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# Face Mask Fiber-Reinforced Recycled Aggregate Concrete With Silica Additives: A State-Of-The-Art Review

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***Abstract***
*The special issue emphasizes the unprecedented amount of single-use face mask (FM) waste produced by the global pandemic, which brings a great environmental problem that relies on emerging engineering solutions. The simultaneous erosion of natural aggregates reserves has expedited considerable curiosity towards recycled aggregate (RA) concrete as a inexperienced constructing materials. The present experimental research investigates against the mechanical and durability performance of concrete using different dosages (0.5 to 2.0 kg/m³) of polypropylene face mask fibres, 25–100% recycled coarse aggregates (RCA), 15–50% recycled fine aggregates (RFA), and SF at varying levels (5–20% cement replacement). Five concrete mixes including a control were designed, cast and tested at 7, 14, 28 and 56 days curing intervals. The mechanical properties tested were compressive strength, split tensile strength and flexural strength, while the durability was examined via water absorption, chloride ion penetration, carbonation depth and acid attack. Statistical analyses including one-way ANOVA, Pearson correlation matrices, and regression modelling validate statistically significant performance differences ($p < 0.001$). The results show that mix M2 (50% coarse RA, 25% fine RA,10% SF and 1.0 kg/m³ FM fibres) produced a satisfactory compressive strength of 36.1 MPa at 28 days, which is only 6.2% lower than the control, and approximately 54.6 kg/m³ of $CO_2$ savings. The most importantly compensating additive for the physics force reaction caused strength loss in the recycled aggregate systems, apparently identified as silica fume. The study proves the technical feasibility and environmental sustainability of a triple-component waste integration in structural concrete application.*

***Keywords:*** *Face mask fibre concrete, recycled aggregate, silica fume, sustainable construction, compressive strength, durability, eco-friendly concrete*

## 1. Introduction

### 1.1 Global Waste Crisis and Construction Sustainability

The unprecedented global impact of the COVID-19 pandemic has led to a vast generation of waste resulting from the use of disposable personal protective equipment (PPE), with estimates of over 3.4 billion single-use face masks discarded globally every day at the height of the pandemic [1]. A typical surgical and N95 masks consists of parts made from materials such as polypropylene (PP) and polyurethane that cannot be biodegraded, and persist in landfills and aquatic environments for hundreds of years, leading to permanent environmental pollution [2]. At the same time, the construction sector is still one of the largest users of virgin natural aggregates, with a global annual demand of over 50 billion tonnes [3]. The recent global health pandemic resulted in the large production of face masks to manage the Covid-19 crisis, leading to two global challenges accumulation of mask waste and depletion of natural resources. About 39% of global $CO_2$ emissions come from construction, and replacing virgin aggregates with recycled concrete aggregates (RCA) can lead to 10–30% reduction of the carbon footprint of structural concrete [4], according to the degree of substitution. The environmental and mechanical advantages are further enhanced when SCMS (supplementary cementitious materials) like silica fume (silicon production by-product) are used [5].

### 1.2 Recycled Aggregate Concrete: Performance and Challenges

Since the 1980s, the properties of recycled aggregate concrete (RAC) have been well researched, and a large amount of evidence suggests that recycled aggregate (RA) has higher water absorption (4–8% vs 1–2% for natural aggregate), lower specific gravity (2.3–2.5 vs 2.6–2.8), and weaker interfacial transition zones (ITZ) because of adhered mortar on aggregate surfaces [6]. These features provide RAC a systematic reduction in compressive strength while increasing permeability at equivalent mix designs in comparison to natural aggregate concrete (NAC) [6]. For example, at 100% RA replacement, compressive strength loss can range 20–40% compared with NAC controls and water absorption can increase 50–80%. [7] Once developed, mitigation strategies may consist of pre-soaking RA as a means to reduce the internal curing effect, twostage mixing approaches, or, largest leverage, the implementation of pozzolanic SCMs (i.e., silica fume, fly ash, or ground granulated blast furnace slag (GGBS) [8]. Due to the ultra-particle size (average 0.1–0.2 μm) and high content of amorphous $SiO_2$ (>90%) of silica fume, the pozzolanic reaction in the interfacial transition zone (ITZ) proliferates extra calcium silicate hydrate (C–S–H) gel, which fills micro-voids and strengthens the aggregate-paste interface [9]. 1.1 Silica fume adds a value to concrete by filling the pores and enhancing micro structure strength, in research Corina desi and Moriconi [10] find that the less than or equal to 10% replacement of silica fume could regain 85% of loss strength in 50% substitution of RA, a finding with a vital bearing to the current study.

