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Experimental Investigation on the Structural Performance of Steel-Concrete Composite Slabs Incorporating Recycled Aggregates from Construction and Demolition Waste

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Abstract. This paper presents a comprehensive experimental study conducted to evaluate the structural behavior of steel-concrete composite slabs incorporating recycled aggregates sourced from construction and demolition waste. The experimental research is related to 12 specimens differing for the lengths (i.e. 240, 280, and 320 cm). Furthermore, four distinct mix designs were considered: a control mix without recycled aggregates, M30 mix containing 30% recycled aggregates, M50 mix with 50% recycled aggregates, and M100 mix comprising 100% recycled aggregates.

Both material-scale and structural-scale tests were conducted to assess the mechanical properties and overall structural performance of the steel-concrete composite slabs. Material-scale tests encompassed a detailed examination of the mechanical characteristics of each mix. Meanwhile, structural-scale evaluations were carried out through a 4-point bending test on each slab specimen, simulating real-world loading conditions. The experimental campaign aimed to shed light on the feasibility and effectiveness of incorporating recycled aggregates from construction and demolition waste into composite slabs, addressing environmental concerns while ensuring structural integrity and performance. The results provide valuable insights into the utilization of sustainable construction materials and offer practical implications for the development of eco-friendly structural systems in the construction industry.

Keywords: sustainability · concrete · recycled concrete · steel-concrete composite slab · steel metal deck

1 Introduction

Nowadays, the efficient use of concrete in construction engenders complex ecological issues. Predominantly dependent on cement, the fabrication of concrete is a notable contributor to CO2 emissions, intensifying the global climate crisis, as documented by

[1, 2] The procurement of essential materials for concrete production, such as sand and gravel, disrupts natural habitats and depletes resources, adversely affecting biodiversity and natural ecosystems.

As a countermeasure to these issues, Recycled Concrete Aggregate (RCA) is gaining recognition as an effective means to alleviate the over-utilization of natural resources, a byproduct of conventional concrete construction, as observed by [3, 4].

Within this realm, steel-concrete composite slabs—an effective assembly of steel and concrete—emerge as an innovative alternative. These structures demonstrate significant environmental and structural benefits, including the conservation of resources through minimized concrete consumption compared to traditional slabs, as elucidated by [5]. The incorporation of RCA within these composite slabs not only conserves raw materials but also streamlines waste management in construction practices, as per findings by [6]. Their relatively lighter mass reduces energy consumption during production and transportation phases. Moreover, the integration of steel decks in these composite slabs contributes to thermal efficiency within buildings, thereby promoting energy conservation in building designs. Recognized for their longevity, composite slabs enhance the durability of construction projects, minimizing the need for frequent maintenance, as noted by [7]. Their prefabricated design expedites on-site assembly, curtailing construction timelines and ecological disturbances. The construction of these slabs also aligns with waste-reduction initiatives, as reported by [8]. Considering the full lifecycle, these slabs are designed for disassembly and material recovery, reinforcing the principles of a circular economy in construction practices.

Given their numerous benefits, there has been a heightened focus on research related to composite slabs integrated with recycled aggregates. Investigations into their flexural behavior, such as those by [9], and bonding characteristics, as examined by [10], have been instrumental in understanding their structural dynamics. Composite slabs are often designed to undergo debonding failure, indicative of a loss in the bond between concrete and steel reinforcement.

The long-term durability of these structures has been scrutinized, with studies like [11] revealing that differential shrinkage could significantly increase cracking in stress-prone areas. The use of RCA may amplify these effects, leading to greater mid-span deflections and cracking, warranting the development of predictive models for long-term behavior, such as the one proposed by [12]. The influence of fine recycled aggregates on shrinkage behavior, as demonstrated by [13], necessitates careful consideration in design. Furthermore, the fire resistance of these materials, explored by [14], has yielded promising results, showing that increased coarse recycled aggregate content may reduce temperature rise within the slabs during fire exposure.

