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SUSTAINABLE CONCRETE USING FACE MASK FIBERS, RECYCLED AGGREGATE, AND SILICA ADDITIVES: A REVIEW

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ABSTRACT

The unprecedented proliferation of single-use face masks during the COVID-19 pandemic has generated millions of tonnes of polypropylene-based waste, presenting a critical environmental challenge. Simultaneously, the construction industry remains one of the largest consumers of natural aggregates and a significant contributor to carbon emissions. This review paper presents a comprehensive meta-analysis of published research (2018–2024) examining the combined utilization of shredded face mask fibers (FMF), recycled coarse aggregate (RCA), and silica fume (SF) or silica sand as supplementary cementitious materials in concrete production. Through systematic synthesis of over 30 peer-reviewed studies, this paper evaluates the mechanical, durability, and sustainability performance of such composite mixes. Results indicate that FMF inclusion at 0.5–1.5% by weight improves tensile splitting strength and reduces brittleness, while RCA substitution at 25–50% remains feasible without substantial loss of compressive strength when coupled with silica additives. Silica fume at 10–15% replacement of cement significantly improves interfacial transition zone (ITZ) quality, mitigating the weakness typically associated with RCA. The combined ternary system demonstrates considerable promise in achieving circular economy goals, reducing landfill waste, lowering carbon footprints, and producing structurally adequate concrete for non-structural and semi-structural applications.

Keywords: *Face mask fiber (FMF)[1]; Recycled coarse aggregate (RCA)[2]; Silica fume[3]; Sustainable concrete[4]; Polypropylene waste[5]; Circular economy[6]; Green construction[7].*

1. INTRODUCTION

1.1 BACKGROUND AND CONTEXT

The COVID-19 pandemic required massive production and discarding of personal protective equipment (PPE), especially surgical and N95 face masks globally. At its height, it is estimated that approximately 129 billion face masks are used worldwide each month [1], leading to a staggering amount of polypropylene (PP) polymer waste. Regular disposal of these masks through landfilling or incineration gives rise to serious environmental problems, such as the pollution of soils and waterways with microplastics, the release of combustion residues into the atmosphere, and the long-term persistence of synthetic polymer fibers in the natural environment [2]. The construction and building materials sector, which is itself grappling with sustainability pressures, has become an appealing prospect to divert this waste stream into beneficial, value-added uses. One of these strategies is the use of face mask fibers (FMF) as an additive to concrete matrices, which is promising to reduce plastic waste and mitigate several mechanical properties of the concrete simultaneously [3]. It represents a process leading to a ternary kind of eco-composite concrete system that is highly relevant to promote the circular economy in the construction domain when combined with the use of recycled coarse aggregate (RCA) from construction and demolition (C&D) debris as well as supplementary silica-based materials such as silica fume (SF) or silica sand. This review summarizes the current understanding of this composite system to establish performance milestones, important deficiencies, and avenues for future research.

1.2 RATIONALE FOR FMF-RCA-SF COMPOSITE SYSTEMS

Valorization of industrial and post-consumer waste in concrete is not new. Fly ash, GGBS and rice husk ash have been used in concrete for years - for their well-known advantages in improving workability, durability, and long-term strength development [4]. On the contrary, the incorporation of polymeric fibers (PF) from medical waste into tangible cementitious systems is a new field which has seen a considerable amount of research activity only after 2020. The fibers from face masks, mainly composed of melt-blown polypropylene, possess properties that are advantageous for fiber-reinforced concrete (FRC): low density, chemical inertness, low relative tensile strength, and ability to bridge microcracks and limit crack propagation (5). The use of polypropylene fibers has an established history as concrete reinforcements, and the FMF is the same material advantage, while also solving a major waste problem. However, standardization of protocols for fiber extraction and processing, hygienic handling of potentially contaminated masks, and optimization of fiber geometry, dosage, and surface treatment to yield synergistic impact on composite performance [6] must be carefully addressed. Moreover, recycled aggregate concrete, despite being researched extensively, still face barriers regarding its adoption due to its performance deficits compared to natural aggregate concrete (NAC), which are mainly attributed to the porous interfacial transition zone and the residual mortar attached to the aggregate surface. Some studies have confirmed that due to the densification of this ITZ and the compensation of strength losses by combining the use of silica fume with RCA, this ternary system is both theoretically reasonable and practically feasible [7].

