ISSN: 1672 - 6553

JOURNAL OF DYNAMICS AND CONTROL

VOLUME 10 ISSUE 06: P48-62

STUDIES ON THE EFFECT OF BRICK WASTE STRENGTH USING TAGUCHI ANALYSIS

Kavitha V.[1*], Jyothi T.K.[2], Girisha H.N.[3], Bharathi Ganesh[4], Jayasimha N.[5], Sujata Timmanaikar[6]

[1]Department of Civil Engineering, Government Sri Krishnarajendra Silver Jubilee Technological Institute, Bangalore, Karnataka, India
[2]Department of Civil Engineering, KR Pet Krishna Government Engineering College, KR Pet, Karnataka, India
[3]Department of Mechanical Engineering, Government Engineering College, Ramanagara, Karnataka, India
[4]Department of Civil Engineering, Sir M Visvesvaraya Institute of Technology, Bangalore, Karnataka, India
[5]Department of Civil Engineering, Government Engineering College, Ramanagara, Karnataka, India
[6]Government Engineering College, Department of Mathematics, Haveri, Karnataka, India

https://doi.org/10.71058/jodac.v10i06004

STUDIES ON THE EFFECT OF BRICK WASTE STRENGTH USING TAGUCHI ANALYSIS

Kavitha V.[1*], Jyothi T.K.[2], Girisha H.N.[3], Bharathi Ganesh[4], Jayasimha N.[5], Sujata Timmanaikar[6]

[1]*Department of Civil Engineering, Government Sri Krishnarajendra Silver Jubilee Technological Institute, Bangalore, Karnataka, India*
[2]*Department of Civil Engineering, KR Pet Krishna Government Engineering College, KR Pet, Karnataka, India*
[3]*Department of Mechanical Engineering, Government Engineering College, Ramanagara, Karnataka, India*
[4]*Department of Civil Engineering, Sir M Visvesvaraya Institute of Technology, Bangalore, Karnataka, India*
[5]*Department of Civil Engineering, Government Engineering College, Ramanagara, Karnataka, India*
[6]*Government Engineering College, Department of Mathematics, Haveri, Karnataka, India*

Corresponding author: kavithamouli12@gmail.com
[†]*All the authors contributed equally to this work.*

Abstract: The growing need for low-carbon masonry materials has led to studies on using construction waste and associated materials as additional cementitious materials. In this study, Brick Waste Powder (BW) is used as a partial substitute for cement paste (cement + water) in masonry mortar. The goal is to enhance sustainability without reducing structural integrity. The optimisation of the 3 key parameters, namely water-to-cement ratio (W/C) of 0.7, 0.8, and 0.9, BW replacement level (RL) of 10%, 20%, and 30%, and the curing period (CP) of 7, 28, and 90 days, is carried out using the Taguchi Technique of analysis. L9 orthogonal array is employed to optimise these parameters. The workability and compressive strength of all mixtures are evaluated against the control mortar of the MM5 grade standard (≥6 MPa), which is normally preferred for masonry applications. All BW-modified mortars satisfied or surpassed the required strength criteria, indicating that BW is an effective cementitious modifier. To clarify the influence of parameters, analysis of variance (ANOVA) revealed that the CP is the most significant factor, accounting for 67.5% of the variation in strength development, followed sequentially by RL and W/C. Furthermore, the Taguchi method indicated that a 0.7 W/C, a 20% BW RL, and a 90-day CP are optimal. This specific combination of parameters provides the highest compressive strength satisfying the required workability. The SEM (Scanning Electron Microscopy) and EDAX (Energy-Dispersive X-ray Analysis) findings confirmed the results obtained from optimisation through the Taguchi technique, demonstrating enhanced packing density and increased formation of C–S–H gel phases at appropriate RL. The findings show that BW can effectively replace up to 20% of the cement paste in masonry mortar without compromising its strength or performance. The use of the cement paste replacement method is a practical solution for developing cost-effective, circular-economy-oriented, and carbon-efficient binder systems in construction.

Keywords: Brick waste[1], paste replacement method[2], Taguchi optimisation[3], masonry mortar[4], SEM[5], EDAX[6]

https://doi.org/10.71058/jodac.v10i06004

1 Introduction

The production of construction and demolition waste (CDW) has increased markedly in both developed and developing nations, with burnt brickdebris representing a significant fraction of the overall waste stream in countries such as India and China. Studies on CDW management reveal that poor segregation, inadequate on-site handling, and ineffective landfilling practices consistently lead to substantial environmental impacts, resource depletion, and increased pressures on land use [1], [2], [3]. Significant quantities of brick waste (BW) are produced from demolition activities and post-earthquake restoration efforts, as demonstrated by global events such as the 2010 Haiti earthquake [4]. The expansion of infrastructure and extensive redevelopment initiatives in India are expected to generate 150–165 million tonnes of CDW annually, with nearly 1% officially recycled or processed scientifically [5], [6]. National studies show that brick and masonry debris constitute approximately 30–50% of total CDW, with variations depending on building type and age. Applying this composition range to national CDW generation indicates that India produces approximately 45-82 million tonnes of brick and masonry waste annually [3], [7].

The generation of CDW in Karnataka demonstrates a similar trend. Bengaluru produces an estimated 2,500 to 6,700 tonnes of CDW daily, with variations depending on the reporting year and source [8], [9]. Furthermore, Bengaluru is projected to produce around 30% of CDW among Indian cities [10], [11]. This shows that the BW is one of the largest but underutilized CDW resources in India. Additionally, the BW debris from CDW in landfills contributes to air pollution, leachate generation, soil and water pollution, and prolonged decomposition. To address these challenges, the recommendation to use this material through cementitious reuse aligns with contemporary circular economy principles and the requirements of sustainable construction practices [12], [13].

Building on this context, BW, characterized by high concentrations of aluminosilicates and micro-fillers derived from fired clay, exhibits reactive pozzolanic potential according to prior studies. This reactivity enhances the rheology, densification, and long-term durability of cementitious matrices through secondary C–S–H gel formation and pore refinement [14], [15], [16]. The mineralogical composition typically resembles metakaolin or calcined clays, enabling BW to serve as both a reactive binder and a filler-grade modifier [17], [18], [19], [20]. Although many studies have examined the reuse of materials such as marble, granite, ceramic, slag, and silica fume as partial substitutes for cement or paste to improve strength and durability [21], [22], [23], [24], there remains a notable gap in the systematic optimization of BW for cement paste replacement, particularly via modern statistical Design of Experiments (DOE) methodologies. This research aims to address this gap.

