EXPERIMENTAL STUDY ON STRENGTH AND WORKABILITY OF SUSTAINABLE CONCRETE INCORPORATING COTTON FIBERS AND MARBLE WASTE

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Abstract- This study investigates the dual use of cotton fibers (CF) and waste marble aggregate (WMA) as sustainable alternatives to conventional coarse aggregates in concrete. Driven by environmental concerns and resource depletion, the research introduces five mix designs with WMA ranging from 0% to 100% and a constant 2.5% CF by weight. Compressive and flexural strengths were evaluated at 28 and 56 days. Results revealed a peak performance at 50% WMA, surpassing control values and demonstrating improved mechanical behavior and sustainability. The study supports sustainable engineering practices by reusing industrial waste materials in concrete applications. The findings promote scalable use of industrial waste for non-structural concrete applications aligned with climate-resilient infrastructure goals.

Keywords- Sustainable Concrete; Cotton Fibers; Waste Marble Aggregate; Mechanical Properties.

1. Introduction

Concrete's global ubiquity in infrastructure comes at an ecological cost due to quarrying of aggregates and energy-intensive cement production [1]. The processing of marble into finished products generates approximately 30–40% of solid waste by weight, resulting in an estimated 690,000 to 920,000 tons of marble waste annually [2]. The global textile industry generates approximately 92 million tons of waste per year, with only 25% being reused or recycled, and the remaining 75% disposed of in landfills or incinerated [3,4]. Disposal of these byproducts imposes environmental hazards, pushing research toward integrating waste into concrete [5].

WMA has been found to improve compressive strength and reduce cost and energy consumption when optimally used [6]. Cotton fibers (CF), though organic, improve flexural strength and crack resistance through a bridging mechanism and better moisture retention during curing [7]. However, both materials, when excessively used, can negatively affect workability and cohesion [8]. Hence, this study presents a combined system of CF and WMA in concrete, aimed at improving both mechanical performance and sustainability. Previous research demonstrates variable success in replacing conventional aggregates with WMA. Kore and Vyas reported 18% improvement in compressive strength with up to 50% WMA [6]. Sunil and Varghese validated improved workability and strength using WMA in concrete mixes [9]. CF have been less studied, but Tang et al. found 9% enhancement in flexural strength at 0.8% cotton knitted fiber waste content by weight of cement [8]. Bartulović et al. showed 21% gain in flexural strength with 2.5% cotton fabric waste, though compressive strength dropped by 10–28% at higher content [7]. Saca et al. corroborated CF's role in improving ductility but warned of reduced compressive performance beyond 2.5% [10]. In addition, Bartulović et al. [7] demonstrated that incorporating CF enhances tensile and flexural strength, reduces shrinkage, and delays the onset of micro-cracking in concrete. The study confirmed that fiber dispersion and morphology contribute significantly to matrix integrity when waste CFs are dozed below 3%.

These studies suggest that a 50% WMA and 2.5% CF mix offers the best balance between strength and sustainability. Therefore, this research aims to evaluate the compressive and flexural strength of CF-WMA concrete on 28 and 56 days to determine the optimal WMA content for performance and sustainability. This study uniquely evaluates the combined effect of cotton fibers and waste marble aggregate on both strength and workability. Unlike prior research, it focuses on their synergistic use and provides localized insights relevant to sustainable construction in Pakistan.

2. Research Methodology

2.1 Details of test matrix

WMA sourced from local quarries replaced coarse aggregates at 0%, 25%, 50%, 75%, and 100% by weight. CF (cut to 6–8 cm × 2 cm) was added at a fixed 2.5%. A drum mixer was used to prepare concrete with a mix ratio of 1 (cement): 2.49 (sand): 2.62 (aggregate) by weight and W/C ratio of 0.55. Concrete was mixed in a drum mixer by first dry-blending cement, sand, natural aggregate, and WMA for 2 minutes. Cotton fibres were then added gradually to avoid clumping, followed by the slow addition of water to achieve workability. The mix was placed in standard moulds (150×300 mm cylinders and 150×150×525 mm beams), compacted in two layers using a tamping rod. Specimens were covered with wet burlap, demolded after 24 hours, and cured in water at 23 ± 2°C until testing. Cylindrical and prism samples were tested under ASTM C39 and C293 protocols for compressive and flexural strength at 28 and 56 days. Sieve analysis results of natural aggregate and WMA are shown in Figure 1, indicating comparable particle size distributions within ASTM limits. This supports the fair comparison of both materials in the mix design and helps evaluate the influence of WMA on concrete properties. The test matrix is provided in Table 1.

