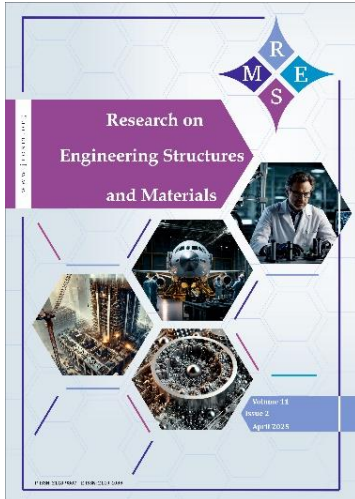




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Waste mortar as sustainable material in reactive powder concrete

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Abstract

This study investigates the feasibility of producing sustainable Reactive Powder Concrete (RPC) through the incorporation of silica fume (SF) and waste mortar (WM) as partial replacements for cement and fine aggregate, respectively. Four RPC mixtures were experimentally evaluated using silica fume contents of 15% and 20% combined with 50% waste mortar replacement. The mechanical performance was assessed through compressive and flexural strength tests at curing ages of 7 and 28 days, supported by statistical analysis of the experimental data. The findings revealed that increasing silica fume content significantly enhanced the mechanical properties due to improved pozzolanic activity, matrix densification, and refinement of the interfacial transition zone (ITZ). The mixture containing 20% SF and 50% WM exhibited the highest mechanical performance among the tested combinations, achieving compressive strengths of 103.18 MPa and 123.80 MPa at 7 and 28 days, respectively, in addition to a maximum flexural strength of 23.5 MPa. Also, the incorporation of waste mortar improved particle packing density and contributed to secondary hydration reactions, resulting in enhanced fiber matrix interaction and crack resistance. Statistical evaluation confirmed acceptable consistency and reliability for most RPC mixtures. The findings demonstrate that waste mortar can be successfully utilized in RPC production without compromising structural performance. While, a full life cycle assessment is required to quantify the exact ecological savings, this substitution highlights a promising avenue for enhancing the sustainability profile of RPC by reducing reliance on cement and natural sand.

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1. Introduction

Ultra-high-performance concrete (UHPC), also referred to as Reactive Powder Concrete (RPC), is an advanced cementitious composite characterized by its exceptional mechanical properties and superior durability. Initially introduced by Pierre Richard and later refined by Marcel Cheyrezy and Nicolas Roux at the French construction firm Bouygues in the 1990s [1,2]. UHPC represents a significant leap in material science. Parallel to these technical advancements, the construction industry faces mounting environmental pressure, as cement production currently accounts for approximately 8% of global CO₂ emissions. Consequently, there is a growing imperative to develop eco-friendly alternatives. Integrating industrial waste into RPC mixtures has the potential to contribute to reducing cement consumption and environmental impact, by serving as a material substitution, which supports the development of sustainable, high-performance materials [3]. In this context, silica fume is an industrial by-product obtained during the smelting process in the silicon and ferrosilicon industry. Silica fume plays an important role in the production of high strength and high-performance concrete. Increased environmental awareness

