar to those observed in the flow table test. For all W/C, the penetration depth decreased progressively with increasing RCWP replacement, indicating an increase in mortar consistency and resistance to penetration.

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At a water–cement ratio of 0.70, the cone penetration reduced from 17 mm at 5% replacement to 6 mm at 50% replacement, representing a reduction of approximately 65%. Similar reductions were observed for the W/C of 0.80 and 0.90, confirming that increasing RCWP content consistently increased mortar stiffness irrespective of the water content.

The reduction in cone penetration can be explained by the increased internal friction generated by the angular RCWP particles and their greater water absorption capacity. The fine recycled particles absorb part of the mixing water and reduce the thickness of the lubricating water film surrounding the particles, thereby increasing the resistance of the mortar to cone penetration. Furthermore, the residual hydrated cement paste associated with recycled concrete particles contributes to increased surface roughness, further restricting particle movement during penetration.

A comparison between Figures 2 and 3 indicates excellent agreement between the two workability assessment methods. Both the flow table and cone penetration tests demonstrated that increasing RCWP content progressively reduced mortar workability. While the flow table test measures the dynamic deformation characteristics of mortar, the cone penetration test reflects its static consistency. The consistent trends obtained from both methods indicate that either test can effectively characterize the influence of recycled concrete waste powder on fresh mortar behaviour. However, the combined application of both methods provides a more comprehensive evaluation of mortar consistency and improves confidence in the experimental observations.

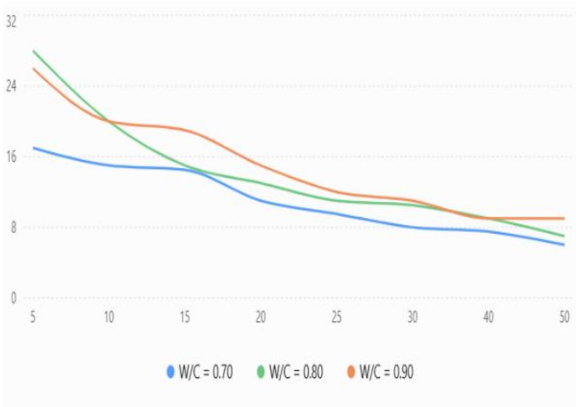

Figure 3. Variation of cone penetration with RCWP replacement at different W/C

The results further indicate that mortars prepared with replacement levels up to 20% exhibited satisfactory consistency for masonry applications, whereas higher replacement levels produced comparatively stiffer mixes that may require additional water or suitable plasticizing admixtures to achieve acceptable workability.

The fresh-state behaviour of mortars containing recycled concrete waste powder is governed primarily by the balance between the particle packing effect and the water demand of recycled particles. At lower RL, the fine RCWP particles improve packing density and maintain acceptable workability. As the RL increases, the higher specific surface area, porous residual cement paste, and angular particle morphology increase water demand and internal friction, resulting in reduced flow values and cone penetration depths. The close agreement between the two workability tests confirms the reliability of the experimental results and demonstrates that

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RCWP can be successfully incorporated in MM4 grade mortar up to approximately 20% replacement without adversely affecting fresh mortar performance.

4.2 Compressive Strength of Mortar Incorporating Recycled Concrete Waste Powder

Compressive strength is the most important mechanical property of cement mortar, as it directly governs its load-bearing capacity and long-term structural performance. The compressive strength of mortar specimens containing RCWP as a partial cement paste replacement was determined after 7, 14, 28, 56, and 90 days of water curing. The results obtained at different RL and W/C are illustrated in Figures 4–7.