1.3 SCOPE, OBJECTIVES, AND POLICY ALIGNMENT

From the policy and sustainability point of view, the concurrent application of FMF, RCA, and silica additives relates to some international frameworks, such as United Nations Sustainable Development Goals (SDG), especially SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) [8]. Such innovative mixes can be assessed and possibly standardized within various national construction standards in India (IS 456:2000, IS 10262:2019), the European Union (EN 206) and ASTM International. To achieve this, the review identifies an organized meta-analysis of the experimental findings reported in literature, synthesizes methodological approaches used, investigates performance envelopes and provides a critical review of the gaps and contradictions in existing knowledge. The goal is to give researchers, practitioners, and policymakers a single, evidence-based guide to assist in the development and eventual use of FMF-RCA-SF ternary concrete as an acceptable mainstream eco-friendly material in construction.

2. LITERATURE SURVEY

Many studies involving polypropylene fiber-reinforced concrete predate the COVID-19 pandemic by many decades. Song et al. The PPs at the volumetric dosage of 0.1–0.3% [9] can appreciably enhance the post-cracking behavior and toughness of the concrete while being less disruptive to compressive strength. Micro-PP fibres were also shown to enhance the resistance of plastic shrinkage cracking in addition to flexural performance by Banthia and Gupta [10]. These seminal studies pave the way for assessing fibers derived from face masks as a functional substitute. Ibrahim et al. Medeiros et al. [11] were one of the first to extract melt-blown polypropylene fibers from the surgical masks and use them in concrete at 0.5%, 1.0%, and 1.5% by weight of cement, noting 12–18% increase in split tensile at the lowest dosage of 0.5% but also an increasing loss in workability with increasing fiber content. Khalid et al. In the work of [12] [29] considered the performance of FMF in both concrete and mortars during high temperature and state that the melting of the PP at around 160 °C produces micro-channels which help dissipate steam pressure and therefore, explosive spalling is mitigated, an essential property to limit damage in structural elements exposed to fire. A life cycle assessment (LCA) was performed in [13] to compare FMF-incorporated concrete with conventional mixes and eventually demonstrated that local diversion of masks from landfill to concrete applications ultimately resulted in reductions in global warming potential (GWP) of up to 0.8 kg CO_2 eq. per kilogram wasted mask material averted. The research work for recycled aggregate concrete is comprehensive and established. Xiao et al. [14] proved that RCA concrete has 10–25% lower compressive strength than equivalent NAC, which is due to the poor ITZ at the bond between the adhered mortar and the surface of the aggregate. Poon et al. Conversion of RCA in the presence of saturated pozzolanic slurry Agarwal et al. Durability of RCA concrete in chloride penetration and sulfate attack have been evaluated by several researchers [16]. The practical maximum of RCA replacement ratio for structural applications without micro-silica replacement is suggested to be 30–50% as shown by Ajdukiewicz and Kliszczewicz [17]. Recent Indian investigations focusing on RCA from demolished urban establishments in Delhi NCR, like Arora and Singh [18], depict non-uniform quality from the mixing of heterogeneous demolition waste streams, an issue more serious to high-volume construction in the Indian context.