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has further helped the usage of industrial by-products to develop the sustainability of concrete production. The utilization of industrial by-products has become an attractive alternative for enhancing sustainability in concrete production [4]. Silica fume, ultra-fine sand (150–600 μ m), and superplasticizer are conventionally employed in the formulation of reactive powder concrete; the incorporation of superplasticizer is imperative in RPC applications due to the exceedingly low water/binder ratio, approximately 0.2. This minimized water/binder ratio is crucial for attaining the desired compressive strength, which is typically around 120MPa or less. Steel fibers are commonly integrated into RPC to enhance the concrete ductility, given that the combined material inherently exhibits considerable brittleness. A fractional volume ratio of 2%–3% is generally implemented to mitigate the risk of abrupt of the concrete failure. The RPC matrix exhibits a high density attributable to the significant utilization of Supplementary cementitious materials, in combination with fine sand; consequently, the packing density of the cementitious matrix is significantly enhanced, which accounts for the exceptional mechanical strength and durability characteristics of reactive powder concrete (RPC). Most RPC mixtures reported in the literature do not incorporate coarse aggregates, as the interfacial transition region between cement matrix and coarse aggregates is considered the weakest phase within the concrete microstructure [5]. Reactive powder concrete (RPC) is designed in order to achieve elevated strength, durability, and sustainability in structural applications. Compared with high-performance concrete (HPC), RPC displays greater compressive and flexural strengths, greater toughness, and markedly lower porosity and permeability. Microstructural analyses verify that silica fume improves bond between fiber and cement matrix, leading to improved fiber pullout energy [6]. The literatures show observed silica fume ranges across many experimental studies used in RPC studies are roughly: 10% to 30% by weight of cementitious material, many recent works focus on (15–25) % of SF. Several authors report performance improvements up to about (20–25)% SF, beyond which workability problems or diminishing returns in strength are observed [7,8,9]. The incorporation of silica fume at replacement range of (0–20)% significantly improves the mechanical performance of RPC. When the SF content was 15%, the 28-day flexural and compressive strengths were the highest [2]. While rapid urbanization has positioned the construction industry as a cornerstone of national economies, it has simultaneously created a critical need for sustainable waste management due to the massive generation of demolition debris. However, this growth has resulted in the generation of large quantities of construction and demolition waste, leading to acute environmental effects. An effective approach to managing this waste is its utilization in concrete production in the form of recycled coarse and/or fine aggregates [10].

Concrete is the most commonly utilized construction material worldwide; however, the vast extraction of virgin raw materials required for its production has caused significant environmental impacts. In response to growing sustainability concerns, numerous research studies have been conducted to investigate the incorporation of waste materials as partial or full replacements for conventional constituents in concrete, aiming to reduce environmental problems while maintaining or enhancing material performance [11]. The optimum levels of replacing dune sand by waste foundry sand 5%, 10%, 15% and 20% respectively [12]. Utilization rate of coal gangue as a sand replacement at different replacement ratios weight from 0– 100% was studied in reactive powder concrete (RPC) [13]. The evaluation of recycled fine aggregate incorporated into new concrete mixes was performed through tests on the hardened plain concrete. The investigation examined the using of the influence of recycled fine aggregate on new concrete mixes was investigated by means of experimental tests performed on hardened plain concrete specimens. The mixes were prepared with fine aggregate replacement ratios of 0% (control mix), 25%, 50%, and 100% concrete product, fine aggregate incorporated in concrete mixes with replacement ratios of 0% (control), 25%, 50%, and 100% [14]. The glass sand contents varying from (10 % to 50 %) as fine aggregate replacement [15].

Despite the extensive research on reactive powder concrete (RPC), most previous studies have primarily focused on optimizing silica fume content and mechanical performance under conventional material compositions. However, limited attention has been given to the combined effect of silica fume and the incorporation of recycled or waste based fine materials as partial

replacements for natural sand, particularly in terms of their influence on both compressive and flexural behavior of RPC.

Therefore, this study aims to investigate the synergistic effect of silica fume and waste mortar in Reactive Powder Concrete. Although silica fume is widely used to enhance RPC performance and waste mortar has been considered as a sustainable replacement material, their combined effect has not been systematically evaluated. This study addresses this gap by providing a comprehensive assessment of their interaction and its implications for mechanical properties, durability, and sustainability. The research specifically evaluates their effect on compressive strength and flexural strength. Furthermore, this study seeks to evaluate the selected replacement levels to identify the most effective mixture that achieves a balance between enhanced mechanical properties and environmental sustainability. The novelty of this work lies in combining high performance RPC technology with sustainable material utilization, contributing to reducing cement consumption and promoting eco-friendly construction practices.

2. Materials

In this study, all constituent materials were selected to meet the performance requirements of Reactive Powder Concrete. Ordinary Portland cement, fine sand, silica fume, superplasticizer, steel fibers, water, and waste mortar were evaluated in terms of its type, physical and chemical properties, gradation, strength characteristics, fineness and compatibility with the other components.