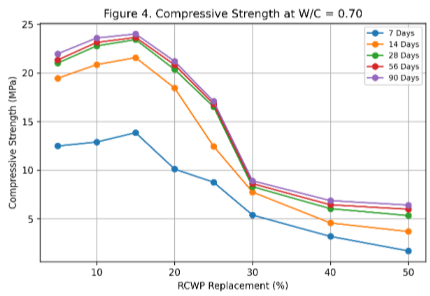

Figure 4 Compressive Strength Development of RCWP Mortar at W/C = 0.70

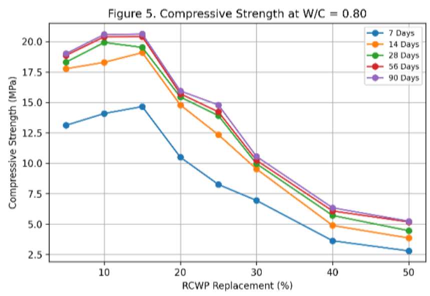

Figure 5 Compressive Strength Development of RCWP Mortar at W/C = 0.80

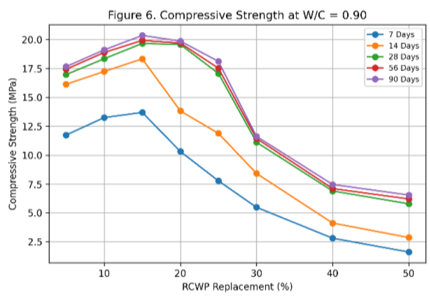

Figure 6 Compressive Strength Development of RCWP Mortar at W/C = 0.90

4.2.1 Effect of RCWP Replacement on Strength Development

Figures 4–6 show that the compressive strength of all mortar mixtures increased continuously with curing age, irrespective of the RL or W/C. The progressive increase in strength from 7 to 90 days confirms the continued hydration of cement and the gradual densification of the

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cementitious matrix. However, the magnitude of strength development was significantly influenced by the proportion of RCWP incorporated into the mortar.

At a W/C ratio of 0.70, the compressive strength increased from 12.49 MPa at 7 days to 21.97 MPa at 90 days for the 5% RCWP mixture, whereas the 15% RL exhibited the highest strength throughout the curing period, reaching 23.43 MPa at 28 days and 24.01 MPa after 90 days. Compared with the 5% mixture, the 15% RCWP mortar exhibited an increase of approximately 11.5% in 28-day compressive strength. This improvement indicates that a moderate incorporation of finely ground RCWP contributes positively to the mechanical performance of mortar.

The improvement observed at lower replacement levels can primarily be attributed to the micro-filler effect of RCWP. The fine particles effectively occupy the voids between cement grains and fine aggregates, producing a denser particle packing arrangement and reducing the volume of capillary pores. This refined microstructure promotes more efficient stress transfer within the hardened matrix, resulting in higher compressive strength. In addition, the fine recycled particles provide numerous nucleation sites that accelerate the precipitation of hydration products, particularly calcium silicate hydrate (C–S–H) gel, during the early stages of curing. Consequently, mortars containing approximately 10–15% RCWP exhibit slightly higher strengths than those prepared with lower RL.

4.2.2 Influence of Higher Replacement Levels

Beyond the optimum, a progressive reduction in compressive strength was observed for all curing ages. At 25% RCWP, the 28-day compressive strength decreased to 16.52 MPa, while further increasing the RL to 50% reduced the strength to only 5.33 MPa. Similar trends were observed for the 56- and 90-day curing periods.

The reduction in compressive strength at higher RL is primarily associated with the cement dilution effect. Since RCWP is considerably less reactive than Portland cement, increasing its proportion decreases the quantity of clinker minerals available for hydration. The reduction in cementitious material consequently limits the formation of hydration products responsible for strength development. Moreover, recycled concrete particles generally possess irregular morphology and higher porosity than cement particles, leading to increased water absorption during mixing. The reduction in free water available for hydration further contributes to incomplete cement hydration and a more porous hardened microstructure.

At RL of 30–50%, the reduction in compressive strength became particularly significant, indicating that the beneficial filler effect was insufficient to compensate for the loss of cementitious material. The pronounced reduction observed at these higher RL suggests that excessive incorporation of RCWP adversely affects matrix continuity and increases the proportion of interconnected pores, resulting in lower mechanical resistance.