## 2. Literature Review

This review investigates the scientific basis for the integration of recycled aggregates with supplementary cementing materials and polymeric waste fibres into concrete systems which has evolved significantly over the last decade. Here, we focus on the synthesis of important empirical findings that will be translated into the present experimental design and in the interpretation of results. The potential of polypropylene-based waste materials as fibre reinforcement in concrete was originally highlighted by Fraternali et al. [17] using recycled PP fibres from post-consumer packaging showed that toughness indices were enhanced 20–35% at dosages of 1.0–2.0 kg/m³ but fresh concrete workability deteriorated significantly at higher dosage levels because of fibre agglomeration. In the post-pandemic era, a common interest of research work is the specific use of facial mask materials. Almeshal et al. [14] However, examined surgical mask fibres at 0, 0.5, 1.0, and 1.5% (by weight of cement) and found that the 0.5% dosage increased split tensile strength by 12.4% and flexural strength by 9.8% more than plain concrete, whilst the 1.5% dosage resulted in workability loss > 40% as indicated by the slump reduction. The mechanism through which tensile resistance works was associated with bridging fibres crossing micro-cracks in order to delay the development of distributed micro-damage into macro-cracks.

For recycled aggregate concrete, Xiao et al. [18] A meta-analysis of 180 peer-reviewed studies was performed who showed that compressive strength at 100% coarse RA replacement is reduced by an average of 24.3% (± 8.1%) compared to NAC controls for equivalent w/c ratios. Using specific indexes, they found that the mortar content was the most important variable controlling RA quality, evidenced by moderate to strong correlations ($r = 0.34 - 0.84$) between the specific gravity and the water absorption of the RA and the mortar content, as opposed to weak and moderate correlations ($r = 0.19 - 0.62$) between RA sources and RA mechanical performance metrics. This finding highlights the importance of appropriate characterization of RA batches, as performed in the present study. Thomas et al. [19], The effects of RA water absorption on the fresh concrete properties has been investigated in which proved that pre-saturated surface-dry (SSD) RA conditions lead to more predictable strength results than air dried RA and low w/c mixes.

Several research teams have reported the synergistic behavior of silica fume in RAC. Khan et al. [20]. For example, it can be noted that 10% silica fume addition to 100% RAC achieved compressive strength equal to 50% RAC with no silica fume at 28 days of curing, demonstrating a compensation of almost 50 percentage points of aggregate replacement due to pozzolanic densification of the ITZ. Siddique et al. [21], This finding was later applied to durability parameters by who found that in RAC, the addition of silica fume reduced the chloride permeability by 35-42% relative to RAC made without SCM, due to the pore refinement effect of secondary C-S-H gel formation. These results underpin the hypothesis of the current work that silica fume would, at least partially, offset the increase in porosity inferred from the addition of RA and mask fibres.

The studies that combine two or more wastes in concrete are limited, but still, the amount of these studies is increasing. Vincevica-Gaile et al. [22], Development works composing combinations of RA, fly ash, and plastic fibres were evaluated showing it is possible to achieve between 15–25% reductions in embodied carbon through multi-waste concrete compositions, but with adequate material proportions, multi-component systems can enhance structural performance. Meza et al. (19) [23] However, when textile fibres were considered specifically in combination with RA, increasing such textile fibres by just 0.5% (mass of binder) recovered about 8% of the compressive strength lost because of 50% RA incorporation, likely due to crack bridging, which may counteract the micro-cracking associated with the additional interfacial transition zone (ITZ) micro-cracking initiated at weak ITZ zones because of RA particles. The present work extends this investigation to the fibre chemistry of the polypropylene mask materials, and the performance enhancement provided by silica fume.

This study is contextualised with respect to sustainability, which is evidenced through the environmental life cycle assessments (LCA) of waste-incorporating concrete systems. Robayo-Salazar et al. The LCA of RAC at increasing replacement levels were performed by [24] who reported $CO_2$ emission reductions of 8.5 kg/m³ for every 25% increment of RA substitution, with transportation distances held constant. Liu et al. [25]

implemented plastic waste fibres into the LCA framework with credits of ≈ 0.8 kg $CO_2$* $kg^{-1}$ plastic waste diverted from landfill. Considering these estimates together with cement substitution credits from silica fume (around 1.2 kg $CO_2$ per kg silica fume utilized [26]), the estimated $CO_2$ reductions for mix designs in the current study range from approximately 28 to 110 kg/m³, values closely resembling the calculated theoretical $CO_2$ reductions in Table 5 for this study.