Many researchers have conducted various studies with reference to the strength, durability, and efficiency of mortars by replacing aggregates and binders using three different methods: *(i) Cement replacement method*, which replaces cement with sustainable materials mainly to reduce the environmental carbon footprint.[25], [26], [27], *(ii) Aggregate replacement method,* replacing natural aggregates with sustainable materials, often recycled or industrial by-products, to promote sustainability and resource conservation [19], [28], [29], [30], [31] and *(iii) Paste replacement method,* by reducing the paste (cement and water)without changing the W/Cby incorporating fine fillers or powders to enhance the performance [24], [32], [33], [34], [35], [36].

https://doi.org/10.71058/jodac.v10i06004

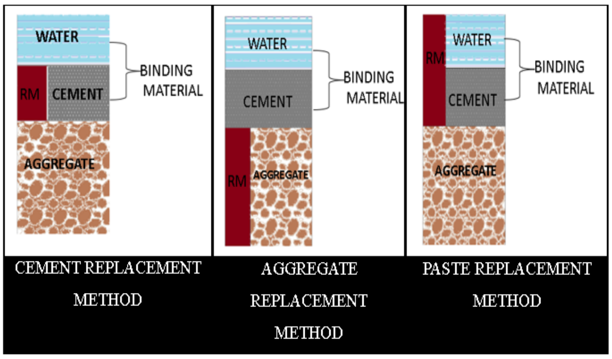


Figure 1 Methods of replacement of waste in Mortar

These methods (Figure 1) are effective, as discussed above, to attain a reduction in the use of cement and natural resources, thus enabling sustainable construction. The established methodologies included the replacement of cement with materials like fly ash, silica fume, and slag, which have not only reduced the carbon footprint but also enhanced the strength and durability of mortars [23], [26]. The aggregate replacement methodology is focused on using recycled materials such as crushed concrete and glass and provides a greener solution without affecting the performance of these materials [30], [31], [39]. On the other hand, the paste replacement methodology involves the replacement of cementitious paste, which constitutes the binder and water combined with an appropriate substitute, while keeping the volume of paste constant and by minimizing the usage of the paste. This results in enhancing the sustainability and efficiency of mortars without compromising the total quality of the mortar [35], [36], [37], [38]. Paste replacement, replacing cement and water together without changing W/C, has been found to have the potential to reduce cement consumption, lessen the carbon emissions, increase the packing density, enhance the pozzolanic reactivity, and alter the pore structure to ensure better durability and performance in mortar and concrete. [12], [14], [21], [27]. Despite extensive research on aggregate replacement or cement replacement methods, the systematic optimisation of BW as a substitute for cement paste, considering factors such as W/C, CP, and RL, remains underexplored. This study employs a structured Taguchi L9 DoE and analysis of variance (ANOVA) to identify optimal factor combinations that improve compressive strength in control mix-MM5 masonry mortar, establishing a performance-based framework for the effective use of BW as a low-carbon binder solution within the context of CDW-based binders. Ghazy, optimized geopolymer bricks fabricated from recycled concrete aggregate by using a Taguchi array; the methodology was demonstrated to be effective in both factor screening and performance prediction [40], [41]. The Taguchi methodology is recognized for its capability in reducing experimental runs, identifying critical control factors, improving signal-to-noise ratio (S.N), and producing robust, repeatable performance results under a variety of conditions [42], [43], [44], [45]. Despite these benefits, the application of this method to BW blended mortars, especially in masonry-grade mixes such as MM5, has not been extensively investigated.

According to studies on the paste replacement method, researchers found that using 15-30% BW as inert fillers in cementitious paste with a W/C of 0.4-0.55 improved compressive and flexural strength [37]. This improvement resulted from reduced porosity and increased mortar matrix density, leading to improved water permeability, acid resistance, and shrinkage resistance[38], [39].Additionally, a superplasticiser is required to maintain adequate workability at low W/Cs [38], [39].

Many studies on the utilization of BW in cementitious systems have focused on low W/C to attain increased

https://doi.org/10.71058/jodac.v10i06004

strength. Low W/C inherently result in high strength and poor workability, rendering them unsuitable for MM5 masonry mortar, which requires sufficient flowability and ease of application.[35], [36], [37]. To address this limitation of workability, numerous researchers utilize superplasticisers, which raises material costs and an alternative approach, increasing the W/C to enhance workability, is generally avoided because it reduces strength.

This identifies a distinct research gap: insufficient scientific inquiry into achieving high workability at higherW/Cs without sacrificing strength, particularly in MM5-grade mortar. The paste replacement method offers a viable solution, as fine, reactive materials like BW can enhance packing density, refine the microstructure, and mitigate strength loss associated with higher W/Cs. This study systematically optimises this approach by exploring different RLs, CPs, and W/Cs, using a Taguchi L9 orthogonal array and ANOVA to optimize and quantify the effects of W/Cs, RL, and CP on the compressive strength of MM5 masonry mortar [40]. Key findings demonstrate that factor-level optimisation and performance validation create a practical framework for using fired brick waste as a low-carbon cementitious paste substitute, supporting sustainable waste management and circular material utilization.

1.1 Objective of the Study

This paper evaluates and optimizes BW to replace cement paste by using the paste-replacement method. W/C will remain constant, targeting high workability with a compressive strength of at least 6MPa, which is the minimum characteristic strength required for MM5 masonry mortar [41]. This study applies the Taguchi L9 orthogonal array (a statistical method for efficiently designing experiments), S/N, Means(optimization tools), and ANOVA - a statistical technique that provides a way to determine whether variables are significant or not) to find the best combination of W/C, BW RL, and CP to ensure maximum performance at workable consistency without requiring superplasticizers (chemical admixtures that increase workability of fresh concrete) and a durable, sustainable, economical mortar formulation suitable for practical masonry use.

2. MATERIALS AND METHODOLOGY

The required masonry mortar is produced by mixing ordinary Portland Cement 53 grade(OPC), M-Sand, and BW as per the defined proportion.

2.1 MATERIALS

CEMENT: OPC, conforming to Bureau of Indian Standards (B.I.S.)specifications, was used in the present investigation. The cement had a specific gravity (ratio of the density of cement to the density of water) of 3.18 as per IS 4031 (Part 11):1988 re-affirmed (RA)-2021 [42], and a fineness (measured by the percentage retained on a standard sieve, indicating how fine the cement particles are) of 3.4, conforming to IS IS 4031 Part 1:1996 RA-2021 [43].

Manufactured sand (M-Sand): M-Sand, an artificial sand manufactured by crushing large, hard stones and processed as per the grade requirements, was procured from a crusher in Ramanagaram taluk. The specific gravity of the M-sand was 2.63, and the fineness modulus of the M-sand was 3.37, which conforms to IS 2386 (Part 3):1963 RA-2021 [44].

https://doi.org/10.71058/jodac.v10i06004

BRICK WASTE POWDER: BW collected from the dump yard of a brick manufacturing unit was powdered using a disintegrator. Materials passing through a 90-micron sieve were used in this study. The BW having a specific gravity of 2.47, a water absorption of 0.30%, and a wet-sieve analysis for fineness assessment showed that the sample contained 95% sand, 2% clay, and 3% silt.

