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OPTIMIZING MATERIAL REPLACEMENT STRATEGIES FOR ENHANCED STRENGTH PERFORMANCE OF SUSTAINABLE CONCRETE

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ABSTRACT

Sustainable concrete is an important pathway to decrease dependence on conventional cement and natural aggregates and to ensure adequate mechanical performance. This study compared various approaches for improving the strength performance of sustainable concrete by replacing materials. For the design, the experimental data consisted of five concrete conditions (conventional concrete, cement replacement, fine-aggregate replacement, coarse-aggregate replacement, and combined/all-material replacement), and a quantitative comparative design was used. The compressive strength and split tensile strength were obtained after 7, 14 and 28 days from three replicates for each curing age. The performance differences were analyzed using descriptive statistics, percentage improvement, one-way analysis of variance, post-hoc comparisons, and correlation analysis. The strength of all concrete groups was enhanced with the curing age. The combined material replacement gave the maximum compressive strength of 26.10 MPa at 28 days that shows a 24.26% improvement over the conventional concrete, and the split tensile strength of 4.46 MPa at 28 days that improves by 17.10% over the conventional concrete. There were significant differences in the compressive strength between replacement strategies at all curing ages, and significant differences in split tensile strength were also noted. The overall strength-performance index, which was normalized, also supported the condition of combined replacement as the strongest condition. These results show that it is possible to coordinate the replacement of several concrete constituents to improve the mechanical properties and allow more sustainable use of materials in the concrete industry.

1. Introduction

One of the more versatile construction materials with a relatively high compressive strength, easily available and durable is concrete and thus it is largely utilized. Conventional concrete production, however, puts significant environmental strain due to the heavy use of cement, natural sand and coarse aggregates. Energy consumption and carbon emissions are especially linked to cement production, while the extraction of raw aggregates continuously depletes resources and disturbs the ecology. As a result, sustainable concrete has become a major focus in the construction industry to minimize environmental impact without compromising engineering performance. Reuse of CDW as recycled aggregate is an effective way to reduce landfill disposal and reliance on virgin resources (Akhtar & Sarmah, 2018). Recycled aggregates have also proven to hold great promise for concrete use when their properties and replacement percentages are carefully controlled (Tam et al., 2018). Alternative binder systems such as geopolymer-based concrete also contribute to the move toward cleaner and less impactful construction materials (Hassan et al., 2019).

Typically, material replacement strategies include partial substitution of cement, fine aggregate, coarse aggregate or a combination of all. The use of supplementary cementitious materials like GGBS, metakaolin, and other mineral admixtures helps in reducing the use of Portland cement and enhances some of the microstructural and mechanical properties. Good bond, durability, and microstructural properties have been reported in recycled concrete containing GGBS, which has proven its potential in sustainable structural applications (Majhi & Nayak, 2019). High-volume GGBS has also been successfully used in recycled aggregate concrete systems under activated conditions (Majhi et al., 2020). Another effective supplementary material is metakaolin, for its pozzolanic activity and its ability to improve mechanical performance and durability (Homayoonmehr et al., 2021). Research on the use of RCDA along with metakaolin has shown positive results for the performance, particularly with integrated replacement strategies (Muduli & Mukharjee, 2020).

Materials like waste foundry sand and recycled fine aggregate can be used to replace the fine aggregate. The effect of using waste foundry sand on the mechanical behavior of concrete has been studied and shown to be potentially strength-based sustainable applications (Behnood & Golafshani, 2020). They have also been used to produce self-compacting concrete and have shown some improvement in performance when used under specific replacement conditions (Parashar et al., 2020). However, as fine recycled aggregate can affect workability, durability, strength, cost, and environmental performance, careful proportioning is essential (Hafez et al., 2020; Nedeljković et al., 2021). Comparative studies have also demonstrated that the performance of recycled fine aggregates varies when used with natural coarse aggregates and recycled coarse aggregates (Singh et al., 2022). In addition, recycled concrete and brick powders can be used as supplementary cementitious materials to produce more environmentally friendly concrete (Likes et al., 2022).

Compressive strength is the most important parameter in determining the quality and capacity of concrete, while split tensile strength gives valuable data about the resistance to cracking and tensile stresses. Replacement type, material characteristics, mixture composition, and curing age are factors that influence the strength of sustainable concrete. The use of supplementary cementitious materials has been shown to significantly affect the compressive strength of recycled aggregate concrete (Xie et al., 2020). Similarly, the mechanical performance of recycled aggregate concrete has been modeled using advanced prediction techniques, with a strong correlation between the constituent properties and the compressive strength obtained (Golafshani et al., 2021). Strength builds up in most cases with the age of curing, while hydration and pozzolanic reaction continue.

