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Advancing sustainable concrete through the use of recycled aggregates for low-carbon and circular construction

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Abstract. This study addresses the growing problem of construction and demolition waste, which has increased significantly over recent years due to rapid urbanization and infrastructure development. Such waste contributes to the depletion of natural resources and the scarcity of conventional building materials. To mitigate these issues, this research examines the use of recycled aggregates, sourced from various construction waste streams, as partial or full replacements for natural aggregates in concrete construction. The primary objective is to evaluate the effect of various types and replacement ratios of recycled aggregates on the compressive strength of concrete mixes. In this study, the coarse aggregates were substituted in varying proportions and particle sizes, and their performance was compared. The experimental program involved casting multiple concrete specimens using recycled interlock pavers, recycled blocks, and recycled tiles as coarse aggregates. Compressive strength tests were conducted at curing ages of 7 and 28 days. Results indicate that incorporating recycled interlock pavers as coarse aggregate yielded the highest compressive strength among all tested materials, reaching 28.33 MPa after 7 days and 37.33 MPa after 28 days. In contrast, using recycled block material at a 100% replacement level resulted in significantly lower strength values, with 14.63 MPa at 7 days and 23.37 MPa at 28 days. These findings suggest that the type and quality of recycled aggregate have a significant impact on the mechanical performance of concrete. The study highlights the potential of selecting appropriate recycled materials to produce sustainable, high-performance concrete while reducing environmental impacts.

Introduction

The rapid pace of urbanization and the development of infrastructure have led to an unprecedented increase in construction and demolition (C&D) waste. This waste reflects serious environmental concerns, including a lack of natural resources and a lack of traditional construction materials [1]. To resolve these challenges, the recycled aggregate (RA), obtained from demolished concrete structures, has emerged as a promising alternative to the natural aggregate (NA). Using RA in new concrete production not only replaces massive waste from landfill but also reduces dependence on raw materials, supporting circular construction practices [2].

In urban settings where controls and enforcement of regulations on the site are weak, construction activities are also a significant contributor to the airborne particulate pollution. Excavation, demolition, loading of materials and vehicles on-site are some of the operations that generate very high volumes of coarse particulate matter (particles with aerodynamic diameter less than 10 micrometres) and fine particulate matter (particles with aerodynamic diameter less than

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2.5 micrometres). Such emissions compromise the quality of the environment in the immediate surroundings and pose respiratory and other health hazards to the workers and local communities. Evidence-based research of construction sites proves the significant number of particulate emissions at earthworks and foundation phases and highlights the efficiency of dust-reduction techniques, like water spraying, enclosure, and behavioural controls in the minimisation of dust formation [3-5].

Recycled aggregate, however, varies significantly from NA in terms of physical and mechanical properties. Due to the adherence to the old mortar, its high holes, low density, and weak relationships typically compromise the durability of low-strength, high water absorption, and recycled aggregate concrete (RAC) [6-9]. These deficiencies require targeted remedies to increase RA quality before it can be firmly employed in high-demonstration concrete applications [10]. Several alteration techniques, such as mechanical strengthening, chemical fecundation, and solution coatings, have been extensively studied, aimed at reducing the holes, improving the surface properties, and enhancing the mechanical properties [11-16].

Recent investigations highlight the ability of several treatment approaches to enhance the mechanical and durability performance of recycled aggregate. For example, the fecundation with polymer, silica fumes, or nano-content has been shown to reduce water absorption and improve the interface transition zone between recycled aggregate and cement paste [10-16]. Likewise, the process of washing with water is effective in removing impurities and reducing the adherent mortar, which improves the quality of both fine and coarse recycling aggregate [17]. Salary covering techniques have also demonstrated the ability to reduce porosity and increase RAC's mechanical strength [16]. These treatments collectively contribute to the development of high-quality RA, which enables its use in structural-grade concrete [1].