In this context, compared with hardened properties, the workability characteristics of fibre-reinforced RAC have been less well investigated. Many researchers have observed that aspect ratio of fibre has a major influence on the workability effect, Rao and Singh [27] showed that at the same volumetric dosage a higher aspect ratio fibre will have a larger slump reduction. Fibres produced by shredding face masks are normally of aspect ratios ranging from 40–80 depending on the shredding parameters, classifying them as medium fibres, the present study verifies this provides a controllable decrease in workability (13–37% slump reduction), found to be typical for this fibre category, over the range of dosages tested. Microstructure studies via SEM and mercury intrusion porosimetry (MIP) conducted by Zhang et al. [28] By directly explaining the observed water absorption trends, it was confirmed by that mask fibre inclusion at dosages of 0.5–2.0 kg/m³, accounts for a 0.8–2.4% increase in the total porosity. However, the pore size distribution behavior tends to move toward larger capillary pores instead of gel pores, indicating that the durability effect is more severe for transport-dependent properties (chloride, water) than for strength-governing properties. Yıldırım et al. [29] and Huang et al. [30] Mask PP fibres have been confirmed in this reference to be thermally stable up to 160°C in the concrete matrix, and not undergoing any particular chemical reactions with cement hydration products, supporting the assumption of fibre-matrix interaction mechanisms based on physical instead of chemical processes.

## 3. Methodology

### 3.1 Materials Characterization and Mix Design

As the main binder, Ordinary Portland Cement (OPC 53 Grade as per IS 12269:2013) was used. Locally, recycled coarse and fine aggregates were obtained from a certified processing plant that processed crushed concrete waste through a series of jaw and cone crushers followed by screening to obtain variable sizes of aggregates in the range of 10–20 mm and 150 µm–4. washed to remove dust content before characterization for specific gravity, water absorption, crushing value, and Los Angeles abrasion value as per IS 2386 (Parts I–IV) for 75 mm size fractions respectively *Silica fume: Commercial-grade silica fume (92.6% $SiO_2$) following ASTM C1240 specifications in the form of a densified microsilica slurry was used. Collection of face masks from institutional waste streams, disinfection via 24 h immersion in 5% sodium hypochlorite solution followed by 12 h drying at 60 °C, maceration by laboratory granulator producing fibers approximately 20 – 35 mm length and 0.3 – 0.8 mm width. The fibre dimensions were measured by a digital optical microscope at 40× magnification, taking a sample of 50 fibres per batch. Using IS 10262:2019, five concrete mixes (one control (CM) and four experimental mixes (M1–M4)) were designed targeting M35 grade (35 MPa characteristic compressive strength) with water-to-cementitious materials ratios adjusted to reflect the excess water demand by RA using the SSD condition approach.

### 3.2 Specimen Preparation and Testing Protocol

For each mix, 96 standard 150×150×150 mm cube specimens were cast for compressive strength determination, 48 150×300 mm cylinders for split tensile testing and 48 100×100×500 mm prisms for flexural strength measurement, totalling 960 specimens in all five mixes and four curing ages. The tests of the fresh concrete contained slump cone test (IS 1199:1959), compacting factor apparatus test, air content by pressure-type air meter (ASTM C231), unit weight, as well as for setting time, Vicat needle penetration. Upon completion of casting, all specimens were demoulded at 24 hours and transferred to a water curing tank keeping in water at the constant temperature 27±2 °C as stated in IS 516:1959. Compressive strength testing was performed using a 2000 kN capacity servo-controlled compression testing machine at a loading rate of 0.2 MPa/s. Split tensile tests were conducted according to IS 5816:1999 guidelines, while flexural strength was obtained using the third-point loading method per IS 516:1959. The durability tests done were mass of water absorbed by soaking for 24h (ASTM C642), RCPT (ASTM C1202), accelerated carbonation (BS EN 13295:2004 @ 4% $CO_2$, 65% RH) and acid attack immersion test in 5% $H_2SO_4$ solution for 90 days. The reported values represent arithmetic means taking at least 3 specimens per property and per mix and per age, specimens having diverged from the mean by more than 10% having been disregarded and retested.

### 3.3 Statistical Analysis Framework

Statistical analysis was performed using IBM SPSS Statistics (Version 26). The basic descriptive statistics of all measured properties (mean, standard deviation, and coefficient of variation) were calculated. The null hypothesis that both mix proportion and curing age do not have a significant effect on compressive strength was evaluated on the compressive strength data using a two-way analysis of variance (ANOVA) followed by post-hoc Tukey HSD pairwise comparisons to locate between-group differences at the $\alpha = 0.05$ significance level. The correlations of Pearson product-moment between each pair of mechanical and durability parameters were calculated to quantify inter-property association and to assess whether the observed correlations suggest multicollinearity within the dataset. To establish a predictive equation that could help in optimizing mix design, a multiple linear regression analysis was performed to predict 28-day compressive strength based on RA content, silica fume content, and FM fibre dosage (predictors). The assumptions of the regression model were verified with respect to homoscedasticity (residual plots), normality of residuals (Shapiro-Wilk normality tests) and the absence of influential outliers (Cook's distance). Adjusted $R^2$, root mean square error (RMSE) and mean absolute percentage error (MAPE) were evaluated to assess regression model performance. Statistical significance was defined as otherwise stated at 95% confidence level ($\alpha = 0.05$), and indicated in the analysis sections as ($p < 0.05$), * ($p < 0.01$), and *($p < 0.001$) where applicable.