While a number of studies investigated recycled or supplementary materials, fewer studies investigated the combination of cement, fine aggregate, coarse aggregate and recycled replacement strategies under the same experimental conditions. This makes it hard to identify directly the strategy that offers the best ratio of compressive and tensile performance. It is therefore necessary to systematically compare to determine the relative effectiveness of individual and combined replacement approaches.

The purpose of the present study is to compare the various strategies of replacing materials to enhance the strength performance of sustainable concrete. In particular, it compares conventional concrete and cement, fine aggregate, coarse aggregate and combined replacement mixtures; measures the 7, 14 and 28 day compressive strength; measures the split tensile strength at the same ages; identifies the best overall strength performance for the replacement strategy; and quantifies the strength improvements for the replacement strategy compared to the conventional concrete.

2. Materials and Methods

2.1 Research Design

In this study, the research design was a quantitative comparative design that involved analysis of experimental concrete data. This was aimed at comparing the performance of conventional concrete with various sustainable material-replacement strategies in terms of their strength performance in the same curing period. The compressive strength and split tensile strength at 7, 14, and 28 days were analyzed.

2.2 Dataset and Experimental Groups

The dataset included five Excel workbooks that included experimental strength data and physical characterization data (T, 2023). There were five concrete groups considered, such as conventional concrete, cement-replacement concrete, fine-aggregate-replacement concrete, coarse-aggregate-replacement concrete, as well as combined material-replacement concrete. There were three replicate observations of each group at each curing age. The compressive and split tensile strengths were given separately, which gave 45 age-specific values for each strength aspect.

2.3 Materials and Replacement Strategies

The dataset was a representation of a number of sustainable and supplementary construction materials. Among the cementitious replacement materials were Alccofine, metakaolin and ground granulated blast-furnace slag (GGBS/GGBFS). Fine-aggregate options were sand (foundry sand and copper slag), and coarse-aggregate options were recycled coarse aggregate and sintered fly-ash aggregate. These substances constituted cement, fine aggregates, coarse aggregates, and mixed replacement plans. The standard performance was conventional concrete.

2.4 Material Characterization

Physical property tests that were in the dataset were used to characterize the constituent materials. Cementitious materials and aggregates were reported to have specific gravity. Sieve analysis was used to determine the particle-size distribution of both natural and replacement aggregates. Impact value, flakiness index and elongation index were also used to assess aggregate quality. These properties were exploited to interpret variations in strength performance among replacement strategies.

2.5 Compressive Strength Assessment

Cube specimens were tested to determine compressive strength at curing ages of 7, 14 and 28 days. The data included failure load and compressive strength in N/mm 2, which is equal to MPa. At each curing age, three replicate measurements were taken of each concrete group. Strength development with time and comparison of replacement strategies with traditional concrete were done using the mean strength values.

2.6 Split Tensile Strength Assessment

Cylindrical tensile strength was measured at 7, 14 and 28 days of curing. N/mm 2 was reported as failure load and calculated tensile strength. Each concrete group had three replicate observations at each age of curing. These measurements were employed to evaluate the effect of various material-replacement strategies on tensile resistance and cracking-related performance

2.7 Study Variables and Performance Evaluation

Material-replacement strategy was the main independent variable, which included conventional, cement replacement, fine-aggregate replacement, coarse-aggregate replacement, and combined replacement. Age consideration was also taken as an independent variable whereby three levels were taken, 7, 14 and 28 days. Compressive strength and split tensile strength were the dependent variables. Mean strength, variability, strength gain with curing age, and percentage change were used to evaluate performance in comparison to conventional concrete. The most effective strategy was determined mainly due to its compressive and tensile strength performance which was mainly good at 28 days.

2.8 Statistical Analysis
Each concrete group and curing age was analyzed using descriptive statistics such as mean, standard deviation, minimum as well as maximum. There was also a determination of the percentage improvement compared to traditional concrete. It was analyzed using one-way analysis of variance in which statistical assumptions were met and analyzed the differences in the strength of the five replacement strategies at each of the curing ages. Post-hoc pairwise comparisons were made after significant results. Where necessary, correlation analysis was also used to determine the relationship between the curing age and strength development. A p-value of $p < 0.05$ was used to establish statistical significance.