RAC's mechanical behaviour is an important factor in its acceptance as a construction material. Studies stated that while RAC often demonstrates less compressed power than natural aggregate concrete (NAC), customized mix design and RA treatment can significantly narrow this difference [11,13,14]. The inclusion of supplementary cementitious materials (SCMs) such as fly ash, silica fume, or mineral admix is also shown to increase the efficiency, strength, and stability of RAC mixture [18]. These strategies not only enhance RAC performance but also decrease environmental effects linked with cement production.

Durability is another major idea, as RAC is usually more vulnerable to water entry, chloride ingress, and carbonation, caused by its porous microstructure [12]. Research has verified that proper treatment of RA combined with controlled moisture conditions can reduce these issues [15,20]. Moisture conditioning plays an important role in improving the strength of the bond and reducing shrinkage in RAC mixtures [20]. In addition, recent studies have emphasized that the accurate measurement of water absorption in RA is necessary to design durable RAC; for this purpose, standardized test methods have been developed [21].

Despite these advances, variability in RA properties remains a significant hurdle to adopting it widely. Factors such as source material, crushing process, and replacement ratio affect all RAC performance [13]. For example, the high replacement level of recycled aggregate frequently reduces mechanical strength and durability, but partial replacement strategies have been successful in attaining a balance between stability and performance [19]. In addition, the installation of standardized specifications, such as the British and ASTM standards [2-5,20], provides a framework for quality control in RA use, ensuring more reliability in behaviour.

On a large scale, the use of RA supports permanent growth targets by reducing waste, conserving natural resources, and reducing greenhouse gas emissions from cement and total production [1,14]. The mass implementation of RA in concrete production has already been displayed in urban projects, especially in Europe and Asia, highlighting its practical feasibility [17]. However, further efforts are required to adapt to treatment methods, improve the stability of

performance, and promote policy measures that encourage recycling practices in the construction industry.

In summary, RA represents a viable pathway towards more durable and environmentally skilled construction. While challenges related to strength, durability, and variability persist, innovative treatment methods and customized mix designs have greatly improved its performance. The standardized test protocol [2-5,19] and by following the advantage of the supplementary materials, RAC can achieve equal properties of traditional concrete. Continuous research and technological innovation will be required to completely unlock the RA's ability, which is the foundation stone of low-carbon, circular construction practices [6-21].

Experimental Program and Materials

The practical program was designed to evaluate the behaviour of concrete that incorporates a recycled set as a partial or complete replacement for natural coarse sets. Before casting, all sets were characterized by sieve analysis to determine the particle size distribution. In the laboratory, moisture content, water absorption, and specific gravity were determined in the saturated surface-dry (SSD) position. These early tests ensured that the adjustment could consider water absorption variations, which could maintain stability in the effective water-to-cement ratio in all mixtures.

The mix design maintained a constant cement content and a similar fine total ratio for all batches, ensuring direct equivalence. Natural sand obtained from Sohar City was used as fine aggregate, and its grading was verified as per BS 882: 1992 [22]. The cement used throughout the study was the simple Portland cement type I, which complied with BS EN 197–1: 2000 [23]. To avoid any potential variability in hydration, potable water was used for both the continuous mixture and treatment. The adopted design trail mix was 1:2:4/0.5 (cement: sand: gravel/water).

The thick total component included both natural and recycled sources. Natural crushed aggregate, with a maximum particle size of 20 mm and BS 882: 1992 [22], was classified and collected from the Sohar region, and reference was served as an aggregate. Recycled options were obtained from locally available construction and demolition waste. These consisted of crushed concrete blocks, releasing concrete interlocking units from local industries, and broken tiles. Each recycled aggregate type was introduced, classified, and tested to ensure compliance with the BS 882: 1992 [22] specifications before being introduced in the mix design.

Natural sets with recycled options were replaced by weight at replacement levels of 25%, 50%, 75%and 100%. The water-to-cement ratio was nominally fixed at 0.5, but the adjustment was implemented where some recycled sets were required to offset high absorption capacity. Workability was assessed immediately through the slump test after the mixture, while compressive strength was determined on hard concrete samples in the specified treatment ages.