2.1 Cement

Ordinary Portland Cement (OPC) was employed in the experimental program of this study. This type of cement is classified as a general-purpose cement and is suitable for all applications where the specific properties of other cement types are not required. In this article, the cement used for produce concrete (OPC) provide via Al-Mass Company. The physical properties and chemical analysis of the cement employed showed in tables (1) and (2). The compliance of the cement was verified according to the Iraqi Standard (IQS No. 5/2019) [16].

Table 1. Physical properties of the cement

Initial Setting Time (hour: min.)	1:08	45 (Min.)
Final Setting Time (hour: min.)	4:30	10:00 (Max.)
Fineness (Blaine) in m ² /kg	425	250 (Min.)
Compressive Strength (MPa)		
At 2 days	16.5	>10
28 days	.744	>42.5

Table 2. Chemical analysis of the cement

Oxide	Test result	According to IQS Limits
CaO%	60.41	
SiO ₂ %	21.84	
Al ₂ O ₃ %	4.72	
Fe ₂ O ₃ %	3.60	
MgO%	1.50	≤ 5%
SO ₃	2.3	≤ 2.5%
Loss on Ignition%	3.27	≤ 4%
Total	97.72	
Free lime %	1.12	
Insoluble Residue%	1.12	≤ 1.5%
L.S.F	0.83	0.66-1.02
M.S.	2.63	
M.A.	1.31	
C ₃ S%	38.67	

Oxide	Test result	According to IQS Limits
C ₂ S%	31.74	
C ₃ A%	6.42	
C ₄ AF%	10.95	

2.2 Fine Aggregate

Fine sand generally requires a higher water content to achieve a given level of workability due to its larger specific surface area. In this study, fine sand was utilized as a constituent material, passing through a 0.6 mm sieve; the fine sand was tested for its physical properties and sieve analysis in accordance with the Iraqi specifications (IQS No.45/1984) [17]. The test results are presented in tables (3) and (4).

Table 3. Sieve analysis of fine sand.

Sieve size (mm)	Cumulative passing%	Limits of Iraqi specification No.45/1984)
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.6	99	80-100
0.3	46	15-50
0.15	8	0-15

Table 4. Physical properties of fine sand.

Properties	Test result	Limits of Iraqi specification No.45/1984
Specific gravity	2.64	/
Fineness modulus	2.6	/
Absorption	2.3%	/
Sulfate content	0.244%	≤ 0.5 %

2.3 Waste Mortar

Waste mortar was utilized as a partial replacement for fine aggregate (sand) in the RPC mixtures to produce sustainable Reactive Powder Concrete and to conserve fine sand resources. The waste mortar was obtained from the remains and residues of cement plastering works from some buildings, passing from sieve 0.6mm. Table(5) display graded the nominal particle size distribution of the waste mortar according to requirements of (IQS No. 45/1984) and (Fig. 1) [17].



Fig. 1. Waste mortar sand

Table 5. Particle size distribution of waste mortar

Sieve size (mm)	Cumulative passing%	Iraqi specification No.45/1984) Limits)
10	100	100
4.75	100	95-100
2.36	100	95-100
1.18	100	90-100
0.6	100	80-100
0.3	49	15-50
0.15	15	0-15

2.4 Silica Fume

Silica fume was utilized as a mineral admixture that added to Reactive Powder Concrete mixtures. The physical and chemical characteristics, in addition to the strength activity index of silica fume, were evaluated in accordance with ASTM C1240 [18]. Table (6) presents the chemical analysis of silica fume and (Fig. 2).