3. Results
3.1 Physical Characteristics of Conventional and Replacement Materials
The constituent-characterization data proved the existence of obvious differences among traditional and sustainable replacement materials. The coarse aggregate that was recycled also had flakiness and elongation indices of 6.08% and 20.90%. These differences demonstrate that there are significant disparities in density, particle properties and impact resistance among the alternative materials and offers a significant material foundation for the subsequent strength performance interpretation. There were significant differences between the replacement materials. Specific gravity was 1.67 in the case of Alccofine, and 3.71 in the case of metakaolin. The impact value of recycled coarse aggregate was 15.00% with flakiness and elongation indices of 6.08% and 20.90 respectively and an impact value of 26.32 was recorded with sintered fly-ash aggregate. These differences can affect the mechanical properties of the concrete mixtures produced.

3.2 Compressive Strength Development Across Replacement Strategies
For all concrete conditions, compressive strength was found to rise steadily as the curing age progressed. Conventional concrete had mean strengths of 13.48, 18.90 and 21.01 MPa for 7, 14 and 28 days as shown in Figure 1. The mean values obtained for all replacement strategies were higher as compared to those of the conventional specimens during the curing period. The all-material replacement consistently resulted in the highest compressive strength, both at 7 days (17.32 MPa) and at 28 days (26.10 MPa). The second best condition was when the coarse aggregate was replaced at 28 days with a value of 24.41 MPa.

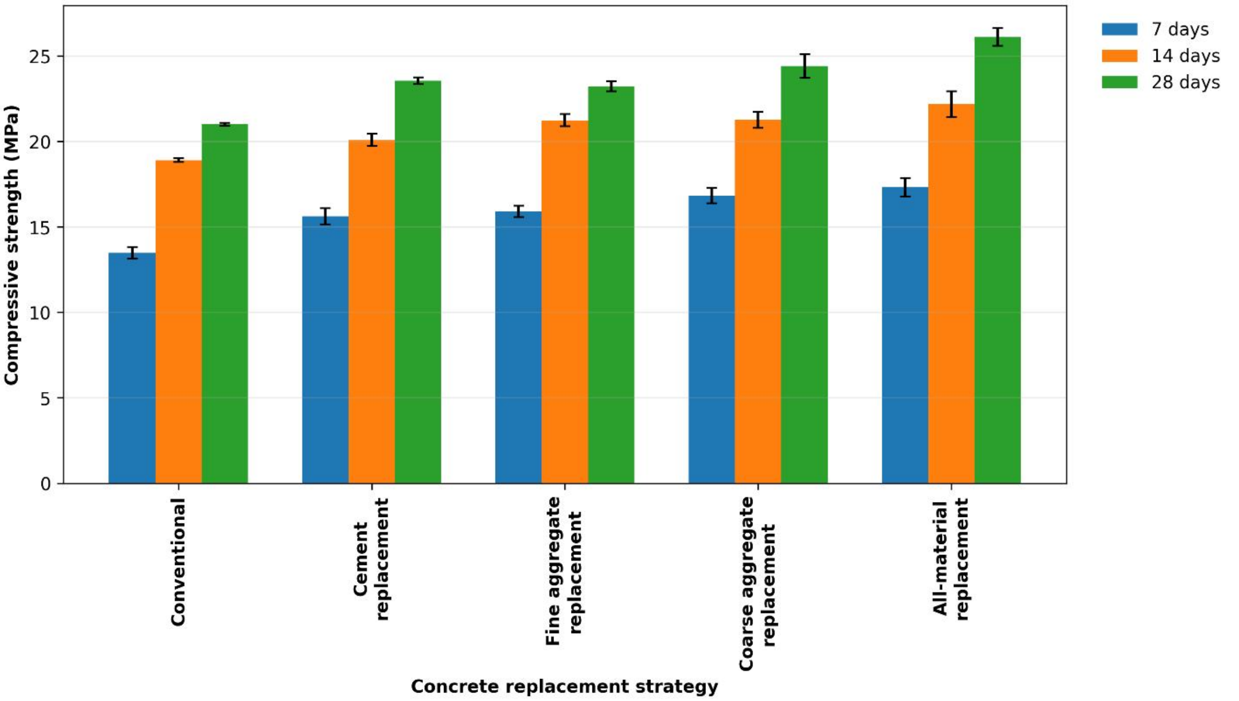

Figure 1. Compressive strength development of different concrete replacement strategies at 7, 14, and 28 days