By checking the impact of the block, interlock, and tiles obtained from systematically fresh and hard concrete properties, the experimental program not only provides a reliable technical assessment but also contributes to furthering sustainable construction practices. The approach addresses two pressure challenges in the construction sector: construction and demolition environmental burden of waste and lack of natural resources, aligning the study with global efforts towards low-carbon, resource-skilled, and circular construction.

Results and Discussion

The experimental program provided valuable insight into the influence of the recycled aggregate on the physical, fresh, and hard properties of concrete. Tests of water absorption, moisture content, and specific gravity are characterized by the internal difference between natural and recycled aggregate, while the slump and the compressive strength test highlighted their impact on the performance of the concrete mix. Together, these findings display the importance of careful materials and mixing adjustments when incorporating recycled aggregate in structural applications.

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The physical properties of the aggregate detected a clear difference between natural and recycled aggregates. Water absorption tests showed that the natural coarse aggregate has a dense structure, which has only 1% absorption, while the natural sand has reached 3.5% due to its fine particle size and high surface area. In contrast, the recycled aggregate demonstrated continuous high absorption: 4.5% for crushed blocks, 3.6% for interlock, and 6.0% for tiles. These results confirm that recycled aggregates are naturally more porous than natural aggregates, a factor that can significantly affect the effective water-to-cement ratio and result in the functioning capacity and mechanical performance of concrete.

Moisture content tests emphasized differences. Fine aggregate recorded the highest value of 3.6%, reflecting the ability to maintain water. The natural coarse set again showed the lowest at 0.5%, while the recycled set recorded a high level: 2.3% for blocks, 1.9% for interlock, and 1.6% for tiles. These values outline the need to absorb the mixture of water and adjust the mixture for free water. Doing so may compromise the failure mixture stability and give rise to inconsistent mechanical performance.

Specific gravity results provided additional evidence of the low density of the recycled aggregate. Natural sand reported a specific value of 2.57, while the natural coarse aggregate overall demonstrated the values of 2.78 to suit the dense mineral structure. The recycled aggregate, however, displays low values due to porosity and residual mortar. Crushed blocks 2.61, interlock between 1.52, and tiles 1.47. This lower density not only highlights weak total structures but also suggests a high void ratio that affects both fresh and hard concrete properties.

The effects of these physical properties were reflected in the slump test results, which measured the functioning of fresh concrete. Natural aggregate mix attained 85 mm, serving as a baseline. The concrete with crushed blocks showed the lowest slump value equal to 65 mm, due to high water absorption and angular particle size, which is the limited flow capacity. Interestingly, there was a slight increase in workability as the level of block replacement increased, possibly due to the release of internal water during the mixture. In contrast, tile-based concrete gained a high slump of 90 mm. Smooth texture and low angularity of tile pieces increased lubrication and particle packing, improving workability. Interlock mix demonstrated intermediate behaviour, with a slump value equal to 80 mm, suggesting that the interlock provided a balance between absorption and condensation, the ability to work close to the natural total concrete.

Fig. 1 shows that the weight of the concrete decreases as the replacement percentage of natural aggregation increases; the effect varies according to the type of material used. The benchmark weight of the concrete cube with a natural set is 8.68 kg, against which all recycled mixtures are compared. Among the three types, concrete with recycled tiles exhibits the steepest decline, dropping from about 8.38 kg at 25% replacement to nearly 7.75 kg at 100%, indicating the influence of its lower density and higher porosity. Concrete with recycled block also shows a reduction, from around 8.55 kg at 25% replacement to 8.32 kg at 100%, though the decline is less pronounced. In contrast, concrete with recycled interlock maintains the highest stability, ranging from 8.60 kg to 8.45 kg, remaining closest to the benchmark of natural aggregate. This demonstrates that while recycled aggregates generally reduce the weight of concrete, interlock-based recycled aggregate provides the best performance in preserving cube weight compared with block and tiles.