Table 6. Chemical analysis of silica fume

Oxide Composition	Oxide Content %	ASTM C-1240 Limitations
SiO ₂	92	≥ 85
Al ₂ O ₃	0.50	---
Fe ₂ O ₃	1.25	---
Na ₂ O	0.35	---
K ₂ O	1.10	---
CaO	0.37	< 1
MgO	0.99	---
SO ₃	0.29	< 2
L.O.I.	3.15	≤ 6.0
Strength Activity Index	170	> 105



Fig. 2. Silica Fume

2.5 Water of Mixture

Tap Water employed in the mixing and curing concrete specimens, may affect not concrete strength but in addition setting time. In general, mixing water is rarely a factor in concrete strength. Mixing and curing water had a temperature at (25°C± 2) (IQS No. 1703/1992) [19].

2.6 Steel Fibers

A straight shape and an average tensile strength of more than 2300 MPa used in this work. Table (7) demonstrates the steel fiber properties and in (Fig. 3). Steel fibers were added in this study at a percentage by 2% volume of concrete [20].

Table 7. Properties of steel fibers utilized

Property	Value
Surface	Brass coated
Density	7860 kg/m ³
Tensile Strength	> 2300MPa
shape	Straight
Melting Point	1500°C
rate of length	13mm±1mm
Diameter	0.2mm±0.05mm
Aspect ratio (Lf/Df)	65



Fig. 3. Steel fibers used in this study

2.7 Superplasticizer

The superplasticizer (high- range water reducer) is employed to enhance homogeneity and reduces the risk for segregation. Its use of superplasticizer ensured adequate workability for efficient mixing and casting. The specific product used is based on modified polycarboxylic ether (Glenium 54), purchased from Master Builders Solutions construction chemicals (BASF), conforming to ASTM C494 [21]. Table (8) shows the superplasticizer properties.

Table 8. the superplasticizer properties

Form	Whitish to straw colored liquid
Relative density	1.07
PH	5-8
Dosage	0.50 and 1.75 liters per 100kg

3. Experimental Methods

3.1 RPC Design

The constituent materials were mechanically mixed following a controlled sequence to ensure uniform distribution and adequate workability. Initially, dry materials (cement, silica fume, sand, and waste mortar) were blended to achieve homogeneity, followed by the gradual addition of water and superplasticizer. Steel fibers were then introduced to ensure uniform dispersion without agglomeration. Strength requirements depend on the intended employ of the concrete. The relationships of strength, mix proportion, and cement factor are complex. Mixtures having strengths outside the ranges demonstrated can be made by varying the mix proportions. The experimental program consisting of four trial mixtures was conducted to determine the most effective proportions of silica fume, waste mortar, water-to-binder ratio, and superplasticizer dosage required to achieve the target workability and mechanical performance of RPC. Silica fume was incorporated as a cement replacement at levels of 15% and 20% to optimize particle packing

density. The selection of 50% waste mortar as a replacement for natural sand was based on achieving a sustainable balance without critical loss in workability, as observed during the initial trial mixes. In this study, silica fume was used as a partial replacement for cement. The replacement percentages were calculated by mass of cement, while the total binder content was maintained constant throughout the mixtures. The mix proportions were determined based on the total binder content (cement + silica fume). Silica fume replacement was calculated as a percentage of the cement mass, whereas the waste mortar replacement was calculated relative to the mass of the fine aggregate. The superplasticizer (SP) dosage was maintained at 3.5 L per 100 kg of cement. The absolute value of 33.25 L/m^3 presented in table (9) was derived by applying this specific dosage rate to the cement content used in the mixtures.

Table 9. Detailed mix proportions of RPC mixtures (kg/m^3)

Mix No.	OPC Kg	Silica Fume %	Silica Fume Kg	Steel fiber Kg	Fine Aggregate Kg	Sand waste mortar%	Sand waste mortar Kg	Water Kg	SP Liter
M1	807.5	15	142.5	157	1050	0	0	171	33.25
M2	760	20	190	157	1050	0	0	171	33.25
M3	807.5	15	142.5	157	525	50	525	171	33.25
M4	760	20	190	157	525	50	525	171	33.25

3.2 Mixing Process

- All dry constituents were initially mixed for 2 minutes to ensure a uniform distribution of the materials (cement, silica fume, sand or waste mortar).
- After adding 70% of the mixing water, the mixture was constantly mixed for a further 3 minutes.
- After adding 15% of the water mixture containing 70% superplasticizer, the mixture was stirred once more for three minutes.
- For one minute, the mixing was halted.
- To ensure that the fiber was evenly distributed, the residual water and superplasticizer were incorporated into the mixture and mixing for 4 minutes. After that, steel fibers were added and mixed for 1 minute, for a total of 14 minutes.