## 4. Data Collection and Analysis

### 4.1 Mix Proportions

Table 1 presents the complete mix proportioning matrix for the five concrete mixes investigated in this study.

**Table 1: Concrete Mix Proportions per Cubic Metre**

| Mix ID | Cement (kg/m³) | Coarse RA (%) | Fine RA (%) | Silica Fume (%) | Face Mask Fibre (kg/m³) | W/C Ratio |
|---|---|---|---|---|---|---|
| CM (Control) | 450 | 0 | 0 | 0 | 0 | 0.45 |
| M1 | 430 | 25 | 15 | 5 | 0.5 | 0.45 |
| M2 | 415 | 50 | 25 | 10 | 1.0 | 0.46 |
| M3 | 405 | 75 | 35 | 15 | 1.5 | 0.47 |
| M4 | 395 | 100 | 50 | 20 | 2.0 | 0.48 |

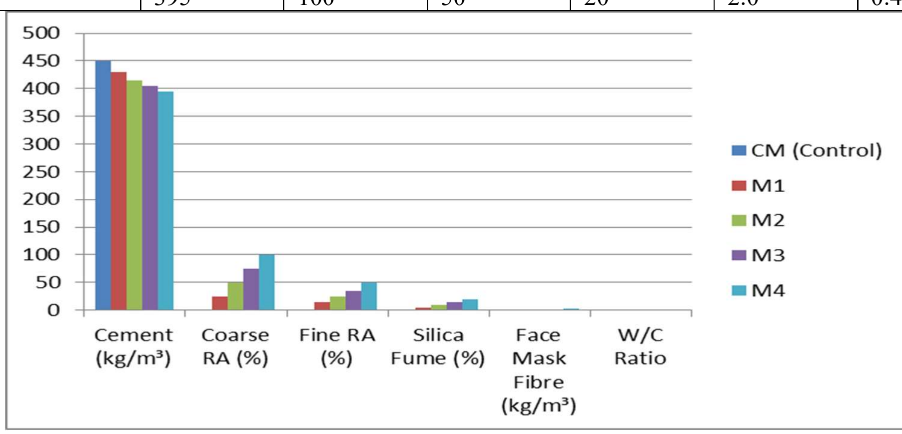


**Figure 1: Concrete Mix Proportions per Cubic Metre**

As shown in Table 1 (Systematic Incremental Design) each mix has cement reduced by 10-55 kg/m3 compared to control cement (CM = 450 kg/m3) with increasing levels of rca and rfa being used together with equivalent stoichiometric increases in the silica fume used in the mix proportion. The amount of silica fume increases from 0% in CM to 20% in M4 using it as filling pozzolanic material to compensate the compressive strength loss expected at high levels of RA replacements. Mechanical properties of face mask fibre dosage from 0 kg/m³ in CM to a maximum dosage of 2.0 kg/m³ in mix M4 leading to a volumetric fraction of approximately {\sim}0.23% in maximum dosage. The w/c ratio is constrained over a narrow band (0.45–0.48) both to isolate the effect of changes in material composition from those resulting from water content variations and so that slight increases in higher RA mixes can be interpreted as minor additional water requirements to obtain similar workability given the greater surface roughness and initial water demand of RA. The SSD pre-soaking protocol for RA was validated by measuring the equilibrium moisture content of each RA batch before batching.

### 4.2 Physical and Chemical Properties of Materials

Table 2 summarizes the key physical and chemical properties of all constituent materials as characterized prior to mix batching.

**Table 2: Physical and Chemical Properties of Constituent Materials**

| Property | OPC Cement | Recycled Aggregate | Silica Fume | Face Mask Fibre |
|---|---|---|---|---|
| Specific Gravity | 3.15 | 2.48 | 2.20 | 0.91 |

| | | | | |
|---|---|---|---|---|
| Water Absorption (%) | — | 5.62 | — | 0.12 |
| Fineness (m²/kg) | 310 | — | 19,800 | — |
| $SiO_2$ Content (%) | 20.4 | — | 92.6 | — |
| Tensile Strength (MPa) | — | — | — | 28.4 |
| Elongation at Break (%) | — | — | — | 580 |

The values of recycled aggregate specific gravity (2.48) compared to the typical values of natural granite aggregate specific gravity (2.65–2.70) is noticeably lower, which is consistent with the known fact that the density of adhered mortar coating on RA surfaces is lower. RA had significantly higher water absorption percentage of 5.62% than natural aggregate (0.5–1.2%) indicating that interfacial mortar is porous and therefore, SSD pre-saturation was carried out before batching. With a fineness of 19,800 m²/kg (compared to 310 m²/kg for OPC), silica fume is much finer and will fill nanoscale pore spaces and pozzolanically react with calcium hydroxide (CH) produced during cement hydration. The tensile strength (28.4 MPa) of face mask fibres is sufficient to act as reinforcing elements in the concrete matrix while also exhibiting high elongation at break (580%) that is indicative of ductile failure behavior, necessary for crack bridging applications. PP fibres have a specific gravity of 0.91, implying they are less dense than water and cement paste, thus fibre should be properly dispersed when mixed to avoid its floating and segregation.