WATER: Water is one of the most important ingredients, after cement, used to make mortars. The water used for mixing and curing must be pure and free of harmful concentrations of oils, acids, alkalis, salts, sugar, and organic materials, per clause 5.4 of IS 456:2000 Amended-2024 [45]. Potable water is used for the mix.

2.2 METHODOLOGY

2.2.1 Mix Proportion

An experimental study was carried out on mortars with a mix proportion of cement: M-Sand of 1:4 to achieve mortar grade MM5 with a characteristic strength of 6MPa, as per Table1 of IS 2250:1981 RA-2020 [41]. Specimens were prepared by proportioning, mixing raw materials, testing workability, casting, curing by immersion as per the procedure mentioned in relevant IS code, and testing for compression. Cement paste was replaced with BW by weight. Higher W/Cs were adopted: (1) for developing effective, chemical-admixture-free mortar mixtures and (2) to address research shortfalls on required workability, paste-replacement mortars.

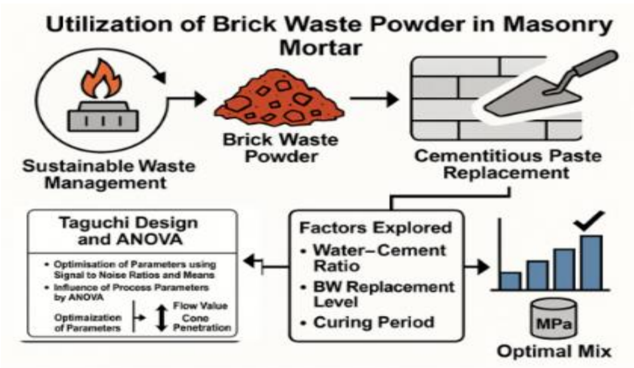


Figure 2 Flow Chart Representing the Brick Waste Utilisation and Optimisation in Masonry Mortar

2.2.2 Design of experiments

While the process objectives are kept, the variance is reduced by the Taguchi robust parameter design. TheDoE, investigates how input factors affect output variables. Taguchi's orthogonal arrays allow systematic variation and data collection across several factor levels. While ANOVA identifies the primary factors affecting compressive strength, it also quantifies each factor's proportional contribution and determines whether the observed deviations are statistically significant. The S/N for "Larger is the Better" criteria, variance was measured to support robust design. In the present study, an L9 orthogonal array with three parameters and three levels was used to examine the effects of different parameter combinations: W/C, RL, and CP on the performance of masonry mortar. The three parameters and the three levels are: (i) W/C - 0.7, 0.8, 0.9; (ii) RL - 10%, 20%, 30%; and (iii) CP - 7 days, 28 days, 90 days.

2.2.3 Paste replacement method

The cement paste content is replaced with BW with a constant W/C. No additional superplasticisers are used

https://doi.org/10.71058/jodac.v10i06004

to achieve a workable mix.

2.2.4 Preparation of Specimen

The specimens are prepared for the different percentage of replacement of BW following the guidelines as per Appendix-A of IS: 2250:1981 RA- 2020[41].

- First, mix the materials - cement, BW, and M-sand to ensure uniformity in dry form.
- Add water according to the specified W/C.
- Mix the materials mechanically for 3 to 5 minutes.
- Cast the mix in 50 mm cube moulds in two layers using standard tamping techniques.
- Surface finishing and curing were conducted at 27 ± 2°C prior to testing.

2.2.5 Workability

Mortar workability affects masonry strength and durability. Workability is assessed as follows.

2.2.5.1 The Flow Table Test: This test evaluates the mortar spread on a flow table after a set number of strokes. The flowability is assessed according to IS 2250:1981 RA-2020 (Appendix B) [41], by measuring the horizontal spread diameter in mm of the mortar.

2.2.5.2 Cone Penetration Test: This test evaluates the consistency of mortar, with a standard cone penetrating a mortar sample for a set time under its own weight. The measurement of the penetration depth determines mortar workability, which is assessed in accordance with ASTM C780-06a[46].

The flow table test is a widely adopted method for assessing the consistency of cement mortar. In this research, the consistency, as indicated by the flow table value, was compared to the cone penetration depth. In this research, an attempt was made to correlate the consistency of the flow table value and cone penetration depth.

2.2.6 Compressive Strength

Compressive strength is the major characteristic of mortar, a common characteristic needed to assess any type of mortar that represents the resistance of mortar against axial loading. Compressive strength was measured as per IS 2250:1981 RA-2020 [41], to assess its suitability for structural use. The tests were carried out on mortar cubes, and five specimens of size 50mm x 50mm x 50mm for each mix and each CP.

2.2.7 Data Analysis and Optimisation

Using Minitab Software and the Taguchi technique, the S/N was computed for the "Larger is the better" option, with Signal being the compressive strength due to W/C, RL, and CP, and noise being the operator inconsistency, variation in compaction, mixing, curing, temperature and humidity. The main-effect plots were used to determine the optimal values. Anova was used to study the influence of process parameters. The anticipated optimal strength was validated through confirmatory experiments.

3. Results

The results of various tests are tabulated, analysed and discussed in following sections.

https://doi.org/10.71058/jodac.v10i06004

3.1 Workability

Figure 3 illustrates a uniform, monotonic increase in workability, as measured by both flow table value and cone penetration value, with the W/C increasing from 0.4 to 1.5 in the control mortar. At lower W/Cs of 0.4 to 0.6, the mortar is stiffer, with low-flow characteristics, indicating inadequate particle lubrication. The workability is increased progressively by increasing the W/C, and therefore the flow increases, from about 90 mm at W/C = 0.4 to more than 230 mm at W/C = 1.5, and cone penetration values approach 50 mm.

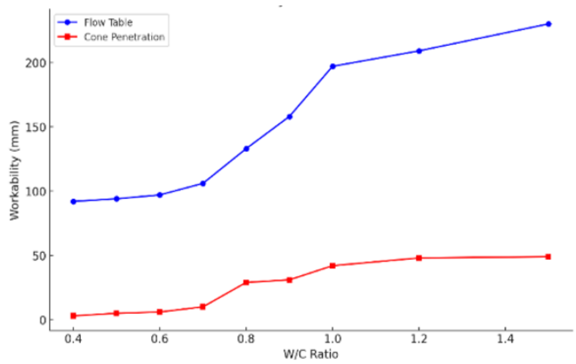


Figure 3 Workability of Normal Mortar

Figure 4 represents the workability property of masonry mortar incorporated with various percentage of BW replaced for cement paste and also varying W/C ratios. At lower RL (5–10%), BW has negligible detrimental effects on the flow pattern of mortar, particularly with W/C of 0.9, where initial flows exceed 200 mm owing to an increased water film surrounding the particles.