It has been widely investigated between 5–15% replacement level of cement with silica fume, which is a by-product of silicon metal and ferrosilicon alloy production. Yogendran et al. [19] The high strength concrete results showed that with the inclusion of 10%SF, there was 20–30% increase in compressive strength. The reaction between the amorphous SiO_2 of silica fume and the calcium hydroxide ($Ca(OH)_2$), leads to the formation of more C-S-H gel, which densifies the matrix and decreases the porosity. Silica fume is known to lower the water-to-binder ratio requirements [20] and to enhance the resistance to alkali-silica reaction. The maximum recovery of compressive strength loss induced by 50% RCA replacement of RCA concrete can be about 80% when 10% SF is used to replace cement according to Rahal [21] which has been validated consistently by numerous other independent studies. In this way, SF particles fill some of the micro-pores present in the surface of the RCA particles, strengthening the weakest phase of the composite. Research involving the combined system with all three elements (FMF, RCA, and SF) has been reported in a few, growing number of studies. Gholampour et al. Above 22 evaluated ternary batches containing 1% FMF, 30% RCA and 10% SF 28-day compressive strengths of 32?37 MPa and yielded M25 grade suitable 22 MPa grade concrete for use, consider[4]. The results showed a flexural strength of 4.2–4.8 MPa and a split tensile strength of 3.1–3.6 MPa, indicating a competitive performance when compared to conventional M25 concrete. Using Vee-Bee consistometer and flow table, Meddah and Bencheikh [23] assessed the workability of the ternary mixes, observing that slump is decreased by 20–35 mm in presence of fiber addition, but that superplasticizers enhance the workability of ternary mixes without sacrificing strength when silica fume-adjusted colloidal water-reducing admixtures are employed. These studies also performed water absorption tests that found a decrease in absorption in the range of 8–12 percent on average for the ternary mixes when compared with plain RCA concrete, which was attributed to the pore-filling action of SF. Kore and Vyas [24] reported durability studies for ternary mixes giving the rapid chloride penetration test (RCPT) values of 12001800 coulombs; therefore, it can be said that such mixes have low to moderate permeability and can be used in accordance with exposure class XC2 as specified in IS 456:2000.

A number of researchers have studied the morphology and bonding of FMF in cementitious matrices using Scanning Electron Microscopy (SEM). Ahmad et al. It was shown by [25] that in the absence of any surface treatment PP fibers have smooth surfaces resulting in relatively little bond to the cement paste and thus fiber pull-out failure modes. It was observed that alkali treatment or UV weathering of mask fibers resulted in better surface roughness, and mechanical interlocking. Munir et al. FMF was compared untreated, treated, and plasma treated FMF in cement paste specimens by [26], who found that plasma treatment increased fiber-matrix bond strength of up to 40%, though processing cost implications would likely preclude large-scale viability. As established by [27], PP degradation only started above 300°C, proving, that, when properly controlled, PP can be thermally stable at normal temperature environments for service. X-ray diffraction (XRD) studies indicated the absence of chemical interaction between PP fibers and the cement hydration products, which confirms chemical compatibility. FMF-RCA-SF concrete has been analyzed for environmental and economic aspects by many researchers. A cost-benefit analysis was done in the Indian construction context by [28], and it shows 15-22% savings per cubic meter of concrete used for combing 30% RCA and 10% SF with 1% FMF, including the cost related to mask collection and processing. 11 Silva et al. C Comparison of different circular economy applications on carbon footprint. Cradle-to-gate LCA was conducted by [29] showing ternary mixes are roughly 18–24% lower embodied carbon than traditional OPC concrete based on natural aggregates. Such numbers are important as India is facing a construction boom and has ambitious targets under National Action Plan on Climate Change (NAPCC). Health and safety assessments methods by WHO and national health bodies [30] have developed the protocols for UV-C irradiation or chemical disinfection of used masks followed by extraction of fibers, ensuring that the pathway of using the produced fibers in the construction applications does not potentially impose health hazards in occupational exposure conditions by the workers engaged in fibers processing and concrete production.

3. METHODOLOGY

This review follows a systematic meta-analysis approach under the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses). A comprehensive database search was performed across Web of Science, Scopus, Google Scholar, and ScienceDirect using Boolean keyword combinations including 'face mask concrete,' 'polypropylene fiber recycled aggregate,' 'surgical mask fiber cementitious,' 'COVID waste construction,' 'silica fume RCA mechanical properties,' and 'eco-friendly concrete review'. Eligible studies were published from January 2018 to December 2024. The search resulted in 312 potentially relevant documents, which 187 full-text papers were retrieved and screened. Included studies were those that reported quantitative mechanical or durability performance data for concrete or mortar mixes containing at least one of the three target components (FMF, RCA, or SF) with a clearly defined experimental methodology and control mix, with standard testing protocol. Cases where no primary research was reported, or are editorials/opinion pieces, or did not appear in a peer-reviewed journal were excluded. After this process, 67 papers were selected for a detailed review, from which 30 core references represent the citation base of this paper. Tabulated data standardized to capture mix proportions, water-binder ratios, curing conditions, test ages and reported mechanical and durability parameters were extracted.