3.3 Casting

The molds were cleaned and a tiny layer of oil was applied to the inside to keep the concrete from adhering on the mold's walls and ready for casting samples in accordance with ASTM C192/C192M [22], and the samples were then covered for a full day with polythene sheet.

3.4 Samples Curing

After demolding, the concrete specimens were immediately cured by full immersion in water tanks maintained at a controlled temperature of $25^\circ\text{C} \pm 2^\circ\text{C}$ until the designated testing ages of 7 and 28 days.

3.5 Tests

3.5.1 Fresh Properties

The flow table test was conducted to determine the appropriate water-to-cement ratio (w/c) and evaluate the workability of the RPC mixtures through the measurement of flow spread values. The flowability of the fresh mixtures was evaluated using the flow table test in accordance with ASTM C1437, as shown in (Fig.4).

3.5.2 Compressive Strength

Compressive strength was determined in accordance with ASTM International (ASTM C109/C109M-2020) using cube specimens of $(50 \times 50 \times 50) \text{ mm}$. Three specimens were tested for

each mixture at curing ages of 7 and 28 days, and the average value was adopted as the compressive strength result, as shown in (Fig. 5).



Fig.4. Flow table test of RPC mixtures



Fig. 5. Compressive strength testing machine used for specimen testing

3.5.3 Flexural Strength

Flexural strength was determined in accordance with ASTM) C348,2016) using prismatic specimens of dimensions $40 \times 40 \times 160$ mm. The specimens were tested undergo a center-point loading test, the flexural strength machine as shown in (Fig.6).



Fig. 6. Flexural strength test setup showing the center point loading configuration for prism specimens

4. Results and discussion

4.1 Workability of RPC

The workability of RPC mixtures was determined by using the mortar flow table test in accordance with (ASTM C1437, 2020) [23]. The main aim to carry out flow table test is to determine the best superplasticizer dosage and w/c required to achieve workability for ease of handling and replacement. Based on the preliminary trials, the optimum superplasticizer dosage was fixed at 3.5 liters per 100 kg of OPC and W/C Ratio 0.18, Table (10) show the measured flow spread values for each RPC mixtures.

Variations in flow among the mixtures reflected the competing physical effects of silica fume and mortar waste. Increasing silica fume from 15% to 20% led to a reduction in flow, primarily due to the increase in ultrafine particles and the specific surface area, which raises water demand that agree with [2]. Mixtures containing 50% mortar waste (M3, M4) showed a clear reduction in flow, with values to 200 and 190 mm, respectively. This reduction is mainly due to the porous and

angular nature of mortar waste particles, which increase internal friction and absorb part of the mixing water agree with [13].

Table 10. Flow spread values for each RPC mixture

Mix No.	Flow spread mm
M1	255
M2	250
M3	200
M4	190

4.2 Compressive Strength

The results of compressive strength are shown clearly in table (11) and (Fig. 7), incorporation of silica fume at 20% in mix M2 increased the strength to 100.35 MPa, representing an improvement of approximately 11.5% compared to the control mix. Similarly, mix M3 (15% silica fume with 50% sand waste mortar) achieved 97.93 MPa, showing an increase of about 8.8%. The highest enhancement was observed in mix M4 (20% silica fume with 50% sand waste mortar), which reached 103.18 MPa, corresponding to an increase of approximately 14.6% relative to M1.