As the RL exceeds 15–20%, the flow value reduces more significantly across all W/C. At 30–50% RL of BW, the flow values converge to approximately 95–100 mm across all W/C. The flow value is followed by the cone penetration value, the highest penetration depth coming from W/C 0.9 and reaching up to 48 mm at 5% RL.

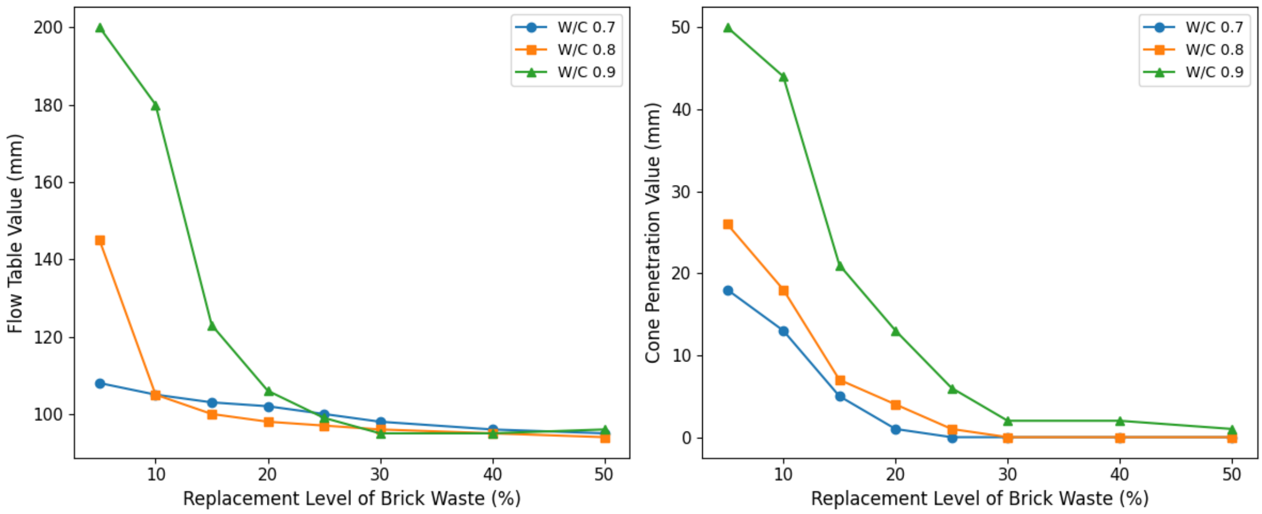


Figure 4 Workability of Brick Waste Incorporated Mortar

The assessment of workability using flow table and cone penetration tests revealed that the fresh properties of brick-waste-modified masonry mortar are influenced by both the W/C and the quantity of BW RL. Higher W/C (0.8–0.9) significantly increased the horizontal flow and vertical penetration owing to increased free-

https://doi.org/10.71058/jodac.v10i06004

water availability, while lower W/C mixes (0.7) retained a stiffer consistency. However, the increased BW content reduced workability in every W/C ratio, whereas a sharp decline occurred for replacement rates higher than 20%, since tiny and porous brick particles absorbed water, increasing internal friction. Flow measurements exhibited greater sensitivity to variations in W/C, indicating greater deformability, whereas cone penetration showed less consistent changes, indicating enhanced cohesion and paste thickening.
The integrated analysis shows that 20% BW gives the most optimum fresh-state performance, providing adequate spread for masonry application while maintaining acceptable plasticity. This indeed confirms that paste replacement is a better approach than excess water addition to attain the required workability in the field without losing strength.

3.2 Compressive Strength

The compressive strength (Table 1) of the nine runs of the L9 array of Taguchi-designed mortar mixes ranged from 4.39 MPa to 30.38 MPa, indicating significant sensitivity to adjustments in W/C, BW RL, and CP. Importantly, all mixes exceeded the MM5 minimum requirement of 6 MPa, confirming the feasibility of BW as a sustainable cement paste replacement.

3.2.1 Impact of Brick Waste Replacement Level

Of the three levels of BW replacement - 10%, 20%, and 30%, the 20% level of BW replacement consistently yields the highest compressive strength from all CP. This, therefore, could be attributed to two complementary mechanisms:
(i) *Filler Densification*: The fine BW particles (<90 µm) act as micro-fillers, thus increasing particlepacking, reducing voids, and giving optimal capillary pore structure. The increase in paste density leads to an increase in early-age strength.
(ii) *Pozzolanic Reactivity*: The aluminosilicate-laden brick debris engages with calcium hydroxide liberated during cement hydration, resulting in the formation of supplementary C–S–H gel. The creation of this secondary gel substantially enhances long-term strength, particularly observable at 28 and 90 days. At 30% BW RL, severe cement dispersion transpires, diminishing available clinker and compromising the binder matrix.

Table 1 Experimental Layout Using L9 Orthogonal Arrays

Run	Water-Cement Ratio	Replacement Level (%)	Curing Period (Days)	Compressive Strength (MPa)	Signal/ Noise Ratio	Mean (MPa)
1	0.7	10	7	9.05	19.13	9.05
2	0.7	20	28	30.38	29.65	30.38
3	0.7	30	90	21.36	26.59	21.36
4	0.8	10	28	22.83	27.17	22.83
5	0.8	20	90	27.97	28.93	27.97
6	0.8	30	7	4.39	12.85	4.39
7	0.9	10	90	23.44	27.40	23.44
8	0.9	20	7	10.42	20.36	10.42
9	0.9	30	28	11.59	21.28	11.59

https://doi.org/10.71058/jodac.v10i06004

3.2.2 Impact of Water–Cement Ratio

The W/C has a significant and consistent impact on strength development. Mixtures with a W/C of 0.7 consistently produced the highest compressive strengths. This can be attributed to:

• Reduced capillary porosity

• Improved bonding between paste and aggregates

• Improved and more homogeneous binder matrix

In contrast, high W/C (0.8 and 0.9), although beneficial for workability, produced higher free water and an adversely affected paste microstructure, leading to reduced overall strengths. This underscores the study's primary rationale: workability should be enhanced by paste optimisation rather than by introducing excessive water.

3.2.3 Significance of Curing Period

The CP is the main factor affecting compressive strength. From 7-90 days, strength improved significantly, reflecting the synergistic effect of cement hydration and the progressive pozzolanic activity of BW. Longer curing promoted:

- Ongoing hydration of unreacted cement particles
- Augmented generation of secondary C–S–H
- Pore refinement and densification of microstructure

The 90-day strength values were constantly the highest, indicating the favourable long-term effect of BW on matrix strength development.