The breadth of knowledge on steel-concrete composite slabs is vast yet incomplete, presenting numerous avenues for further investigation to leverage their full potential in sustainable construction. Thus, this paper seeks to contribute to this growing body of knowledge by presenting initial results from an experimental study that evaluates the mechanical performance of recycled concrete composite slabs. Span lengths of 240 cm, 280 cm, and 320 cm, along with aggregate replacement ratios of 30%, 50%, and 100%, were examined, stressing out that the inclusion of recycled aggregates at a structural level does not detrimentally affect mechanical strength. This introduction is succeeded by an exposition on material characteristics in Sect. 2, an analysis of the concrete's mechanical properties in Sect. 3, and a discussion of flexural tests conducted on the composite slabs in Sect. 4, culminating in concluding observations in Sect. 5.

2 Construction Materials

2.1 Cement and Aggregates

This study utilized a commercially available cement known as TECNOCEM A-LL 42.5 R. The recycled aggregates, both fine and coarse, were sourced from the rubble of a dismantled reinforced concrete structure in Cagliari. In contrast, the natural aggregates were procured from a regional quarry. The properties of these materials are summarized in Table 1. To enhance the workability of the concrete, a superplasticizing agent was incorporated into every batch. The water used in the concrete mix adhered to the purity and temperature standards set forth by ASTM C1602 [15].

Table 1. Characteristics of Aggregates.

Component	Max Size Aggreg. (mm)	Wat. Absorption (%)	Dry density (kg/m^3)
Coarse Natural	12.5	0.9	2690
Fine Natural	5	1.5	2830
Coarse Recycled	12.5	6.4	2460
Fine Recycled	5	12.9	2240

2.2 Steel Sheets

The metal components used were steel sheets, whose dimensions are specified in Fig. 1. These sheets were fabricated from S280GD grade steel, characterized by a nominal yield strength of 280 MPa and an ultimate tensile strength of 360 MPa.

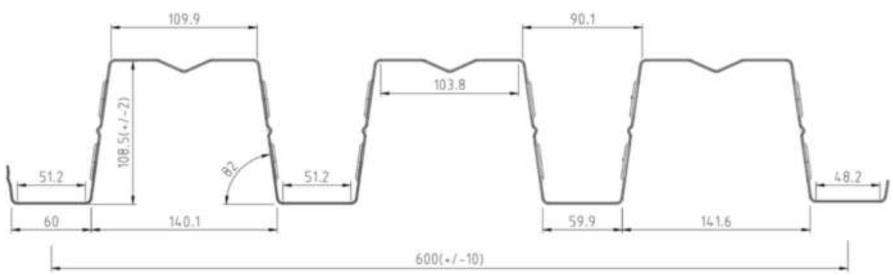

Fig. 1. Cross-section geometry of the Steel Sheets (referred to as SG110–600)

3 Characteristics of Concrete Mixes

3.1 Mix Variants

The investigation entailed the assessment of four concrete blend variants to investigate the effects of replacing traditional natural aggregates with recycled alternatives derived from concrete construction and demolition waste. Table 2 outlines the specific details for each variant. The nomenclature for the blends uses two digits: the initial digit represents the proportion of fine natural aggregates substituted by their recycled counterparts, while the subsequent digit indicates the replacement rate for coarse natural aggregates. A uniform water-to-cement ratio of 0.51 was sustained across all blends to ensure the validity of comparative analysis.

Table 2. Design of Concrete Blends.

Blend	Cement (kg/m^3)	Fine Recycled (%)	Coarse Recycled (%)
M0-0	366	0	0
M30-30	366	30	30
M50-50	366	50	50
M100-100	366	100	100