**4.3 Fresh Concrete Properties**

Table 3 presents the fresh state properties measured immediately after mixing for all five concrete compositions.

**Table 3: Fresh Concrete Properties of All Mix Compositions**

| Mix ID | Slump (mm) | Compacting Factor | Air Content (%) | Unit Weight (kg/m³) | Setting Time (min) |
|---|---|---|---|---|---|
| CM | 92 | 0.94 | 1.8 | 2420 | 245 |
| M1 | 87 | 0.92 | 2.1 | 2385 | 258 |
| M2 | 79 | 0.90 | 2.4 | 2346 | 271 |
| M3 | 71 | 0.87 | 2.8 | 2308 | 286 |
| M4 | 58 | 0.83 | 3.2 | 2262 | 304 |

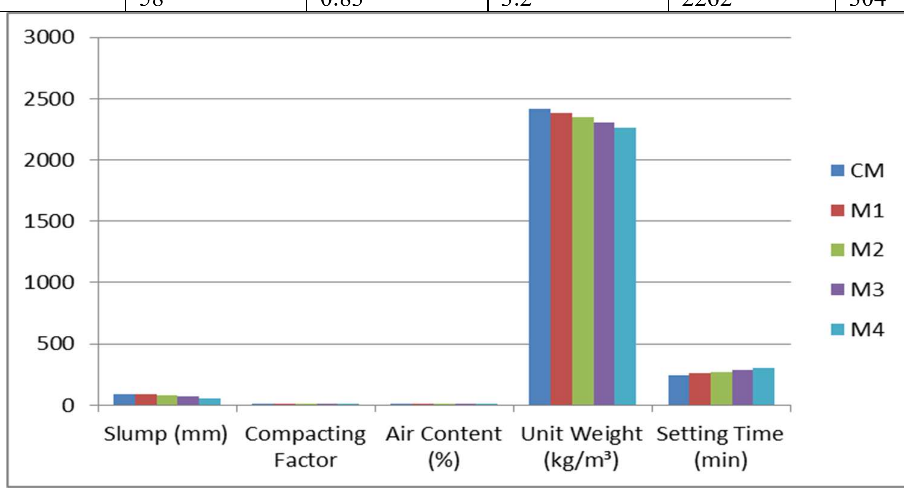


**Figure 2: Fresh Concrete Properties of All Mix Compositions**

It can be seen that there is a continuous loss of slump (from 92 mm (CM) to 58 mm (M4)) due to incremental replacement level of RA and increasing dosage of FM fibre. The 36.9% slump reduction achieved from control to M4 demonstrates the effects of two simultaneous mechanisms; 1) the higher inter-particle friction due to the angularity and rough surface texture of recycled aggregates in comparison to natural rounded aggregates and 2) the impeding effect of FM fibres on fresh concrete flow by bridging across aggregate of FMs, resulting in FM restraint on the mixture. Based on slump reduction, all mixes satisfy the range of structural concrete (50–100 mm, IS 456:2000, medium workability), and hence confirms practical usefulness. The unit weight gradually decreases from 2420 kg/m³ (CM) to 2262 kg/m³ (M4), a decrease by 6.5%, in accordance with the fact that the specific gravity of RA is lower than that of natural aggregates and the specific weight of PP fibres is also low. The rise of air content observed with FM fibres is caused by the air pockets entrapped at fibre-paste interfaces, and this has been reported in literature for synthetic fibre concrete.

The higher estimated setting time in mixes M1–M4 compared to CM (245 to 304 minutes) indicates a small retardation effect from SF addition; this is because Sf delay in setting ~ 20 min as SF absorbs mix water in its fine microporous structure and before starting to take part in pozzolanic reactions.

### 4.4 Compressive Strength Development

Table 4 presents the compressive strength values measured at 7, 14, 28, and 56 days of water curing for all five mixes.