4.2.3 Effect of Water–Cement Ratio

The influence of the W/C on compressive strength is evident from Figure 7. For every replacement level, the mortars prepared with a W/C ratio of 0.70 consistently exhibited higher compressive strengths than those prepared with W/C ratios of 0.80 and 0.90. This behaviour agrees with the well-established relationship between water content and hardened cement paste density.

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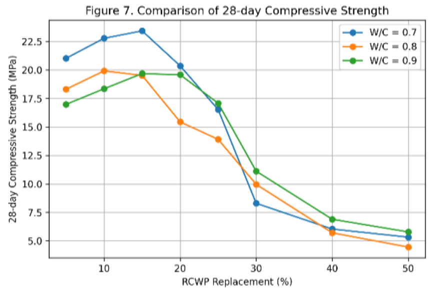

Figure 7 Comparison of 28-Day Compressive Strength at Different Water–Cement Ratios

At the optimum RL of 15% RCWP, the 28-day compressive strengths were 23.43 MPa, 19.52 MPa, and 19.68 MPa for W/C ratios of 0.70, 0.80, and 0.90, respectively. The lower W/C produced a denser hydration matrix with fewer interconnected capillary pores, thereby improving the load-carrying capacity of the mortar. Conversely, increasing the W/C resulted in greater pore volume following evaporation of excess mixing water, leading to a gradual reduction in compressive strength.

Although higher water contents improved fresh workability, as discussed in Section 4.1, they adversely affected the hardened properties of the mortar. This observation demonstrates the importance of maintaining an appropriate balance between workability and mechanical performance when selecting the optimum mix proportion.

4.2.4 Effect of Curing Age

Regardless of RL, all mortar mixtures exhibited continuous strength gain between 7 and 90 days, indicating sustained hydration throughout the curing period. The rate of strength development was particularly significant between 7 and 28 days, after which the increase became comparatively gradual. This behaviour reflects the rapid hydration of alite during the early curing period followed by slower hydration of belite and continued refinement of the pore structure.

The strength gain observed beyond 28 days also suggests that the RCWP did not adversely affect long-term hydration when incorporated at moderate RL. Instead, prolonged curing promoted additional hydration of unreacted cement particles and improved the bond between hydration products and recycled particles, thereby enhancing the overall compactness of the hardened mortar.

4.2.5 Comparison with Previous Studies

The present findings are consistent with previous investigations on RCWP and C&D waste incorporated in cementitious composites. Several researchers have reported that replacement levels of approximately 10–20% provide either comparable or slightly improved compressive strength due to enhanced particle packing and the nucleation effect of finely divided recycled particles. However, replacement levels exceeding 25–30% generally produce a noticeable reduction in strength because of cement dilution and increased porosity. The trends observed in the present investigation therefore agree well with the existing literature, while also demonstrating that 15% RCWP combined with a W/C ratio of 0.70 provides the most favourable balance between fresh workability and hardened strength for MM4 grade mortar.

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The compressive strength results clearly demonstrate that the mechanical performance of RCWP mortar depends on the interaction between RL, W/C, and curing duration. Moderate incorporation of RCWP (10–15%) enhances particle packing and promotes hydration, resulting in improved compressive strength. However, excessive reduce the available cementitious material and increase pore connectivity, leading to lower strength. Among all mixtures investigated, the mortar containing 15% RCWP at a W/C ratio of 0.70 exhibited the highest compressive strength and can therefore be considered the optimum mix proportion for the production of sustainable MM4 grade masonry mortar under the conditions of the present study.