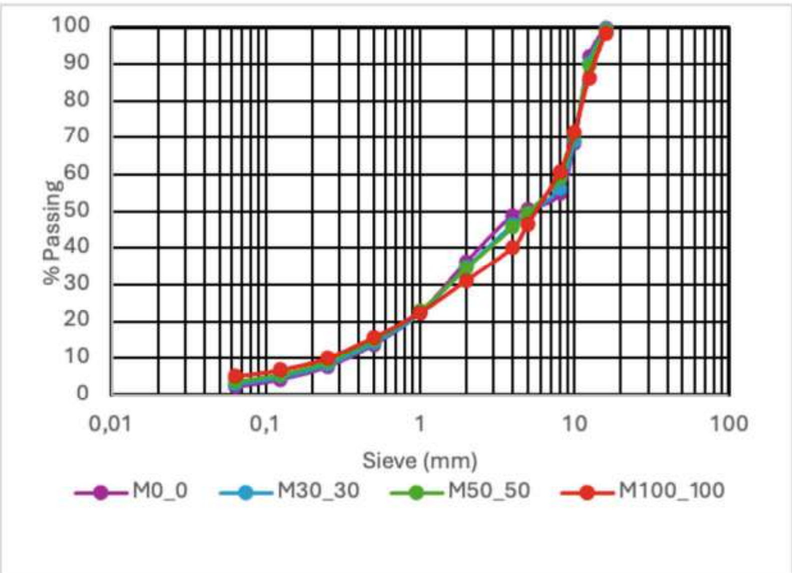

Fig. 2. Particle Size Distribution Curves for Each Concrete Blend

Figure 2 illustrates the particle size distribution curves, revealing significant uniformity across the different blends.

3.2 Concrete Strength

The mechanical integrity of the blends was determined by compressive strength and modulus of elasticity tests, as prescribed by UNI EN 12390-3 [16]. For each variant, 6 cubic specimens with dimensions of 15 × 15 × 15 cm were produced. Half of these were evaluated after 7 days, and the remainder after 28 days.

The outcomes of these compressive strength evaluations for each blend, conducted at the two intervals, are compiled in Table 3. The term CoV refers to the coefficient of variation. It is to be noted that the data for the M50-50 blend at 7 days could not be ascertained due to a malfunction in the testing apparatus.

Table 3. Mechanical Strength of Concrete

Blend	7 Days Strength (MPa)	CoV (%)	28 Days Strength (MPa)	CoV (%)
M0-0	31.4	3.8	43.1	1.7
M30-30	26.0	2.1	32.3	2.9
M50-50	–	–	34.5	8.0
M100-100	18.13	8.4	23.2	3.5

An analysis of Table 3 suggests a trend where an increased inclusion of recycled aggregates correlates with a reduction in compressive strength, and a rise in result variability, especially in the initial testing phase. However, the M 50-50 blend deviates from this pattern at the 28-day mark, suggesting a nuanced interaction at this specific level of aggregate replacement, warranting additional investigation.

3.3 Modulus of Elasticity of Concrete

The modulus of elasticity in compression for the concrete variants was ascertained following the parameters set by UNI EN 12390-13 [17]. Each concrete formulation was represented by two cylindrical specimens measuring 15 cm in diameter and 30 cm in height, which were subsequently subjected to testing. The mean values and corresponding coefficients of variation (CoV) for each concrete mixture are documented in Table 4.

The assessment of the secant modulus of elasticity across the concrete mixtures yields crucial data regarding the rigidity of the materials and their relationship to the incorporation of recycled aggregates. The standard mix M0-0, without any recycled materials, showed the highest mean secant modulus of 34.7 GPa and a coefficient of variation reflecting a higher disparity in measurements at 9.45%. Conversely, the blends with added recycled aggregates—M30-30, M50-50, and M100-100—demonstrated greater consistency, indicated by their respective CoVs of 0.37%, 1.02%, and an exceptionally

Table 4. Modulus of Elasticity for Concrete Mixtures

Blend	Mean Elastic Modulus (GPa)	CoV (%)
M0-0	34.72	9.45
M30-30	22.52	0.37
M50-50	23.74	1.02
M100-100	16.75	0.01

low 0.01%. As indicated by the data in Table 4, there is a clear downward trend in the elastic modulus with the increase in recycled aggregate content, corroborating findings from previous studies such as those by [18], which suggests that higher substitution rates may lead to a lower modulus of elasticity.

4 Flexural Testing of the Steel-Concrete Composite Slabs

This study involved fabricating of steel-concrete composite slab specimens from each concrete mixture, tested at three varying spans of 280 cm, 240 cm, and 320 cm, while maintaining a uniform width of 66 cm and height of 18 cm for all samples.

Each slab underwent a four-point bending test as depicted in Fig. 3.

Fig. 3. Configuration of Testing Apparatus.

The load was applied at two points on each slab, positioned at a quarter-span from the midpoint, using an hydraulic jack restrained by a counterframe.