3.1 Optimization of Strengths using Taguchi Technique

3.1.1 Main Effects and Response Table for signal-to-noise ratio and Means

Figure 5 presents the Taguchi main effects graphs for S/N and means of compressive strengths, clearly showing the effect of each factor: W/C, BW RL, and CP on mortar performance. The main effects plot for S/N shows that the W/C has a decreasing trend from 0.7 to 0.9, indicating that an increased water content continuously weakened the strength response. At a W/C of 0.7, the S/N was the highest, reflecting the fact that a lower W/C provided more reliable and stronger mortar. This is reflected in the main effects plot for means, where the average compressive strength decreases linearly as the W/C increases, corroborating the critical relationship between water content, pore formation, and matrix integrity.

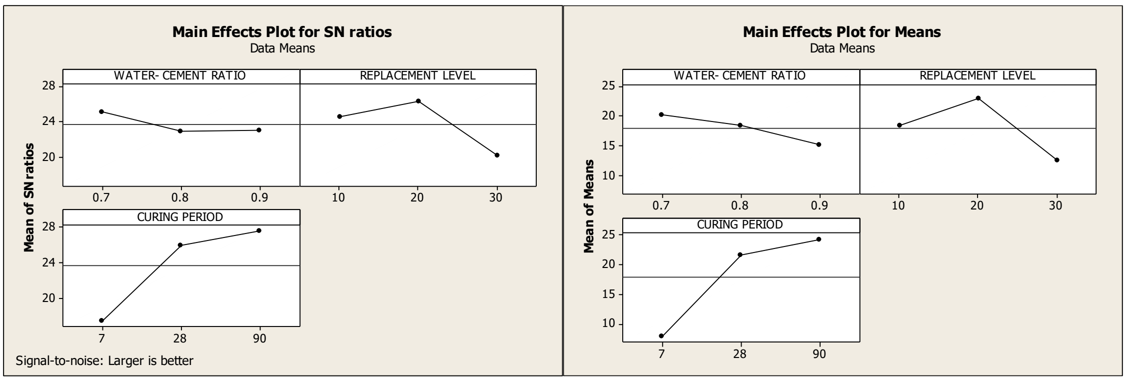


Figure 5 Effect of individual parameters on the average compression strength value for the signal-to-noise ratio and Means

https://doi.org/10.71058/jodac.v10i06004

The RL, expressed as the percentage of binder weight, is considered to be optimum at 20% BW, as reflected by distinct peaks in both S/N and mean plots. While at 10% RL, both pozzolanic and filler effects are suboptimum, for 30% replacement, cement dilution dominates and impairs the integrity of the matrix. 20% BW substitution develops the highest strength and most reliable results, as represented by a sharp rise in S/N value (26.31), with a steep fall at 30%. This confirms that the optimum balance between micro-filler densification and pozzolanic reactivity has been achieved around 20%.

The CP was found to be the most influential factor in the S/N and mean responses. From the S/N plot, it can be observed that there is a sharp rise between 7 and 28 days and a steady, though gradual, rise up to 90 days. This indicates that strength development stabilises and becomes progressively less vulnerable to noise causes as the CP increases. According to the mean plot, compressive strength increased remarkably from approximately 7.95 MPa at 7 days to 21.6 MPa at 28 days, before it reached 24.26 MPa at 90 days. There was an initial strength gain of around 170% from 7 to 28days CP, and it is around 12% strength gain from 28 days to 90 days CP. This confirms the necessity for extended hydration and pozzolanic improvement in BW-modified mortar.

Table 2 Response Table for Signal-to-Noise Ratios and Means

	Signal-to-Noise Ratios			Means		
Level	**W/C**	**RL**	**CP**	**W/C**	**RL**	**CP**
1	25.13	24.57	17.45	20.263	21.44	7.953
2	22.98	26.31	26.03	18.397	22.923	21.6
3	23.01	20.24	27.64	15.15	12.447	24.257
Delta	2.14	6.07	10.2	5.113	10.477	16.303
Rank	3	2	1	3	2	1

These observations are confirmed by the values from the response table for S/N and means (Table 2), showing the highest value of the Delta for S/N ratio for CP as 10.2, followed by that for RL as 6.07, and for W/C ratio as 2.14. From the mean plots, CP had the highest Delta value of 16.303, followed by RL as 10.477, and W/C ratio as 5.113.

The ranking is the same for all the domains for both means and S/N plots. The CP exerts the most significant influence on performance, followed by the RL, and lastly, the W/C. The optimum factor levels, obtained from the S/N and mean optimisation, converge reliably to the following: W/Cof 0.7, BWRL of 20%, and CP of 90 days.

3.3 Influence of Process Parameters by ANOVA for Compressive Strength

ANOVA for compressive strength was performed using the adjusted Sum of Squares for tests from Minitab 16 software. An L9 orthogonal array with three parameters and three levels was studied. From Table 3, the ANOVAfor compressive strength can be observed. Each of the three factors (W/C, RL, and CP) has two degrees of freedom (DF). The error also has two DF. There are eight DF in total.

Table 3 Analysis of Variance for Compressive Strength, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
W/C	2	40.17	40.17	20.09	2.56	0.281

https://doi.org/10.71058/jodac.v10i06004

R/L	2	165.78	165.78	82.89	10.57	0.086
C/P	2	459.09	459.09	229.54	29.28	0.033
Error	2	15.68	15.68	7.84		
Total	8	680.72				

From Figure 5, it can be observed that the W/C ratio influences 5.9% of the compressive strength of the mortar cubes with BW. RL and CP influenced the compressive strength by 24.36% and 67.45%, respectively. From the Taguchi methodology (Table 3), the magnitude of the F-value describes the sensitivity of the response to changes in the level of the factor relative to experimental noise.

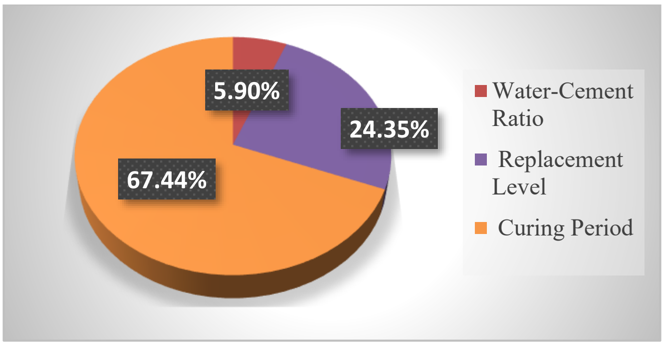


Figure 5 Effect of Process Parameters on Average Compression Strength Value

The larger the F-value, the more consistent and reproducible the changes in compressive strength due to variations in that factor. CP has the greatest F-value of 29.28, which proves that strength gain is highly sensitive to CP. This represents the continuing hydration and secondary pozzolanic actions involved with longer curing, which have become the dominant mechanisms in strength gain within waste-modified mortars. RL, on the other hand, exhibits a moderately high F-value of 10.57, showing a strong but secondary influence on compressive strength, which arises from a balance between the densification of fillers and dilution of the cementitious content. W/C records a low F-value of 2.56, indicating that within the selected Taguchi levels, its influence is comparatively less pronounced.