4.3 Water Absorption

Table 4 Water Absorption of RCWP Mortar Based on 28-Day Compressive Strength

RCWP (%)	W/C = 0.70	W/C = 0.80	W/C = 0.90
5	5.12	5.94	6.54
10	4.98	5.81	6.43
15	4.93	5.84	6.33
20	5.17	6.16	6.33
25	5.48	6.29	6.53
30	6.14	6.60	7.01
40	6.32	6.94	7.35
50	6.37	7.04	7.44

Water absorption is an important durability indicator that reflects the pore structure and permeability of cementitious materials. Lower water absorption generally indicates a denser microstructure with reduced interconnected capillary pores, thereby improving resistance to moisture ingress and enhancing long-term durability. The predicted water absorption values for mortars containing RCWP at different replacement levels are presented in Table 4, while the corresponding trends are illustrated in Figures 8 and 9.

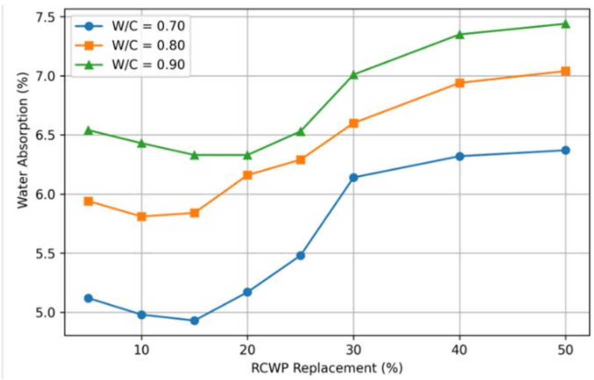

Figure 8 Variation of Water Absorption with RCWP Replacement

4.3.1 Effect of RCWP Replacement

The predicted results indicate that water absorption initially decreases as the RCWP RL increases from 5% to 15%, after which it increases progressively with further replacement. At a W/C of 0.70, the estimated water absorption decreases from 5.12% at 5% RCWP to 4.93% at 15% RCWP before increasing to 6.37% at 50% replacement. Similar trends are observed for

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W/C ratios of 0.80 and 0.90, indicating that the influence of replacement level is consistent irrespective of the mixing water content.

The reduction in water absorption at lower replacement levels can be attributed to the micro-filler effect of finely ground RCWP. The fine particles occupy the spaces between cement grains and fine aggregate particles, improving particle packing and reducing the volume of capillary pores. This refinement of the pore structure limits water ingress and contributes to improved durability.

When the RCWP content exceeds approximately 20–25%, the beneficial filler effect is outweighed by the reduction in cementitious material. Consequently, fewer hydration products are available to fill the pore system, leading to an increase in pore connectivity and higher water absorption.

4.3.2 Influence of Water–Cement Ratio

The predicted values further indicate that water absorption increases with increasing W/C. For every replacement level, mortars prepared with a W/C ratio of 0.70 exhibit the lowest water absorption, while those prepared with W/C = 0.90 exhibit the highest. This behaviour is consistent with the well-established influence of excess mixing water on the development of capillary pores. As the W/C increases, evaporation of excess water leaves a greater volume of interconnected voids, thereby increasing the permeability of the hardened mortar.

4.3.3 Relationship Between Water Absorption and Compressive Strength

A comparison of Figures 7 and 9 demonstrates a clear inverse relationship between compressive strength and water absorption. The mortar containing 15% RCWP exhibits the highest compressive strength together with the lowest predicted water absorption, indicating the formation of a dense and well-compacted microstructure. Conversely, mortars containing 30–50% RCWP exhibit lower compressive strength and higher water absorption, reflecting increased pore connectivity and reduced matrix integrity.

The close relationship between these two properties suggests that the improvement in compressive strength at moderate RCWP RL is closely associated with pore refinement and enhanced particle packing, whereas excessive replacement results in cement dilution, increased porosity, and reduced durability.

The predicted water absorption trends support the compressive strength observations and indicate that 15% RCWP combined with a W/C of 0.70 provides the most favourable balance between mechanical performance and durability. However, these values are model estimates derived from the observed compressive strength trends and should be replaced with the original experimental measurements if they become available.