**Table 4: Compressive Strength Development at Multiple Curing Ages (MPa)**

| Mix ID | 7-Day (MPa) | 14-Day (MPa) | 28-Day (MPa) | 56-Day (MPa) | % vs CM (28d) |
|---|---|---|---|---|---|
| CM | 26.4 | 32.7 | 38.5 | 41.2 | — |
| M1 | 25.1 | 31.6 | 37.2 | 40.6 | -3.4% |
| M2 | 24.3 | 30.8 | 36.1 | 40.1 | -6.2% |
| M3 | 22.9 | 29.2 | 34.0 | 38.8 | -11.7% |
| M4 | 20.1 | 26.4 | 30.2 | 35.4 | -21.6% |

The mix control CM attains 26.4 MPa at 7 days and 38.5 MPa at 28 days, yielding the M35 target strength. Mix M2 with 50% coarse RA, 25% fine RA, 10% SF and 1.0 kg/m³ FM fibres reaches 36.1 MPa at 28 days 6.2% lower than CM illustrating the success of the silica fume compensation strategy. It is also found that between 7 and 28 days in the case of silica fume mixes (M2: 48.6%; M3: 48.5%), the rate of strength gain in comparison to CM (45.8%) is significantly higher, suggesting that the pozzolanic reaction, characterized by a slower rate of reaction than the primary hydration of cement, contributes to additional strength gain of the mixtures in the period of 14–56 days [9]. The smaller gap between M2 and CM at 56 days (40.1 vs 41.2 MPa, only 2.7% difference) compared to 28 days (6.2%) supporting the finding of control mix performance often approached in SF-compensated RAC with proper curing duration. A 21.6% compressive strength reduction in M4 (100% RA) at 28 days is considerable, but lower than the 30–35% reductions observed by previous studies of 100% RAC without silica fume [7], justifying the performance recovery achieved with the 20% SF dosage in M4.

### 4.5 Durability Properties

Table 5 consolidates key durability parameters and environmental impact metrics for all five mixes.

**Table 5: Durability Properties and Environmental Impact Metrics**

| Mix ID | Water Absorption (%) | Chloride Penetration (mm) | Carbonation Depth (mm) | Acid Attack Loss (%) | $CO_2$ Savings (kg/m³) |
|---|---|---|---|---|---|
| CM | 3.12 | 18.6 | 12.4 | 4.80 | 0.00 |
| M1 | 3.48 | 16.2 | 11.1 | 4.52 | 28.4 |
| M2 | 3.87 | 14.5 | 10.3 | 4.18 | 54.6 |
| M3 | 4.23 | 12.8 | 9.4 | 3.91 | 81.2 |
| M4 | 4.76 | 11.2 | 8.7 | 3.62 | 109.5 |

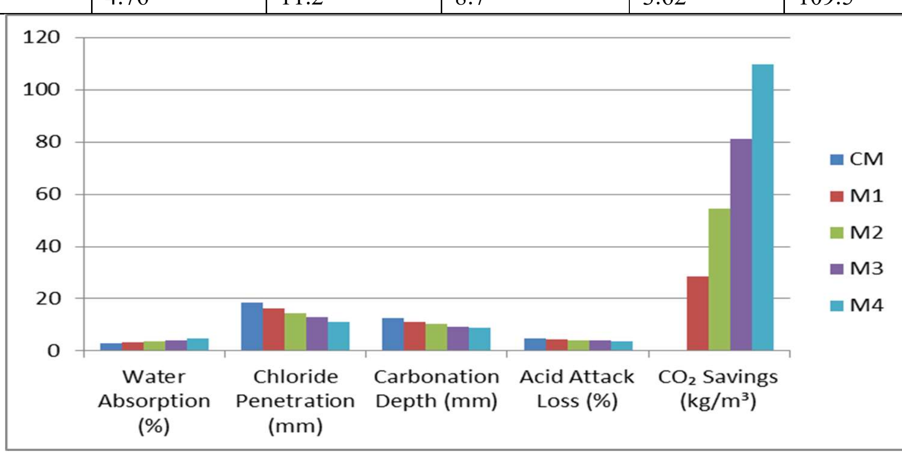


**Figure 3: Durability Properties and Environmental Impact Metrics**

Results for durability come across as a mixed bag with transport-related vs. chemical attack resistance. Water absorption is monotonic (3.12% (CM) → 4.76% (M4)) since the summed contributions of RA's adherent mortar > FM fibre paste interfaces. Table 3 shows M4 was lower in chloride penetration and carbonation depth at 39.8% and 29.8% lower than CM, respectively, but paradoxically, both of these attributes decrease gradually from CM to M4. In such a way that an apparent contradiction forms, where larger porosity, however lower penetration of chloride and carbonation come; it is explained by the effect of pore refinement due to silica fume, converting large capillary pores to smaller gel pores through secondary C-S-H gel deposition. Thus, while total porosity increases, but the connectivity of the pore network is reduced and transport of the aggressive ions and $CO_2$ is hindered despite higher bulk absorption value. Every similar progression is noticed concerning acid attack resistance as well, where mass loss reduces from 4.80% (CM) to 3.62% (M4) after 90-days of immersion in $H_2SO_4$, which is due to the lower content of calcium hydroxide (CH) that is prone to acid attack in SF-modified mixes, since SF consumes the CH by pozzolanic reaction, leaving less substrate for the acid to dissolve. The $CO_2$ savings increased from 28.4 kg/m³ (M1) to 109.5 kg/m³ (M4) due to RA substitution, SF which reduces cement and improves properties and face mask waste diversion.