Table 1 Details of test matrix

Sample ID	CF (%)	WMA (%)	28 Days		56 Days	
			Cylinders (No)	Beams (No)	Cylinders (No)	Beams (No)
CS	0	0	3	3	3	3
CF WMA0	2.5	0	3	3	3	3
CF WMA25	2.5	25	3	3	3	3
CF WMA50	2.5	50	3	3	3	3
CF WMA75	2.5	75	3	3	3	3
CF WMA100	2.5	100	3	3	3	3

Note: CF stands for cotton fibers and WMA stands for waste marble aggregates. Cylinders are 150 mm diameter and 300 mm height. Whereas beams are 150 x 150 x 525 mm.

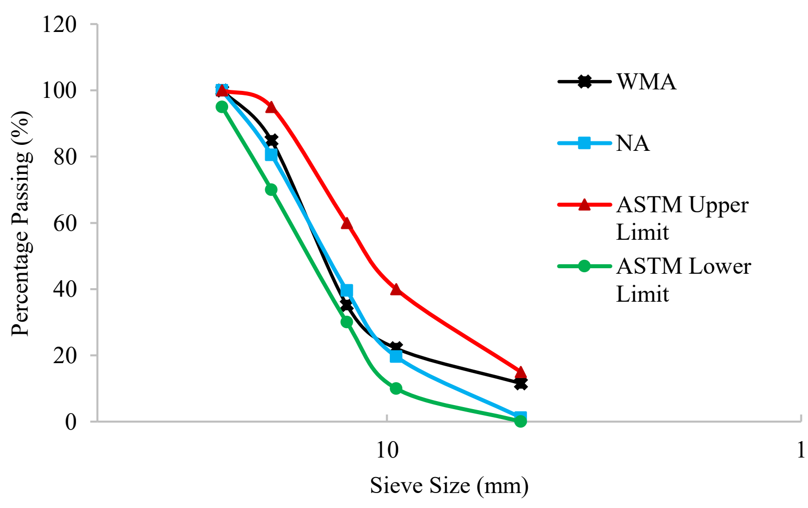

Figure 1: Gradation Curve for natural aggregate (NA) and waste marble aggregates (WMA) sieve analysis

(a) *(b)* *(c)*

Figure 2. Concrete testing process: (a) Slump test, (b) Compressive strength test, and (c) Flexural strength test.

3. Results and Discussion

3.1 Workability

Figure 3 shows a decreasing trend in slump values with increasing WMA and CF content. The control mix exhibited the highest slump of 25.86 mm, while the mix with 100% WMA and 2.5% CF showed the lowest value of 21.39 mm. This reduction in workability is attributed to the angular texture of WMA and the hydrophilic nature of cotton fibers, which increases water demand. These results align with previous findings where increased surface area and fiber inclusion led to reduced slump [6,8]. The reduction in slump may affect concrete placement in field conditions, requiring the addition of superplasticizers or water-reducing agents in practical applications.

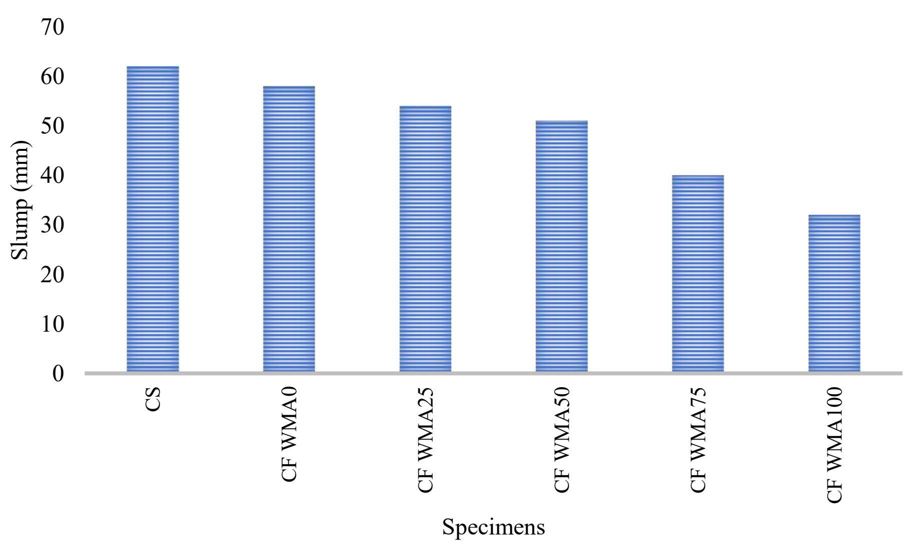

Figure 3. Slump test result of all mixes

3.2 Compressive strength

As shown in Figure 4, compressive strength peaked at 50% WMA, recording 30.51 MPa on 28 days and 32.67 MPa at 56 days. Beyond this level, strength declined due to weaker interfacial bonding and increased porosity. The mix with 75% WMA exhibited a drop of nearly 9% from the peak. These findings are consistent with literature reporting optimal marble waste replacement near 50% [6,9]. The gain in compressive strength at 50% WMA may be due to improved particle packing and pozzolanic interaction of fine marble dust particles, contributing to a denser microstructure.