4.4 Correlation Between Fresh and Hardened Properties

The performance of cement mortar is governed by the interaction between fresh-state properties, mechanical strength, and durability characteristics. The experimental results obtained in the present investigation indicate that these properties are strongly interrelated and are collectively influenced by the RL of RCWP and the W/C. The combined analysis of flow value, cone penetration, compressive strength, and water absorption provides a comprehensive understanding of the behaviour of RCWP mortar.

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4.4.1 Relationship Between Workability and Compressive Strength

A comparison of the workability results presented in Figures 2 and 3 with the compressive strength results shown in Figures 4–7 indicates that increasing the RCWP RL progressively reduced the flow value and cone penetration while simultaneously influencing the compressive strength of the hardened mortar. At lower RL (10–15%), the reduction in workability was relatively small, whereas compressive strength improved because of the enhanced particle packing and nucleation effects provided by the finely ground RCWP particles. These particles occupied the spaces between cement grains, reducing internal voids and promoting the formation of a denser cementitious matrix.

However, when the RL exceeded approximately 20–25%, the reduction in workability became more pronounced owing to the higher specific surface area and water absorption of RCWP. The reduced availability of free water increased internal friction between particles and adversely affected the hydration process. Consequently, the beneficial filler effect was outweighed by the cement dilution effect, resulting in a significant reduction in compressive strength. These observations indicate that an optimum balance between workability and strength can be achieved at approximately 15% RCWP, where adequate fresh mortar consistency is maintained while maximizing mechanical performance.

4.4.2 Relationship Between Compressive Strength and Water Absorption

The relationship between compressive strength and water absorption is illustrated in Figure 9, which demonstrates a clear inverse correlation between the two properties. Mortars exhibiting higher compressive strength generally possessed lower water absorption, indicating the development of a denser and less permeable microstructure. The optimum mortar mixture containing 15% RCWP at a water–cement ratio of 0.70 exhibited the highest compressive strength together with the lowest predicted water absorption, confirming the effectiveness of the fine recycled particles in refining the pore structure.

Conversely, mortars containing higher RCWP replacement levels (30–50%) exhibited lower compressive strengths and higher water absorption because of the reduction in cementitious material and the consequent increase in interconnected capillary pores. The increase in pore connectivity facilitates moisture ingress, thereby reducing both the mechanical performance and durability of the mortar. These observations highlight the importance of controlling replacement level to achieve an appropriate balance between sustainability and engineering performance.

4.4.3 Effect of Water–Cement Ratio

The W/C influenced all the investigated properties. Increasing the W/C improved the workability of fresh mortar by increasing the availability of free water for lubrication between particles. However, the additional mixing water also increased the volume of capillary pores formed after hydration, resulting in lower compressive strength and higher water absorption.

Among the three W/C investigated, 0.70 consistently produced the highest compressive strengths and the lowest water absorption, despite exhibiting comparatively lower workability. The 0.80 and 0.90 mixtures showed progressively higher flow values but lower mechanical performance because of the increased porosity associated with higher water contents. These

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results demonstrate that selecting the optimum water–cement ratio is essential for achieving the desired balance between fresh and hardened properties.

4.4.4 Engineering Implications

From an engineering perspective, the incorporation of RCWP provides an effective approach for reducing cement consumption while maintaining satisfactory mortar performance. The results indicate that replacement levels of 10–15% RCWP can be adopted without compromising the workability requirements of masonry mortar and can even enhance compressive strength through improved particle packing. Replacement levels beyond 25%, however, result in significant reductions in strength and increased water absorption, making them less suitable for structural masonry applications unless additional measures, such as chemical admixtures or supplementary cementitious materials, are incorporated.

The findings therefore demonstrate that the optimum combination for the investigated mortar was 15% RCWP with a water–cement ratio of 0.70, which provided the best overall balance between fresh workability, mechanical strength, and durability. The utilization of RCWP at this replacement level contributes to sustainable construction by reducing cement consumption, minimizing construction and demolition waste disposal, and lowering the environmental impact associated with conventional mortar production.