28 days strength, the reference mix (M1) reached 99.82 MPa. Mix M2 showed an increase to 119.62 MPa, indicating development of about 19.8%. Mix M3 reached 110.72 MPa, reflecting an increase of approximately 10.9%, while, mix M4 recorded the highest compressive strength of 123.80 MPa, representing a 24.0% improvement relative to the control mix. This improvement in mix M4 is likely associated with the synergistic filler and pozzolanic actions of the silica fume and waste mortar particles, which are widely reported in the literature to facilitate pore refinement and densification in RPC microstructure. Similar findings were reported in previous studies, where silica fume improved the interfacial transition zone and enhanced later age strength through secondary hydration reactions. In addition, recycled fine waste materials may provide supplementary pozzolanic reactivity and internal curing effects that further improve matrix compactness, agree with [26]. This behavior has been widely reported in RPC systems, where silica fume contents between 15% and 20% provide optimal strength development. These findings are in agreement with [2], who confirmed that incorporating silica fume up to 20% much improves compressive strength due to enhanced particle packing and pozzolanic reactivity. Furthermore, the role of waste mortar can be attributed to the presence of residual unhydrated cement grains, which undertake secondary hydration, thereby enhancing the bonding structure. This observation aligns with [13] who reported that recycled fine materials can improve compressive strength when suitably incorporated due to internal curing and filler effects.

Table 11. Compressive strength and statistical analysis of RPC mixtures

Mix No.	7 Days (MPa)	7 Days		28 Days (MPa)	28 Days	
		C.V%	S.D(MPa)		C.V%	S.D(MPa)
M1	90.00	7.44	6.68	99.82	25.02	28.90
M2	100.35	19.13	19.32	119.61	1.74	1.60
M3	97.92	14.45	14.14	110.72	5.10	5.64
M4	103.17	11.54	11.90	123.80	16.80	20.80

The statistical analysis demonstrated that the compressive strength results exhibited acceptable consistency and repeatability for several investigated RPC mixtures. The coefficient of variation (CV%) values ranged from 7.44% to 19.13% at 7 days and from 5.10% to 25.02% at 28 days. According to recent studies, CV values below 10% indicate excellent repeatability, whereas values below 20% are generally considered acceptable for reactive powder concrete due to its dense and heterogeneous microstructure [26]. However, the M1 mixture at 28 days exhibited a CV value of 25.02%, indicating comparatively higher variability than the acceptable range. These results describe the dispersion and repeatability of the experimental data only and do not represent inferential statistical significance between mixtures. Among all mixtures, M2 at 28 days showed the

lowest variability with a CV value of 1.74%, reflecting a highly uniform internal structure and consistent hydration behavior agree with [27].

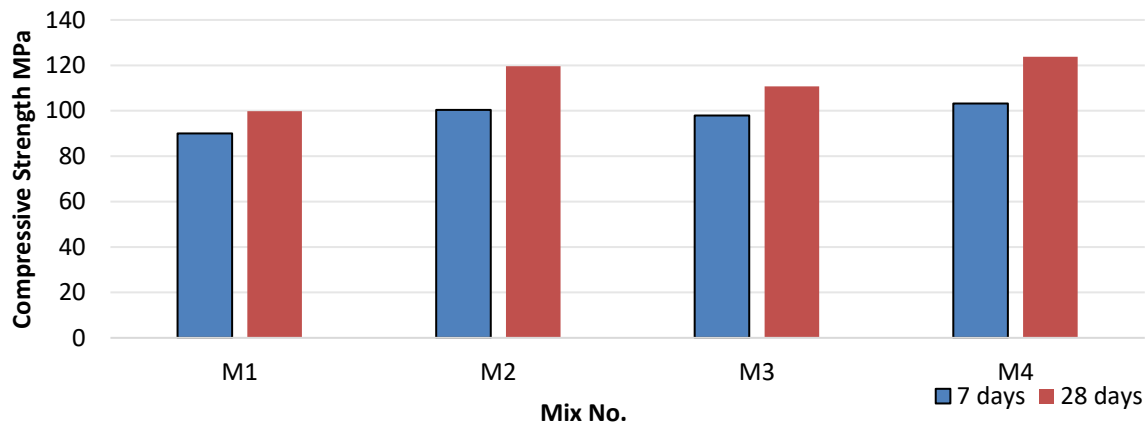


Fig. 7. The results of compressive strength (MPa)