If the P-value is less than 0.05, the P-value (P) is considered significant. Table 3 shows that the P values for W/C, RL, and CP are 0.281, 0.086, and 0.033, respectively. According to the P values, the longer the CP, the more significant the effect. The RLs are moderately significant, while the W/C was less significant in causing an effect on compressive strength.

Table 4 Summary of p-value and Partial Eta-Squared

Factor	p-value	Significance	Partial η^2	Effect Size
W/C	0.281	No	0.719	Large
R/L	0.086	Marginal	0.913	Very Large
C/P	0.033	Yes	0.967	Very Large

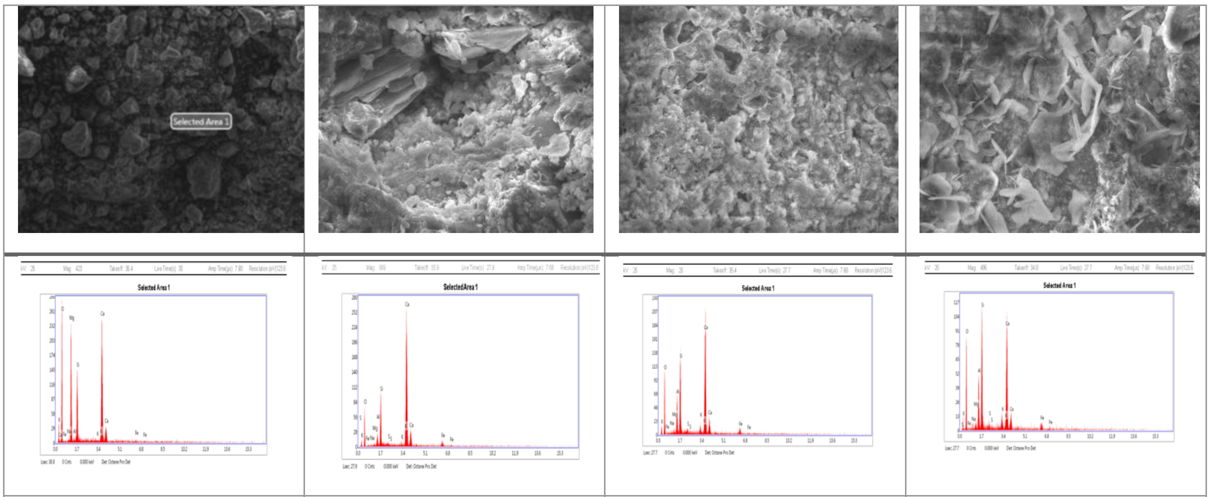
Partial η^2 (Table 4) shows the contribution of each element to the variability. CP with a partial η^2 of 0.967 is the most important control element since it explains about 97% of the changes in compressive strength due to hydration. RL with a partial η^2 of 0.913 explains more than 91% of the changes due to the packing and

https://doi.org/10.71058/jodac.v10i06004

microstructure of particles. W/C with partial η^2 of 0.719 accounts for approximately 72% of the variance, indicating a strong physical effect despite variations due to the conduction of the experiment. Even with low p-values, large η^2 values show that factors in orthogonal array experiments are important for engineering.

3.2 Validation using the morphology of the mortar mixes

Microstructural research using SEM and EDAX (Figure 6) demonstrates that incorporating 20% BW into mortarsoptimises mechanical performance by improving packing density and pozzolanic activity.
Table 5 shows that the brick remnants consisted mainly of SiO_2, Al_2O_3, and Fe_2O_3, displaying a porous structure that influenced both workability and strength.



UNHYDRATED BRICK WASTE	10% BRICK WASTE MORTAR	20% BRICKWASTE MORTAR	30% BRICK WASTE MORTAR

Figure 6SEM and EDAX images of Brick Waste and Hydrated Mortar with Different Brick Waste Replacement Levels.

Table 5 Summary of Microstructural Observation

Mix Type	SEM Observations	EDAX Observations	Interpretation & Validation
Dry Brick Waste	Angular, porous particles; rough surface; micro-cracks; high surface area	High SiO_2, Al_2O_3, Fe_2O_3; low CaO	Details the characteristics of high water-demand and pozzolanic potential; verifies the presence of an aluminosilicate-rich precursor.
10% BW Mortar	BW occupies isolated pores; the matrix exhibits moderate density; there is restricted C–S–H development surrounding BW particles.	Slight increase in Si and Al; CaO still dominant	The filler effect is evident; however, the pozzolanic activity is inadequate at low replacement levels, resulting in moderate strength.
20% BW Mortar (Optimal)	Densest matrix; reduced capillary porosity; continuous formation of C–S–H gel; strong bonding between particles; well-distributed hydration products.	Higher Si/Ca and Al/Ca ratios; reduced $Ca(OH)_2$ peaks → active pozzolanic reaction	Optimal filler densification and a robust pozzolanic reaction provide the maximum strength. Consistent with Taguchi's ideal values (W/C 0.7, RL 20%, CP 90).
30% BW Mortar	Porous architecture; unreacted BW particles; discontinuous gel matrix; weak interfacial regions	Decreased CaO levels; inadequate gel phase formation; elevated presence of unreacted	Excessive dilution of cement results in a weak matrix and a reduction in strength. Verification of Taguchi signal-to-noise

https://doi.org/10.71058/jodac.v10i06004

		aluminosilicates.	ratio and analysis of variance results.

The 10% BW mixture exhibited minimal enhancements in hydration, whereas the 20% BW mixture revealed a dense microstructure with pronounced pozzolanic reactions, resulting in increased compressive strength. In contrast, the 30% BW mixture produced a disjointed structure with reduced compressive strength owing to unreacted particles and insufficient hydration. The results demonstrate that the 20% BW level offers the optimal equilibrium of characteristics in cement-based materials.

This affirms the established correlation that workability is significantly influenced by W/C, and the addition of excessive water continues to be the predominant conventional method for generating workable masonry mortars. Nevertheless, elevated W/C create substantial capillary pores, thereby diminishing strength—underscoring the necessity for alternative methods to promote workability, such as paste replacement.