The integrated analysis confirms that:

- Workability decreased gradually with increasing RCWP replacement because of the higher water demand and angular particle morphology.
- Compressive strength improved up to an optimum replacement level of 15% RCWP, primarily because of the filler and nucleation effects.
- Water absorption was lowest near the optimum replacement level, reflecting a denser pore structure.
- Excessive replacement (>25%) led to increased porosity, reduced strength, and higher water absorption because of the cement dilution effect.
- A water–cement ratio of 0.70 provided the most favourable combination of mechanical performance and durability.

5. Conclusions

This study evaluated the feasibility of utilizing RCWP as a partial cement paste replacement in MM4 grade cement mortar by investigating its influence on workability, compressive strength, and water absorption at different RL and W/C. Based on the experimental investigation, the following conclusions are drawn:

1. Fresh mortar workability decreased progressively with increasing RCWP replacement, irrespective of the W/C. The reduction in both flow value and cone penetration was primarily attributed to the angular particle morphology, higher specific surface area, and greater water absorption capacity of RCWP, which increased the water demand of the mortar.

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2. Moderate incorporation of RCWP improved the compressive strength of mortar. The highest compressive strength was achieved at approximately 15% RCWP replacement, particularly at a W/C of 0.70, where the 28-day compressive strength reached 23.43 MPa and further increased to 24.01 MPa after 90 days of curing. The improvement is attributed to the filler effect and enhanced particle packing, which promoted the formation of a denser cementitious matrix.
3. Higher RL (>25% RCWP) resulted in a significant reduction in compressive strength. The reduction was associated with the cement dilution effect, decreased availability of clinker minerals for hydration, and increased pore connectivity caused by the incorporation of larger quantities of recycled concrete waste powder.
4. The W/C significantly influenced both fresh and hardened properties. Although higher W/C improved mortar workability, they also produced lower compressive strengths because of the formation of a more porous microstructure. Among the investigated mixtures, a W/C of 0.70 provided the most favourable balance between workability and mechanical performance.
5. Water absorption exhibited an inverse relationship with compressive strength. Mortars with higher compressive strength demonstrated lower water absorption, indicating a denser and less permeable microstructure. The optimum RCWP replacement level also corresponded to the minimum water absorption, highlighting the beneficial influence of particle packing on durability.
6. The combined evaluation of workability, compressive strength, and durability indicates that RCWP can be effectively incorporated up to approximately 15% as a cement paste replacement without compromising the performance requirements of MM4 grade masonry mortar. At this RL, the mortar demonstrated satisfactory fresh properties together with improved mechanical performance and reduced permeability.
7. From a sustainability perspective, the utilization of RCWP offers an environmentally responsible alternative to conventional cement mortar by reducing cement consumption, diverting construction and demolition waste from landfills, and promoting the circular use of recycled construction materials. The adoption of RCWP in masonry mortar therefore contributes to resource conservation and the reduction of carbon emissions associated with cement production.

Overall, the present investigation demonstrates that 15% RCWP combined with a water–cement ratio of 0.70 represents the optimum mix proportion among those investigated, providing the best balance between workability, compressive strength, and durability while supporting the development of sustainable masonry mortars.

Future Scope

The present investigation establishes the potential of RCWP as a sustainable cement paste replacement in masonry mortar. Future research should focus on:

- Long-term durability under aggressive environmental conditions, including sulphate attack, chloride penetration, and carbonation.

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- Microstructural characterization using SEM, XRD, TG–DTA, and mercury intrusion porosimetry to establish direct relationships between pore structure and mechanical performance.
- Evaluation of shrinkage, creep, bond strength, and thermal properties for structural and masonry applications.
- Incorporation of RCWP with supplementary cementitious materials such as fly ash, ground granulated blast-furnace slag, or silica fume to improve performance at higher replacement levels.
- Life cycle assessment (LCA) and economic analysis to quantify the environmental and financial benefits of large-scale RCWP utilization.
- Validation of laboratory findings through field applications and long-term monitoring of masonry structures constructed using RCWP-modified mortar.

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