4.3 Flexural Tensile Strength

The flexural strength results presented in Table 12 and Fig. 8 indicate a noticeable improvement in the mechanical performance of RPC mixtures incorporating silica fume and sand waste mortar. The reference mixture M1 exhibited flexural strengths of 12 MPa and 17 MPa at 7 and 28 days, respectively. Increasing the silica fume content from 15% to 20% in mixture M2 improved the flexural strength by approximately 10% at both curing ages, indicating that the additional silica fume contributed to a denser cementitious matrix through the pozzolanic reaction and micro-filler effect. This refinement of the pore structure enhanced the interfacial transition zone (ITZ) between the binder matrix and fine particles, thereby improving resistance to crack initiation under bending stresses agree with [28].

A more pronounced enhancement was observed when 50% sand waste mortar was incorporated. Mixture M3 achieved flexural strengths of 13.7 MPa and 19.6 MPa at 7 and 28 days, representing increases of about 14.2% and 15.3%, respectively, compared with M1. This behavior can be attributed to residual unhydrated cement particles and angular texture of the waste mortar, which enhanced particle packing and improved mechanical interlocking within the matrix. The highest flexural performance was recorded for mixture M4 containing 20% silica fume and 50% sand waste mortar, reaching 15.4 MPa at 7 days and 23.5 MPa at 28 days. These values correspond to increases of approximately 28.3% and 38.2%, respectively, relative to the control mixture. The substantial improvement suggests a strong synergistic interaction between the high silica fume content and recycled mortar particles. From a mechanistic perspective, the enhanced matrix densification improved stress transfer efficiency across the microstructure, while the refined ITZ reduced stress concentration zone corresponding to [29].

Analytically, the observed differences in flexural strength is highly sensitive to microstructural integrity and fiber-matrix interaction in RPC systems. Although steel fibers were maintained constant in all mixtures, the improvement in matrix quality directly influenced the bond behavior between fibers and the surrounding cementitious phase. A denser matrix increases the pull-out resistance of fibers, enabling more efficient stress redistribution after micro-crack formation. This explains why mixtures with higher silica fume and recycled mortar contents exhibited greater flexural resistance rather than merely proportional increases relative to compressive strength. The improved fiber anchorage likely contributed to delaying unstable crack propagation and promoted a more ductile flexural response corresponding to [30].

Regarding statistical evaluation, mixtures M1 and M2 showed moderate coefficients of variation ranging from 8.3% to 10.33%, whereas M3 exhibited the lowest variability (3.02–3.17%), indicating more homogeneous internal structure and consistent crack resistance. In contrast, M4 showed higher variability despite achieving the highest strength values, which may be related to

localized heterogeneity caused by the increased fineness and packing density of the blended materials. Nevertheless, the overall results confirm that the incorporation of silica fume and sand waste mortar can significantly improve the flexural behavior of sustainable RPC while maintaining acceptable experimental consistency agree with [27].

Table 12. Flexural strength and statistical analysis of RPC mixes

Mix No.	7days (MPa)	7 Days		28 days (MPa)	28 Days	
		C.V%	S.D(MPa)		C.V%	S.D(MPa)
M1	12	8.32	0.99	17	8.30	1.41
M2	13.20	10.33	1.37	18.90	10.29	1.94
M3	13.70	3.02	0.44	19.60	3.17	0.62
M4	15.40	19.76	3.03	23.50	19.75	4.33