3.3 Flexural strength

Flexural strength also improved with WMA content up to 50%, reaching 5.097 MPa (28 days) and 5.71 MPa (56 days). Beyond 50%, the increase was marginal or declined slightly. Cotton fibers played a critical role by bridging micro-cracks, delaying failure, and enhancing post-cracking ductility. Similar trends were observed in Bartulović et al. [7] and Saca et al. [10], where natural fibers improved flexural performance but became less effective at higher replacement levels. The improved flexural strength signifies better toughness and crack resistance, which is valuable for pavements and slabs subjected to bending and impact loading.

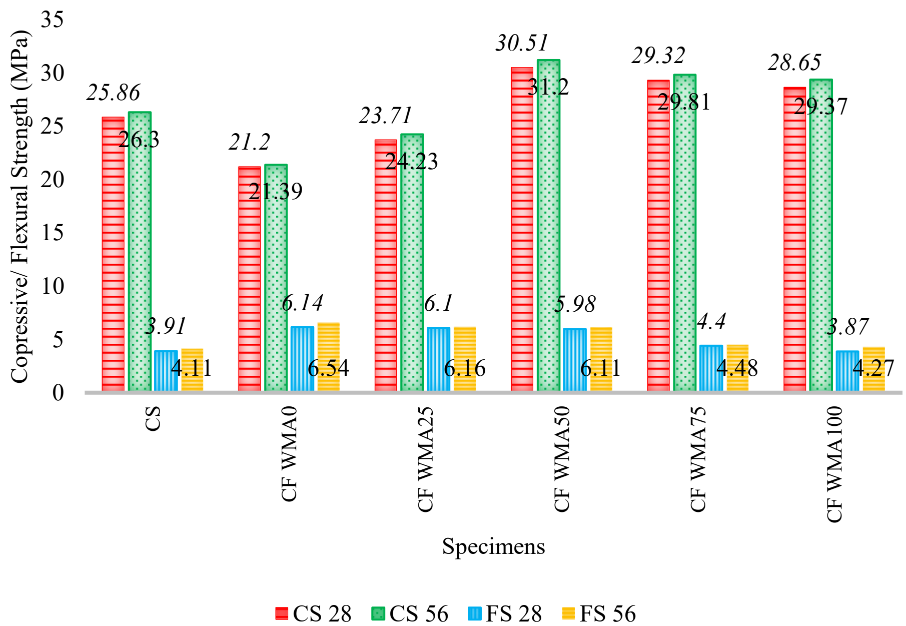

Figure 4. Compressive (CS) and flexural stregth (FS) of concrete mixes at 28 and 56 days.

4. Practical Implementation

The proposed concrete mix using cotton fibers and waste marble aggregate is suitable for non-load-bearing structures, pavement blocks, and boundary walls. Its enhanced flexural strength and crack resistance make it ideal for surfaces exposed to moderate stress. Although the mix achieved compressive strength above 30 MPa, which is adequate for structural use, further studies on long-term durability, environmental exposure, and field-scale implementation are required before recommending it for load-bearing applications. The use of low-cost, locally available waste materials supports sustainability and makes it especially feasible for developing regions like Pakistan. The proposed concrete mix supports climate-resilient infrastructure by minimizing the use of virgin aggregates, reducing landfill waste, and utilizing locally available industrial byproducts. This approach lowers the embodied carbon footprint and promotes circular material use, which are key strategies in mitigating environmental degradation and adapting to long-term sustainability challenges.

5. Conclusion

The following conclusions can be drawn from the conducted study:

1 2.5% CF with 50% WMA yields optimal mechanical behavior.
2 Compressive and flexural strength increased by 18% and 24% compared to the control.
3 Above 50% WMA, both strengths declined, confirming an upper limit for effective WMA replacement.

4 Cotton fibers improve flexural strength and crack resistance but reduce workability.
5 This mix design is recommended for eco-friendly non-structural applications

The above outcome is favorable, indicating the exploration of its in-depth behavior. Next step should be the durability testing along with life cycle assessments.

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