3.3 Comparative Compressive Strength Performance

The same results were obtained from descriptive statistics as well, demonstrating the superiority of the replacement mixtures in terms of strength. As seen in Table 1, the results of all material replacement was found to be higher than the conventional concrete by 28.46% at 7 days, 17.40 % at 14 days and 24.26% at 28 days in terms of mean compressive strength. The 28-day gain of 16.22% was the second best gain from the use of coarse-aggregate replacement. Cement and fine-aggregate replacement also showed better results than control, but the results were less pronounced at 28 days with 12.13% and 10.58% improvement respectively. Standard deviations are generally low indicating a good agreement between the three replicate specimens in each group.

Table 1. Mean compressive strength and percentage change relative to conventional concrete

Replacement strategy	7 days, MPa Mean ± SD (% change)	14 days, MPa Mean ± SD (% change)	28 days, MPa Mean ± SD (% change)
Conventional	13.48 ± 0.34 (0.00%)	18.90 ± 0.11 (0.00%)	21.01 ± 0.09 (0.00%)
Cement replacement	15.63 ± 0.46 (+15.93%)	20.09 ± 0.36 (+6.27%)	23.56 ± 0.19 (+12.13%)
Fine aggregate replacement	15.91 ± 0.34 (+18.02%)	21.24 ± 0.36 (+12.38%)	23.23 ± 0.29 (+10.58%)
Coarse aggregate replacement	16.83 ± 0.45 (+24.84%)	21.26 ± 0.47 (+12.46%)	24.41 ± 0.69 (+16.22%)
All-material	17.32 ± 0.53 (+28.46%)	22.19 ± 0.75	26.10 ± 0.52

replacement		(+17.40%)	(+24.26%)

3.4 Split Tensile Strength Development

The split tensile strength also showed an increasing trend with curing age for all concrete conditions. In the conventional concrete, at 7 days, its value was 2.68 MPa and at 28 days, it was 3.81 MPa as seen in Figure 2. The mean tensile strength at 28 days (3.38 MPa) and 7 days (4.46 MPa) was the highest for all-material replacement. The performance of Fine-aggregate replacement was also good, especially at 7 days and 14 days with the tensile strength of 4.02 MPa at 28 days. Coarse-aggregate replacement exhibited a slight improvement over the control, but gained considerably in strength at 28 days.