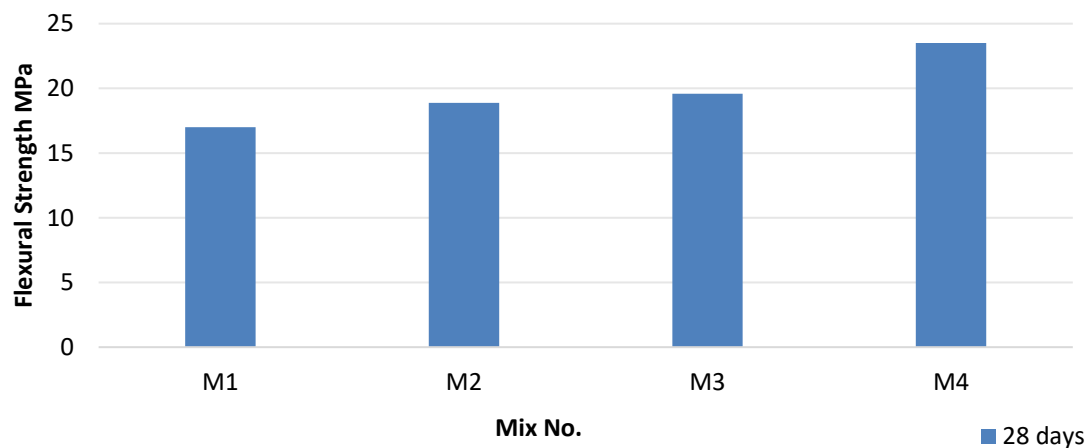


Fig. 8. Comparison of flexural strength of RPC mixes at 28 days

5. Conclusions

Based on the experimental results obtained in this study, the incorporation of silica fume as a partial cement replacement and waste mortar as a partial fine aggregate replacement influenced the fresh and mechanical properties of reactive powder concrete. The main conclusions derived from the experimental investigation are summarized as follow:

- The workability of RPC mixtures was reduced due to the low W/C or water/binder ratio (0.18) and the incorporation of silica fume, which increased the mixture's viscosity; however, the use of a superplasticizer effectively compensated for this reduction and ensured adequate flowability for proper mixing and casting.
- The incorporation of silica fume significantly enhanced the mechanical properties of RPC. Increasing the silica fume content from 15% to 20% resulted in noticeable improvements in both compressive and flexural strengths due to enhanced pozzolanic activity and matrix densification.
- The use of waste mortar as a 50% replacement for fine sand resulted in higher compressive and flexural strengths compared with the reference mixture development. This improvement is attributed to the presence of residual unhydrated cement particles, which promote secondary hydration, as well as improved particle packing and interfacial bonding.
- The merged use of 20% silica fume and 50% waste mortar Mix M4 reached the higher performance, recording compressive strengths of 103.177 MPa and 123.803 MPa at 7 and 28 days, respectively, and the highest flexural strength of 23.5 MPa. This indicates a strong synergistic effect between these materials.

- The statistical analysis showed that most RPC mixtures achieved acceptable compressive strength variability ($CV\% < 20\%$), with mixture M2 at 28 days exhibiting excellent consistency ($CV = 1.74\%$). In disparity, mixture M1 at 28 days showed the highest variability (25.02%), likely due to inhomogeneous particle packing and fiber dispersion. Overall, the results confirm that proper mix design and curing control are critical for minimizing variability in RPC.
- The observed enhancement in flexural strength is likely associated with the refined matrix quality provided by the silica fume, which plays a key role in strengthening the interfacial transition zone (ITZ).
- From a structural behavior viewpoint, RPC mixtures exhibited brittle behavior under compression, while showing semi-ductile behavior under flexural loading due to the presence of steel fibers, which enhanced crack bridging and delayed crack propagation.
- The results of this study demonstrate the technical feasibility of producing RPC by incorporating industrial waste materials. This approach offers a promising alternative for sustainable concrete construction by reducing the reliance on natural raw materials.

Generally, this study demonstrates that the combination of silica fume and waste mortar in RPC not only improves mechanical performance but also advance sustainable construction practices. The conclusions provide a practical basis for enhancing RPC mixtures with enhanced strength and environmental benefits.

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