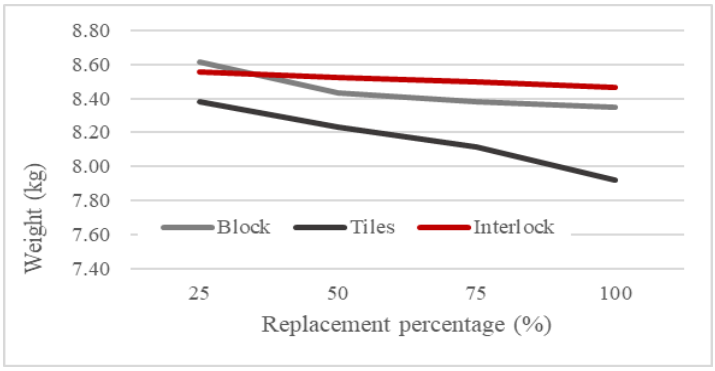
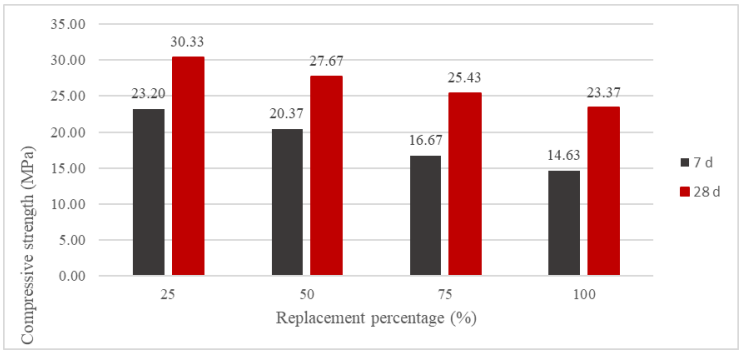
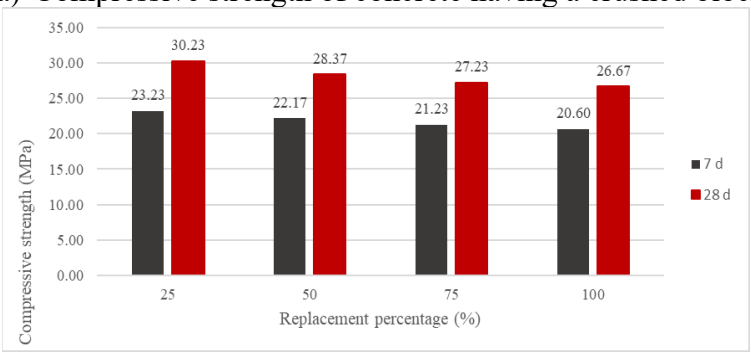


Figure 1: Effect of replacement percentage of RA on the weight of the concrete cube