The deformation of each slab was quantified at eight distinct locations using linear displacement transducers with a standard displacement capacity of 100 mm and a nominal sensitivity of 2 mV/V, a sensitivity tolerance of ±0.1%, and a resolution of 1 μm. For brevity, this paper concentrates on the displacements at midspan.

The testing protocol consisted of three sequential loading cycles, with the initial two ones reaching 30% and 50% of the expected failure load. Upon completing these cycles, a peak load corresponding to debonding failure—where the connection between the concrete and the reinforcing steel is compromised—was achieved for each specimen. Subsequent to this peak, the slabs endured further loading until they reached flexural failure, which manifested at a reduced load, indicating inherent ductility in these structures.

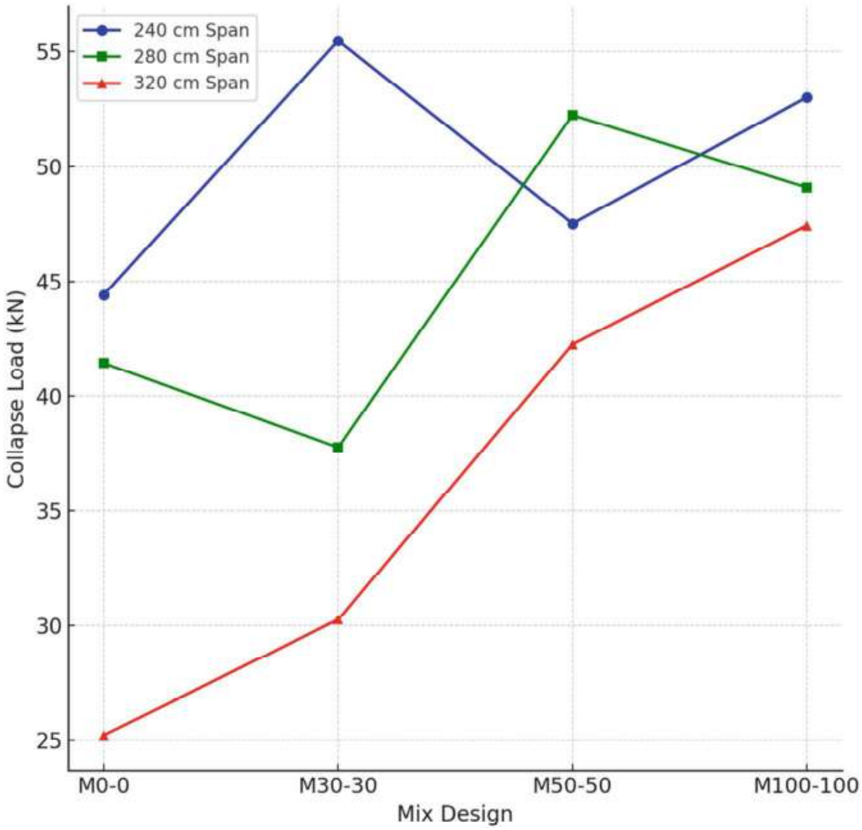

Fig. 4. Failure Load for Each Specimen versus mix design

Figure 4 plots visualizes the failure loads versus mix design, demonstrating the variation in structural endurance across different concrete mixtures and slab spans. The standard mix without recycled content (M0-0) consistently displayed a reduction in failure load with increasing span due to greater bending moments. In contrast, the M30-30 mix showed a heightened failure load at a 240 cm span, implying that moderate levels of recycled aggregates might bolster the structural capacity for specific spans. The M50-50 and M100-100 mixes further revealed an uptick in failure load at spans of

280 cm and 320 cm, suggesting that greater recycled content may enhance the structural integrity under certain conditions.

The synergy between the concrete and steel components is vital to the slabs' load-bearing efficiency. Preliminary findings indicate that the recycled aggregate concrete might strengthen the bond with steel, thereby increasing the failure load as the replacement ratio rises, an intriguing contrast to the compressive strength data shown in Table 3, which indicated a decline with higher recycled content.