4 Conclusions

In this work, BW is used as an alternative sustainable cement paste in MM5 masonry mortar. The assessment is conducted methodically, following a comprehensive program that includes fresh-property evaluation, mechanical tests, statistical optimisation, and microstructural validation.

- Larger W/C improve flow and penetration; too much water weakens the material, according to the workability results. However, controlled paste replacement with BW effectively improved workability without the need for chemical admixtures.
- 20% BW constantly demonstrated the most balanced rheological performance among the mixes, showing its ability to enhance the paste consistency at lower water consumption.
- All Taguchi L9 Mixes outperformed the MM5 strength of 6 MPa, recording strengths between 4.39 and 30.38 MPa. Due to the combined filler densification and pozzolanic synergism that enhanced matrix formation at early and later ages, the mix containing 20% BW showed the best strength.
- The densest and strongest binder matrix was achieved with a 0.7 W/C and was further positively affected by prolonged curing (90 days) due to ongoing hydration and secondary C–S–H gel generation. All of these findings confirm the good performance prospects of BW as a low-carbon cementitious binder.
- Taguchi optimisation revealed that W/C = 0.7, BW = 20%, and CP = 90 days was the best parameter combination that maximises both mean strength and S/N ratio concurrently.
- The ANOVA showed that the CP was the most significant factor, followed by the W/C and the BW replacement amount in BW-modified mortars, therefore indicating the importance of long-term hydration–pozzolanic interactions.
- The statistical results were also validated by the respective tests via SEM and EDAX studies, which indicated that higher BW contents produced matrix discontinuity and loss of strength, while microstructural densification, refinement of pores, and higher silica–alumina activity occurred at the optimum RL.

In this respect, the combination of statistical modelling, microstructural research, and practical tests proves that BW is technically feasible, providing environmental benefits and enhancing performance as a paste substitute in masonry mortar. The paper contributes significantly to the circular economy projects and

https://doi.org/10.71058/jodac.v10i06004

sustainable building techniques with a sound optimization approach and solid practical basis for incorporating BW into the production of mortars with the grade of MM5.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

Funding Declaration

The authors declare that no financial support, grant, or funding was received from any funding agency in the public, commercial, or not-for-profit sectors for the conduct of this research.

5 References

[1] V. A. Dakwale, R. V Ralegaonkar, and S. Ramdeobaba, "Development of sustainable construction material using construction and demolition waste," *Indian Journal of Engineering & Materials Sciences*, vol. 21, pp. 451–457, Aug. 2014.

[2] "Sustainable Construction Waste Management In India." Accessed: Dec. 29, 2025. [Online]. Available: https://earth5r.org/sustainable-construction-waste-management-in-india

[3] "Construction And Demolition Waste 4.1 Introduction." Accessed: Dec. 29, 2025. [Online]. Available: cpheeo.gov.in/upload/uploadfiles/files/chap4.pdf

[4] R. DesRoches, M. Comerio, M. Eberhard, W. Mooney, and G. J. Rix, "Overview of the 2010 Haiti Earthquake," *Earthquake Spectra*, vol. 27, no. 1_suppl1, pp. 1–21, Oct. 2011, doi: 10.1193/1.3630129.

[5] S. Shrivastava and A. M. Chini Rinker Sr, "Construction Materials and C&D Waste in India." Accessed: Dec. 29, 2025. [Online]. Available: https://www.researchgate.net/publication/273693006_Construction_Materials_and_CD_waste_in_India

[6] CPCB, "'Status Report on Implementation of C&D Waste Management Rules," *Central Pollution Control Board, 2022.*.

[7] VG Ram ramkrithik Satyanarayana N Kalidindi, "Estimation of construction and demolition waste using waste generation rates in Chennai, India".

[8] S. K. H. P. A. Samreen, "'Estimation of C&D Waste – Davangere Case Study," *IRJET, vol. 7, no. 8, pp. 1069–1075, 2020.*.

[9] Directorate of Municipal Administration, "'Karnataka State C&D Waste Management Policy,' Government of Karnataka, 2020."

[10] Deccan Herald, "'Who cares about construction waste in Bengaluru," *Deccan Herald*, 2019.

[11] Times of India, "'Bengaluru generates 6,700 tonnes/day of C&D waste: BBMP," 2024.

[12] MoUD, "'Guidelines for Environmental Management of C&D Waste," *Ministry of Urban Development, Government of India, 2017.*.

[13] BMTPC, "'Waste Management Newsletter – World Habitat Day Edition," *Building Materials & Technology Promotion Council, 2018.*.

[14] H. Böke, S. Akkurt, B. Ipekoğlu, and E. Uğurlu, "Characteristics of brick used as aggregate in historic brick-lime mortars and plasters," *Cem. Concr. Res.*, vol. 36, no. 6, pp. 1115–1122, Jun. 2006, doi: 10.1016/j.cemconres.2006.03.011.

[15] T K Jyothi, "Development of geopolymer-lime-pozzolana masonry units/binders using tank-bed soil and brick-powder," 2017.

[16] R. A. Hamza, S. El-Haggar, and S. Khedr, "Marble and Granite Waste: Characterization and Utilization in Concrete Bricks," *Int. J. Biosci. Biochem. Bioinforma.*, pp. 286–291, 2011, doi: 10.7763/ijbbb.2011.v1.54.

[17] S. K. Agarwal and D. Gulati, "Utilization of industrial wastes and unprocessed micro-fillers for making cost effective mortars," *Constr. Build. Mater.*, vol. 20, no. 10, pp. 999–1004, Dec. 2006, doi: 10.1016/j.conbuildmat.2005.06.009.

[18] L. Zhu and Z. Zhu, "Reuse of Clay Brick Waste in Mortar and Concrete," 2020, *Hindawi Limited*. doi: 10.1155/2020/6326178.

[19] Z. Xu *et al.*, "Production of sustainable plastering mortar containing waste clay brick aggregates," *Case Studies in Construction Materials*, vol. 16, Jun. 2022, doi: 10.1016/j.cscm.2022.e01120.

[20] L. Zheng, Z. Ge, Z. Yao, and Z. Gao, "Mechanical Properties of Mortar with Recycled Clay-Brick-Powder," in *ICCTP 2011*, Reston, VA: American Society of Civil Engineers, Jul. 2011, pp. 3379–3388. doi: 10.1061/41186(421)335.

[21] F. A. Selim, F. S. Hashem, and M. S. Amin, "Mechanical, microstructural and acid resistance aspects of improved hardened Portland cement pastes incorporating marble dust and fine kaolinite sand," *Constr. Build. Mater.*, vol. 251, Aug. 2020, doi: 10.1016/j.conbuildmat.2020.118992.