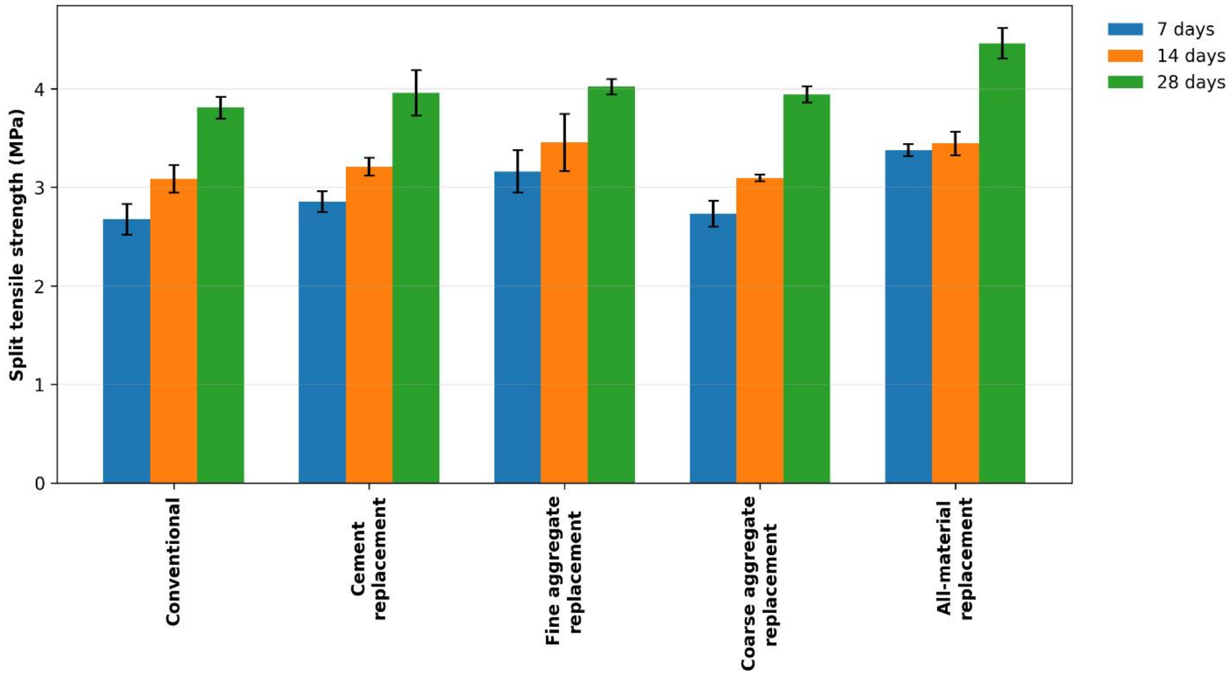

Figure 2. Split tensile strength development of different replacement strategies at 7, 14, and 28 days

3.5 Comparative Split Tensile Strength Performance

The comparative tensile-strength statistics are given in Table 2. The best improvement was achieved in all-material replacement which showed an increase of 26.28%, 11.62%, and 17.10% at 7, 14, and 28 days respectively. Fine-aggregate replacement had a significant early-age response with an increase in tensile strength by 18.17% at 7 days and 11.93% at 14 days. But at 28 days, all-material replacement definitely outpaced all individual replacement categories. The 28-day replacement of cement and coarse aggregate resulted in a smaller increase of 3.97% and 3.47% respectively.

Table 2. Mean split tensile strength and percentage change relative to conventional concrete

Replacement strategy	7 days, MPa Mean ± SD (% change)	14 days, MPa Mean ± SD (% change)	28 days, MPa Mean ± SD (% change)
Conventional	2.675 ± 0.156 (0.00%)	3.086 ± 0.139 (0.00%)	3.808 ± 0.111 (0.00%)

Cement replacement	2.854 ± 0.104 (+6.70%)	3.208 ± 0.091 (+3.98%)	3.958 ± 0.230 (+3.97%)
Fine aggregate replacement	3.161 ± 0.216 (+18.17%)	3.454 ± 0.290 (+11.93%)	4.020 ± 0.079 (+5.58%)
Coarse aggregate replacement	2.732 ± 0.130 (+2.12%)	3.095 ± 0.033 (+0.31%)	3.940 ± 0.083 (+3.47%)
All-material replacement	3.378 ± 0.059 (+26.28%)	3.444 ± 0.120 (+11.62%)	4.459 ± 0.153 (+17.10%)

3.6 Effect of Curing Age on Strength Development

The mechanical performance was greatly affected by the curing age in a positive way. Conventional concrete showed a 55.82% increase in compressive strength after 28 days while the all-material replacement showed a 50.73% increase in compressive strength after 28 days. The corresponding increments in split tensile strength were 42.33% and 31.98%, respectively. The results for the replacement of coarse aggregate showed great improvement in tensile strength, by 44.21% from 7 to 28 days. As shown in Figure 3, the composite strength-development index rose continuously with curing time for all five groups, indicating the continuous development of the mechanical strength. There was a good positive correlation between curing age and the compressive strength ($r = 0.867$, $p < 0.001$) and split tensile strength ($r = 0.897$, $p < 0.001$) obtained from the pooled group age.