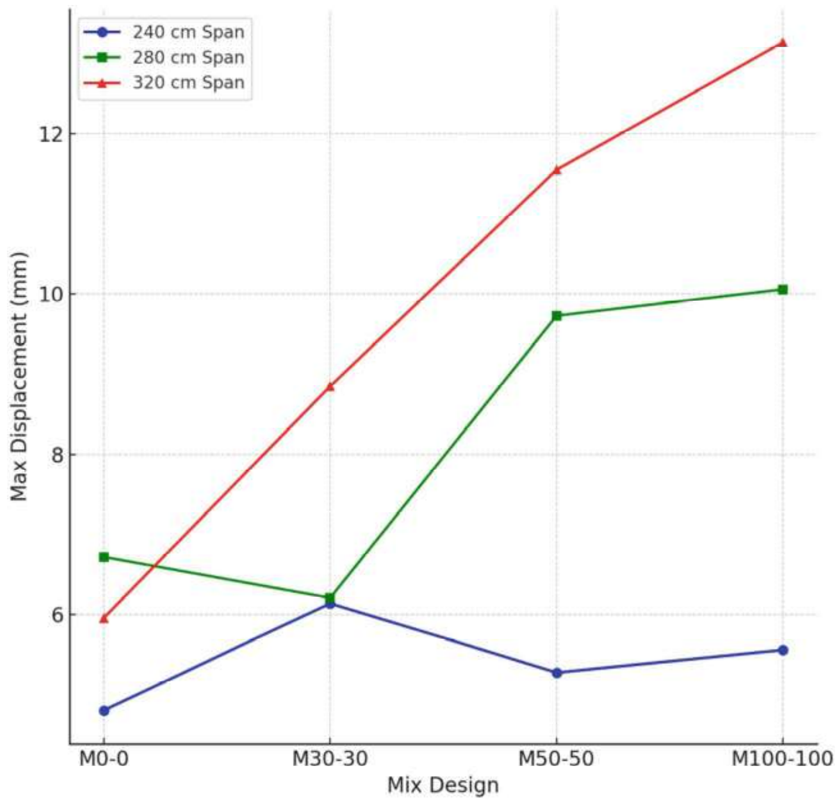

Fig. 5. Maximum Midspan Displacement at Failure Load for Each Blend versus mix design

Figure 5 conveys presents the peak midspan displacements versus mix design, reflecting that all mixtures experienced greater displacement with lengthier spans, in line with typical slab behavior under stress. Mixtures with higher recycled aggregate content, particularly M50-50 and M100-100, exhibited more pronounced displacements, especially at the 320 cm span. These findings suggest that while these mixtures bear the applied loads, they exhibit increased pliability and a reduced modulus of elasticity, factors that should be carefully assessed for structural serviceability. The correlation between higher displacement and increased recycled content, paralleling the reduction in elastic modulus detailed in Table 4, emphasizes the need to balance material sustainability with structural deformation properties.

5 Conclusions

The research presented herein examines the flexural response of steel-concrete composite slabs crafted with a blend of recycled fine and coarse aggregates. The investigation corroborates the effectiveness of recycled aggregates in composite slab construction as a means to reduce environmental impact without a substantial sacrifice in structural integrity. The afore discussed preliminary research outcomes seems very interesting and promising. In particular, it is worth noting that utilizing recycled aggregates to a specified threshold may serve as an efficacious substitute for natural aggregates, in accord with eco-friendly construction methodologies.

The data pertaining to failure loads indicate that composite slabs with recycled materials could potentially match or surpass the load-bearing capacity of traditional concrete slabs, especially over certain span ranges. This revelation contests the preconceived notion that recycled aggregates weaken structural strength and underscores the prospect of optimizing recycled content to meet desired structural standards. Furthermore, the increase in deflections observed in slabs with higher recycled content prompts a reevaluation of serviceability, while also indicating a ductile nature that could be beneficial in scenarios requiring energy dissipation and resilience.

In summary, this study provides persuasive evidence supporting the integration of recycled aggregates in composite slabs, affirming their capability to fulfill structural requisites and foster sustainable building practices. It also accentuates the imperative for continued research to refine the interplay between ecological benefits and structural functionality, ensuring that composite slabs are aptly adapted to diverse construction applications. Further studies are anticipated to fine-tune the concrete mixtures, examine the long-term behavior of recycled aggregate slabs, and fully apprehend their application breadth.

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