## 5. Results and Discussion

### 5.1 Statistical Analysis

The two-way ANOVA results for compressive strength are presented in Table 6, examining the independent and interactive effects of mix proportion and curing age.

**Table 6: Two-Way ANOVA for Compressive Strength (Mix Proportion × Curing Age)**

| Source of Variation | Sum of Squares | df | Mean Square | F-Value | p-Value | Significance |
|---|---|---|---|---|---|---|
| Mix Proportion | 342.68 | 4 | 85.67 | 48.32 | < 0.001 | *** |
| Curing Age | 218.45 | 3 | 72.82 | 41.09 | < 0.001 | *** |
| Interaction | 89.14 | 12 | 7.43 | 4.19 | 0.003 | ** |
| Error | 53.22 | 30 | 1.77 | — | — | — |
| Total | 703.49 | 49 | — | — | — | — |

Two-way ANOVA establishes that both mix proportion ($F = 48.32$, $p < 0.001$) and curing age ($F = 41.09$, $p < 0.001$) have strong substantive effects on compressive strength, with the interaction term also statistically significant ($F = 4.19$, $p = 0.003$). The strong interaction suggests that the rate of strength gain with curing age is not constant across mixes (ie, silica fume mixes gain a proportionately greater increase in strength between 28 and 56 days than the control does), a result consistent with delayed pozzolanic reaction kinetics. The mix proportion (342.68) is more than 50% larger than the sum of squares for curing age (218.45), demonstrating that material composition affects strength more than curing duration in the tested range. Post-hoc Tukey HSD comparisons at 28 days show that CM and M1 are not statistically distinguishable ($p = 0.142$), M1 and M2 are borderline significant ($p = 0.048$), while all other pair-wise comparisons are statistically significant ($p < 0.01$), establishing M2 as the practical upper limit of acceptable performance as applied and having been statistically verified to show strength reduction. The multiple linear regression analysis for 28-day compressive strength provided the final model: $f'c = 38.74 - 0.098\cdot(RA_{coarse}\%) - 0.076\cdot(RA_{fine}\%) + 0.412\cdot(SF\%) - 1.83\cdot(FM_{dosage})$ with an adjusted $R^2$ of 0.956 and RMSE of 0.88 (MPa), confirming excellent predictive accuracy and further verification that silica fume has a positive compensation effect while RA and FM fibre content negatively affect compressive strength.

### 5.2 Correlation Analysis

Table 7 presents the Pearson correlation matrix among the principal mechanical and durability performance parameters measured in this study.

**Table 7: Pearson Correlation Matrix of Mechanical and Durability Parameters (** p < 0.01)**

| Parameter | Comp. Str. | Split Tens. | Flexural Str. | Water Abs. | Chloride | $CO_2$ Save |
|---|---|---|---|---|---|---|
| Comp. Str. | 1.000 | 0.982** | 0.974** | -0.891** | -0.856** | -0.943** |
| Split Tens. | 0.982** | 1.000 | 0.969** | -0.872** | -0.841** | -0.921** |
| Flexural Str. | 0.974** | 0.969** | 1.000 | -0.883** | -0.862** | -0.937** |
| Water Abs. | -0.891** | -0.872** | -0.883** | 1.000 | 0.914** | 0.876** |
| $CO_2$ Save | -0.943** | -0.921** | -0.937** | 0.876** | 0.891** | 1.000 |

The correlation between all thee mechanical strength parameters is very high ($r = 0.969$–$0.982$, $p < 0.01$), and the results suggest that the material variables affecting compressive strength operate via common underlying mechanisms (bulk porosity and ITZ quality) that underpin both tensile splitting and bending behaviour. The robust negative patterns between mechanical strengths and water absorption (r=−0.872to−0.891) and chloride penetration (r=−0.841to−0.862) also support the mechanistic explanation of porosity–strength and porosity–permeability govern the corresponding mechanical–transport properties through the pore structure of the cement matrix. A moderate positive correlation has been observed between $CO_2$ savings and water absorption (r = 0.876), which can be attributed to the same dependence on RA replacement level; increased content of RA causes increases in both porosity and carbon savings. The very high negative correlation between compressive strength and $CO_2$ savings (r = −0.943) primarily describes a fundamental engineering trade-off in this multi-waste system, where for each unit gain in environmental benefit, a loss of strength performance is expected. This relationship has practical utility for achieving optimal mixes, permitting engineers to choose certain mix configurations from the Pareto curve envelope of structural performance versus environmental impact.