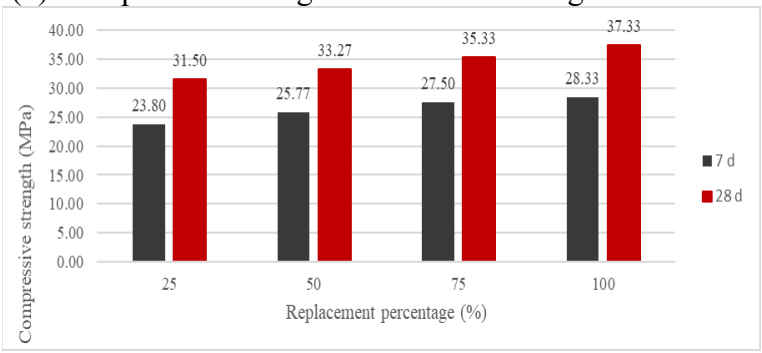
Fig. 3 shows the compressive strength of concrete at 7 and 28 days of curing with different replacement percentages of recycled aggregate. Concrete made with block-based recycled aggregate showed the weakest performance compared to the control mix. At 25% replacement, the compressive strength reached 23.20 MPa at 7 days and 30.33 MPa at 28 days, but as the replacement percentage increased, the strength declined sharply. At 100% replacement, the strength dropped to 14.63 MPa and 23.37 MPa, representing a significant reduction from the benchmark of 25.03 MPa and 38.87 MPa for natural aggregate concrete. These results highlight that block aggregates, due to their higher porosity and lower quality, significantly reduce compressive strength, making them less suitable for structural applications. Concrete with crushed tile-based recycled aggregate exhibited moderate performance, with a less drastic reduction in strength compared to block aggregate. At 25% replacement, the compressive strength was 23.23 MPa and 30.23 MPa at 7 and 28 days, respectively, which is close to the control values. However, as replacement increased to 100%, strength dropped to 20.60 MPa at 7 days and 26.67 MPa at 28 days. This indicates that tile aggregates can be used effectively at low to moderate replacement levels, but higher replacement percentages lead to noticeable losses in mechanical performance. Concrete having crushed interlock-based recycled aggregate demonstrated the best performance among the three types and, in some cases, performed close to the control mix. At 25% replacement, compressive strength was 23.80 MPa and 31.50 MPa at 7 and 28 days, respectively, and it improved with higher replacement levels. At 100% replacement, the strength reached 28.33 MPa at 7 days and 37.33 MPa at 28 days, values very close to the benchmark natural aggregate concrete. These results suggest that interlock aggregates provide better strength development and are the most suitable recycled aggregate type for structural applications, even at full replacement levels. Together, the results depict the complex but promising role of the recycled set in solid production. While crushed blocks and tiles reduce strength and require careful water adjustment due to their holes and low density, interlocks emerge as a highly effective option, providing strength compared to natural aggregates and ensuring adequate functioning. Conclusions emphasize that the suitability of the recycled aggregate is highly dependent on its basic properties. With appropriate characterization and mixing design adjustment, recycled aggregates can significantly reduce dependence on natural resources and contribute to more durable and spherical construction practices.



(a) Compressive strength of concrete having a crushed block



(b) Compressive strength of concrete having crushed tiles



(c) Compressive strength of concrete having crushed interlock

Figure 2: Effect of replacement percentage of RA on the concrete compressive strength

Conclusion

This investigation confirms that recycled sets affect the physical, fresh, and mechanical properties of concrete by material-specific methods. The performance interlock between crushed blocks, tiles, and interlock underscores the need for sewn mixing designs when transitioning to a recycled natural set.

- Concrete with crushed interlock showed the best performance, with compressive strength growing from 37.33 MPa at 100% to 31.50 MPa at 25% replacement, corresponding to a control mixture of around 38.87 MPA. It displays its suitability as a structural option.
- Crushed block aggregate led the weakest mix, where the strength fell from 30.33 MPA at 25% replacement to 23.37 MPa at 100%, which represents a decrease of about 40% compared to the control.
- Tile-based concrete presented moderate behaviour, in which the compressive strength decreased from 30.23 MPa at 25% to 26.67 MPa at 100%, a decrease of about 31% compared with the control, although it still maintains a practical mix.

- The cube weight decreased from 8.68 kg for natural aggregate to 8.35 kg with block and 7.92 kg with tiles at 100% replacement, while interlock showed the least reduction, remaining close to the control at 8.47 kg.
- Concrete with crushed block showed the lowest slump (65 mm compared to 85 mm for the control) but improved at higher replacement levels. Concrete with crushed interlock exhibited a steady increase in slump, reaching 90 mm, while concrete with crushed tiles consistently maintained good workability at about 80 mm.
- Overall, the crushed interlock set provided the most reliable balance of strength, density, and ability to work, making it the closest option to the natural aggregate. Crushed blocks and tiles, while less effective structurally, remain viable for non-structural or partial applications, supporting the permanent reuse of construction and demolition waste.

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