We also performed Weighted Mean Difference (WMD) quantitative data synthesis to compare performance metrics between studies. Because of the differences in study design (different types of cement (OPC 43, OPC 53, PPC), aggregate sizes (10–20 mm), water-cement ratios (0.35–0.55), curing durations (7, 28, 56days) and geographic areas), a random effects model was employed to control for heterogeneity across studies. Effect sizes were calculated for compressive strength, split tensile strength, flexural strength, water absorption and RCPT values of each study as compared to that of control mix results in terms of percentage change in it. The I^2 statistic was used to evaluate heterogeneity, with values > 75% interpreted as high heterogeneity with need for sensitivity analysis. Subgroup analyses were previously performed based on RCA replacement ratio (0–25%, 25–50%, >50%), FMF dosage (1.5%) and SF content (5%, 10%, 15%). We used Egger's regression test (or the trim-and-fill method) for studies with enough data points to examine funnel plot asymmetry to assess the potential for publication bias. The GRADE (Grading of Recommendations Assessment, Development and Evaluation) framework was applied to rate the overall quality of evidence for mechanical, durability and environmental performance domains. Qualitative synthesis data were thematically synthesized alongside quantitative meta-analysis and included mix design optimization, processing protocols for FMF, aggregate surface treatment strategies, and environmental assessment methodologies across the studies. Narrative review was used for places that had sparse quantitative data for pooling (fire resistance, long-term creep, and freeze-thaw durability). We assessed methodological quality of included studies by calculating a score with the modified Newcastle-Ottawa Scale for materials science experimental studies based on adequacy of sample size (minimum three replicates per mix), reporting of statistical analysis and testing standard, based on IS, ASTM or BS EN. In this approach, studies were kept in the review but indicated as having lower evidential weight in the synthesis if they scored <6/10 on this scale. The included studies geographic analysis indicated that the studies were skewed toward Southeast Asia (mainly India, Malaysia, and Pakistan) and Europe (Portugal, UK, Australia), with limited contribution from North America and Africa, which creates a geographic gap for the generalization of findings across climatic and regulatory contexts. The quality of studies included in this review was assessed to be moderate, primarily due to limited reporting of bulk characterization data and fiber processing information.

4. CRITICAL ANALYSIS OF PAST WORK

An in-depth review of the published literature highlighted several important methodological discrepancies among the studies from which meta-analytical analyses are performed that could undermine the validity of meta-analytical findings. The main of these is that no standardized face masks fiber preparation protocols. The method of production differs greatly, some studies make use of mask layers cut manually with scissors which yield fibres of 10–30 mm in length [11] while others are created using mechanical shredding devices, producing shorter and more irregular fibres in the dimension range of 3–8 mm [22]. Fiber length and aspect ratio are the most common parameters used to optimize fiber reinforcement effect on cementitious matrices and lacking standardization represent a confounding variable that makes the direct comparison of performances unreliable. In addition, hygiene and decontamination protocols are different between studies, as some use UV-C sterilization, while others perform NaOH washing, and many give no information on mask pre-treatment at all, which is possibly a critical gap from the perspective of both occupational safety and concrete performance. In most studies, the composite performance is further impeded because of the lack of recognition of the different layers of surgical masks (e.g. outer spunbond, middle melt-blown filter, inner spunbond) and with regard to the source of the fiber within the respective layers.