[22] L. A. Pereira-De-Oliveira, J. P. Castro-Gomes, and P. M. S. Santos, "The potential pozzolanic activity of glass and red-clay ceramic waste as cement mortars components," *Constr. Build. Mater.*, vol. 31, pp. 197–203, Jun. 2012, doi: 10.1016/j.conbuildmat.2011.12.110.

[23] A. Chajec, "The use of granite powder waste in cementitious composites," *Journal of Materials Research and Technology*, vol. 25, pp. 4761–4783, Jul. 2023, doi: 10.1016/J.JMRT.2023.06.253.

[24] A. M. Rashad, "An overview on rheology, mechanical properties and durability of high-volume slag used as a cement replacement in paste, mortar and concrete," Oct. 30, 2018, *Elsevier Ltd*. doi: 10.1016/j.conbuildmat.2018.07.150.

[25] I. S. Buyuksagis, T. Uygunoglu, and E. Tatar, "Investigation on the usage of waste marble powder in cement-based adhesive mortar," *Constr. Build. Mater.*, vol. 154, pp. 734–742, Nov. 2017, doi: 10.1016/j.conbuildmat.2017.08.014.

[26] A. Danish, M. A. Mosaberpanah, M. U. Salim, R. Fediuk, M. F. Rashid, and R. M. Waqas, "Reusing marble and granite dust as cement replacement in cementitious composites: A review on sustainability benefits and critical challenges," Dec. 01, 2021, *Elsevier Ltd*. doi: 10.1016/j.jobe.2021.102600.

[27] R. Gmür, K. C. Thienel, and N. Beuntner, "Influence of aging conditions upon the properties of calcined clay and its performance as supplementary cementitious material," *Cem. Concr. Compos.*, vol. 72, pp. 114–124, Sep. 2016, doi: 10.1016/j.cemconcomp.2016.05.020.

[28] F. G. Cabrera-Covarrubias, J. M. Gómez-Soberón, J. L. Almaral-Sánchez, S. P. Arredondo-Rea, M. C. Gómez-Soberón, and R. Corral-Higuera, "An experimental study of mortars with recycled ceramic aggregates: Deduction and prediction of the stress-

https://doi.org/10.71058/jodac.v10i06004

strain," *Materials*, vol. 9, no. 12, 2016, doi: 10.3390/ma9121029.

[29] A. Kaur and V. S. Sran, "Partial Replacement of Fine Aggregates with Brick Dust," in *International Journal of Advance Research and Innovation*, 2017, p. 141401.

[30] A. Rao, K. N. Jha, and S. Misra, "Use of aggregates from recycled construction and demolition waste in concrete," *Resour. Conserv. Recycl.*, vol. 50, no. 1, pp. 71–81, Mar. 2007, doi: 10.1016/j.resconrec.2006.05.010.

[31] F. Bektas, K. Wang, and H. Ceylan, "Effects of crushed clay brick aggregate on mortar durability," *Constr. Build. Mater.*, vol. 23, no. 5, pp. 1909–1914, May 2009, doi: 10.1016/j.conbuildmat.2008.09.006.

[32] L. G. Li, Z. H. Lin, G. M. Chen, A. K. H. Kwan, and Z. H. Li, "Reutilization of Clay Brick Waste in Mortar: Paste Replacement versus Cement Replacement," *Journal of Materials in Civil Engineering*, vol. 31, no. 7, Jul. 2019, doi: 10.1061/(asce)mt.1943-5533.0002794.

[33] J. J. Chen, P. L. Ng, B. H. Li, and A. K. H. Kwan, "Concurrent paste replacement and aggregate replacement strategy for producing eco-efficient and low-carbon concrete," *Clean Technol. Environ. Policy*, vol. 24, no. 8, pp. 2459–2477, Oct. 2022, doi: 10.1007/s10098-022-02326-w.

[34] L. G. Li, Y. M. Wang, Y. P. Tan, A. K. H. Kwan, and L. J. Li, "Adding granite dust as paste replacement to improve durability and dimensional stability of mortar," *Powder Technol.*, vol. 333, pp. 269–276, Jun. 2018, doi: 10.1016/j.powtec.2018.04.055.

[35] J. J. Chen, A. K. H. Kwan, and Y. Jiang, "Adding limestone fines as cement paste replacement to reduce water permeability and sorptivity of concrete," *Constr. Build. Mater.*, vol. 56, pp. 87–93, Apr. 2014, doi: 10.1016/j.conbuildmat.2014.01.066.

[36] L. G. Li, Z. H. Huang, Y. P. Tan, A. K. H. Kwan, and H. Y. Chen, "Recycling of marble dust as paste replacement for improving strength, microstructure and eco-friendliness of mortar," *J. Clean. Prod.*, vol. 210, pp. 55–65, Feb. 2019, doi: 10.1016/j.jclepro.2018.10.332.

[37] K. Venu Madhava Rao, B. V. Venkatarama Reddy, and K. S. Jagadish, "Flexural bond strength of masonry using various blocks and mortars," *Mater. Struct.*, vol. 29, no. 2, pp. 119–124, Mar. 1996, doi: 10.1007/BF02486202.

[38] Z. F. Jawad, R. J. Ghayyib, and A. J. Salman, "Microstructural and compressive strength analysis for cement mortar with industrial waste materials," *Civil Engineering Journal (Iran)*, vol. 6, no. 5, pp. 1007–1016, May 2020, doi: 10.28991/cej-2020-03091524.

[39] C. Xue, H. Qiao, H. Cao, Q. Feng, and Q. Li, "Analysis on the Strength of Cement Mortar Mixed with Construction Waste Brick Powder," *Advances in Civil Engineering*, vol. 2021, 2021, doi: 10.1155/2021/8871280.

[40] A. Chatterjee and D. Das, "Assessing flow response of self-compacting mortar by taguchi method and ANOVA interaction," *Materials Research*, vol. 16, no. 5, pp. 1084–1091, Sep. 2013, doi: 10.1590/S1516-14392013005000083.

[41] B. of Indian Standards, "IS 2250 (1981): Code of Practice for Preparation and Use of Masonry Mortars."

[42] B. of Indian Standards, "IS 4031-11 (1988): Methods of physical tests for hydraulic cement, Part 11: Determination of density."

[43] B. of Indian Standards, "IS 4031-1 (1996): Methods of physical tests for hydraulic cement, Part 1: Determination of fineness by dry sieving."

[44] B. of Indian Standards, "IS 2386-3 (1963): Methods of test for aggregates for concrete, Part 3: Specific gravity, density, voids, absorption and bulking."

[45] B. of Indian Standards, "IS 456 (2000): Plain and Reinforced Concrete - Code of Practice."

[46] "Standard Test Method for Preconstruction and Construction Evaluation of Mortars for Plain and Reinforced Unit Masonry 1." [Online]. Available: www.astm.org,