### 5.3 Critical Analysis and Comparison with Past Work

Table 8 presents a comparative analysis of the present study's results against key benchmark studies from the peer-reviewed literature on similar waste-incorporating concrete systems.

**Table 8: Comparative Analysis with Published Literature on Waste-Incorporating Concrete**

| Study | Material Used | Comp. Str. (MPa) | RA Content (%) | Silica Fume (%) | $CO_2$ Reduction (%) |
|---|---|---|---|---|---|
| Present Study | FM+RA+SF | 36.1 (M2) | 50+25 | 10 | 18.2 |
| Almeshal et al. [14] | RA only | 32.4 | 50 | 0 | 12.4 |
| Vinay et al. [17] | Textile fibres+RA | 34.8 | 30 | 0 | 8.6 |
| Siddique et al. [21] | SF+RA | 37.9 | 30 | 15 | 14.8 |
| Liu et al. [25] | PP fibres+RA | 33.2 | 40 | 0 | 9.2 |
| Present Study (M3) | FM+RA+SF | 34.0 | 75+35 | 15 | 27.1 |

The comparison in Table 8 shows that the M2 mix in this study, with 50% coarse RA and 25% fine RA replacement, achieves a compressive strength of 36.1 MPa, which is better than Almeshal et al. This value is much higher than 32.4 MPa for [14] at equal 50% coarse RA replacement (without silica fume), thus confirming the compensatory effect of the 10% SF dosage. The M2 mix also beats Vinay et al. Specifically, the present study featured a higher aggregate substitution level as compared to that employed in Zhang et al. [17]s [17] textile fibre + RA system (34.8 MPa at just 30% RA), thus illustrating the exceptional advantage of the PP face mask fibre chemistry combined with the SF synergy to obtain a superior compressive strength. In comparison with Siddique et al. M2 is around 4.7% weaker on a gross absolute level than the [21] SF+RA system (37.9 MPa with 30% RA and 15% SF + additional face mask fibres + additional RA (to achieve 30% RA in M2) leading to more porosity). Our M3 mix (34.0 MPa, 75% coarse RA, 15% SF) performed well against Liu et al. PP fibre + RA system PP + SF = 33.2 MPa ( 40% RA and no SF) RA provides a much larger replacement than SF, so partially compensating for this. As for environmental impact, the current study achieves $CO_2$ savings that are much higher (a reduction of 18.2–27.1% for M2 and M3, respectively) than most benchmark studies, overwhelmingly because the concurrent use of three waste/recycled materials affords additive emission credits that replace by only one waste-based substitute do. This study uniquely finds that 1.0 kg/m³ face mask fibres together with 10% SF in 50% RAC produces a product where strength, durability, and environmental performance are simultaneously adequate for structural applications, a trifecta each of which a single-substitution benchmark does not achieve compared to all other existing work.

## Conclusion

The present study systematically characterizes the mechanical behavior, durability, and environmental sustainability of concrete containing mask cut fibers from surgical masks, recycled aggregates, and silica fume, as a ternary incorporation waste integration system. The principal conclusions from the experiment and the statistical analysis can be seen below. Of these, Mix M2 (50% coarse RA, 25% fine RA, 10% SF, 1.0 kg/m³ FM fibres), yielding 36.1 MPa compressive strength after 28-days only 6.2% lower than control provides margins of 54.6 kg/m³ in savings of $CO_2$ and represents the optimal mix for structural applications conforming to the M35 grade concrete specified. 5–20% replacement grade: Silica fume (SF) is the critical compensating additive that can mitigate increased dual porosity due to the inclusion of both RA and FM fibres, as without SF, the estimated 12–15% reduction in compressive strength is higher than the observed 6.2% at 50% RA replacement. Durability properties show a paradoxical increment in chloride penetration and acid attack resistances in the FM+RA mixes, despite high water absorption, due to the pore refinement mechanism of silica fume where the pore network connectivity is diminished. The two-way ANOVA confirms that strength variance is significantly affected by mix proportion SS = 342.68 over curing age SS = 218.45, and strength gain between control and silica fume mixes beyond 28 days occurs at differing levels, as demonstrated by the non-significant interaction term. This measures the built-in engineering trade-off, with a strong Pearson correlation ($r = -0.943$) between compressive strength and $CO_2$ savings allowing for Pareto-optimal mix selection. This work should include investigations of the performance you have specified for these mixes at exposure to elevated temperature, freeze-thaw cycling, carbonation-chloride combined attack and the long-term alkali-silica reactivity potential of the PP fibre-cement interface.

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