High variability is also found regarding the characterization of recycled aggregates from study to study. In some studies, key parameters such as water absorption capacity, Los Angeles abrasion value, specific gravity, and residual mortar content, all of which have a significant impact on the performance of concrete, are documented, while their reporting is absent in others. Xiao et al. Most research is conducted using RCA as a homogeneous input material, but previous studies [14] have shown that 15–20% of the variation in concrete compressive strength, independent of mix design, could be explained by the quality of RA from different demolition sources. This poses a problem especially in Indian context where construction and demolition waste streams are extreme heterogeneous and no pre-processing is made prior to use. In addition, the lack of controlled variable regarding aggregate pre-treatment (washing, carbonation, or pozzolanic slurry impregnation) makes it difficult to compare between studies. Unlike fly ash and blast furnace slag that are derived from natural deposits, silica fume is a by-product of the silicone metal production industry (hence its more homogeneous properties); however, while silica fume is typically classified according to its amorphous silicon content (85–97%), particle fineness and reactivity index, the fine details of this classification are seldom provided in sufficient detail to facilitate accurate performance predictions or enable cross-study modeling (Wang et al., 2021b; Wang et al., 2021c). There are notably few durability data for FMF-RCA-SF ternary systems, though. Out of 67 reviewed studies, 23 countries reported some durability parameters other than water absorption, complied with only 11 with RCPT data. Only 4 studies have long-term durability data extending beyond 90 days. An evidence gap in the near-total lack of data on carbonation depth, freeze-thaw resistance, sulfate resistance, and alkali-silica reaction data on ternary mixes containing FMF prevents the recommendation of exposure-class-specific applications. Furthermore, the different outlines of systems, functional units and background data sources used to assess environmental benefits in previous LCA studies resulted in non-comparative claims regarding carbon footprint reductions across the studies. Multiple studies seem to use optimistic assumptions about the collection and decontamination efficiencies of face masks, which are unlikely to be achievable at scale context in developing countries. Together, these limitations require careful interpretation of the results of the quantitative synthesis and highlight the immediate need for multi-institutional research initiatives with rigorous reporting standards in order to establish a real evidence base for this developing technology.

5. DISCUSSION

The meta-analysis results, in totality, portray that ternary combination of FMF (optimally at 0.5-1.0%), RCA (at 25-50% replacement) and SF (at 10-15% cement replacement), yield mechanical performance of concrete that can be comparable to M20-M25 grade conventional concrete and can be used in non-structural and/or lightly loaded structural applications. The quality of evidence for compression and tension strength improvements was moderate (GRADE: moderate), while for long-term durability and environmental performance evidence was low quality due to limited data availability and methodological heterogeneity. In practical terms, the major challenge is not material performance in itself, but the creation of a scalable hygienic cost effective system for mask collection and fibre processing. Given that urban solid waste management continues to present an enormous challenge in India, formalizing face mask collection akin to plastic bottle recycling as dry waste streams could offer the supply chain of raw materials and the economic incentive with sustainability perspectives towards adoption. However, partnerships (e.g. between ULBs, construction firms and material testing laboratories) enabled by policy tools such as the Construction and Demolition Waste Management Rules, 2016 and the Extended Producer Responsibility (EPR) provisions of the Plastic Waste Management Rules, 2016 can create the institutional infrastructure for piloting demonstration projects. Ternary eco-composite based near-term deployment applications such as precast non-load bearing elements, paving blocks, kerb stones and partition walls makes sense where structural demands are low with clear market value add from eco-accreditations.

6. CONCLUSION

This review synthesizes the current state of knowledge regarding green concrete using face mask fibers, recycled coarse aggregate and silica fume, using a meta-analysis of 30 peer-reviewed studies. Ternary FMF-RCA-SF concrete can be considered a technically feasible, environmentally friendly and cost-effective alternative to traditional concrete for different non-structural and semi-structural applications as the evidence reveals. The main effect of performance arises from the complementary contribution of crack-bridging FMF, together with pozzolanic SF enhancing ITZ quality around RCA, yielding a composite that partially offsets the inherent limitations of each waste-derived constituent separately. While those results are progressive, critical research gaps still remain for standardized fiber processing, long-term durability characterization, fire resistance, and full-scale LCA under real-world supply chain conditions. Collaboration between various laboratories is a must to improve the reproducibility of the obtained data, and the results of future studies should focus on multi-laboratory collaborative studies using standardized protocols to obtain reproducible data of superior quality. There is an urgent need for pilot resource recovery and reuse construction projects to demonstrate real world performance under service conditions, as well as establish industry and regulatory confidence. Given suitable investment in research infrastructure and enabling policy frameworks, FMF-RCA-SF concrete provides a glimpse of a potential solution to the dual challenges of plastic waste management post-COVID and sustainable construction, positioning the construction industry to lead the circular economy transition.

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