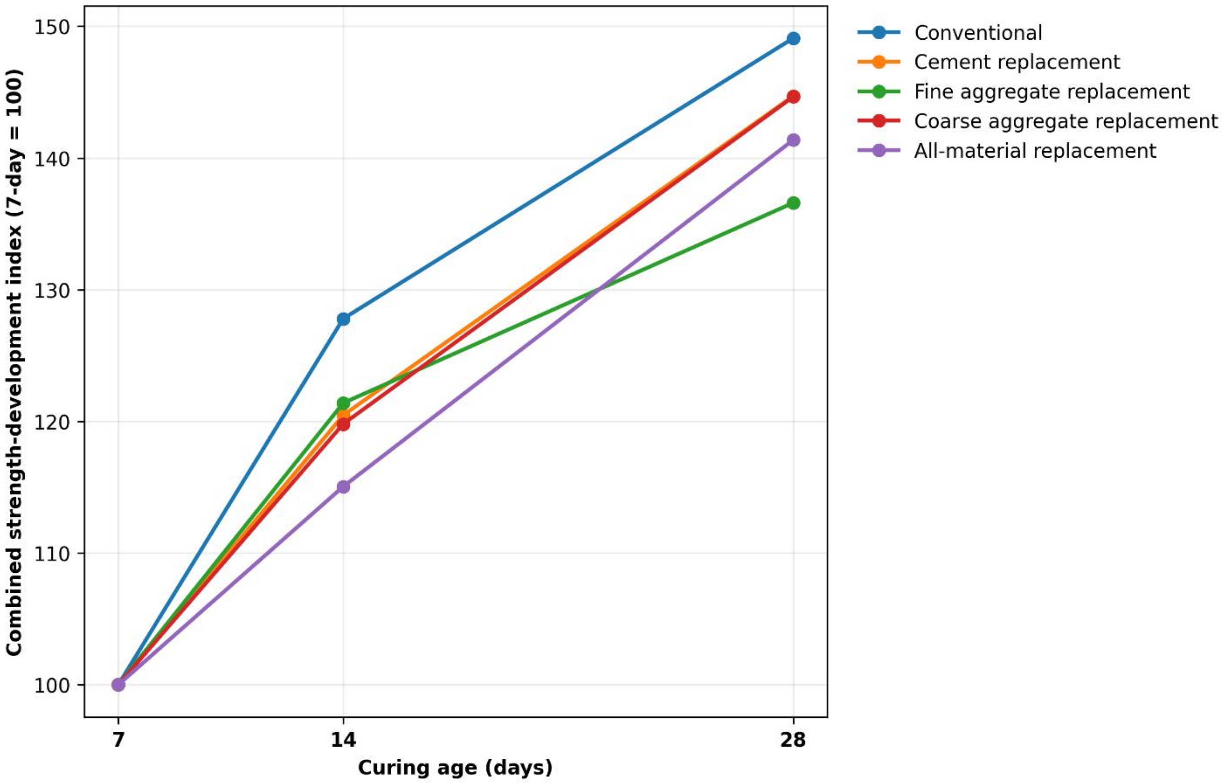

Figure 3. Effect of curing age on combined strength development of different concrete groups

3.7 Statistical Comparison of Material Replacement Strategies

ANOVA revealed statistically significant differences in compressive strength between the five concrete groups at each curing age as reported in Table 3. The effects were significant at 7 days, $F(4,10) = 35.58$, $p < 0.001$; 14 days, $F(4,10) = 22.95$, $p < 0.001$; and 28 days, $F(4,10) = 59.52$, $p < 0.001$. The post-hoc analysis showed that the strength of all-material replacement was much greater than that of all other concrete groups at 28 days.

There were also significant differences in split tensile strength at 7, 14, and 28 days among replacement conditions. Though the overall 14-day tensile ANOVA ($p = 0.038$) was significant, no single pair was significant after multiplicity-adjusted post-hoc testing. All-material replacement was considerably greater at 28 days compared to conventional, cement-replacement, fine-aggregate-replacement and coarse-aggregate-replacement concrete.

Table 3. ANOVA and post-hoc comparison of concrete strength among replacement strategies

Outcome	**Curing age**	**ANOVA, F(4,10)**	**p-value**	**Main post-hoc findings**
Compressive strength	7 days	35.58	<0.001	All materials> conventional, cement and fine aggregate; several replacement groups > conventional
Compressive strength	14 days	22.95	<0.001	All-material > conventional and cement; fine and coarse replacement > conventional
Compressive strength	28 days	59.52	<0.001	All-material > all other groups; coarse replacement > conventional and fine replacement
Split tensile strength	7 days	13.20	<0.001	All-material > conventional, cement and coarse replacement; fine replacement > conventional
Split tensile strength	14 days	3.87	0.038	Overall group effect significant; no adjusted pairwise comparison significant
Split tensile strength	28 days	9.08	0.002	All materials> conventional, cement, fine and coarse replacement

3.8 Overall Strength Performance of Replacement Strategies

A performance-strength index that was summed up over 28 days was calculated as the ratio of compressive and split tensile strength to the conventional concrete baseline and the average of both normalized values. Figure 4 shows that the conventional concrete was given an index of 100.0. The cement replacement and fine-aggregate replacement had similar indices of 108.05 and 108.08,

respectively, and the coarse-aggregate replacement had 109.84. The all-material replacement method had the highest cumulative index of 120.68, which is an approximate percentage of 20.68 mechanical performance over conventional concrete.
Consequently, all-material replacement emerges as the most successful strategy in compressive strength as well as split tensile strength and hence the strongest sustainable replacement overall condition in the given data. But since the dataset lacks multiple dosage levels of each material, these results prove the most successful replacement category but not the optimum replacement percentage.

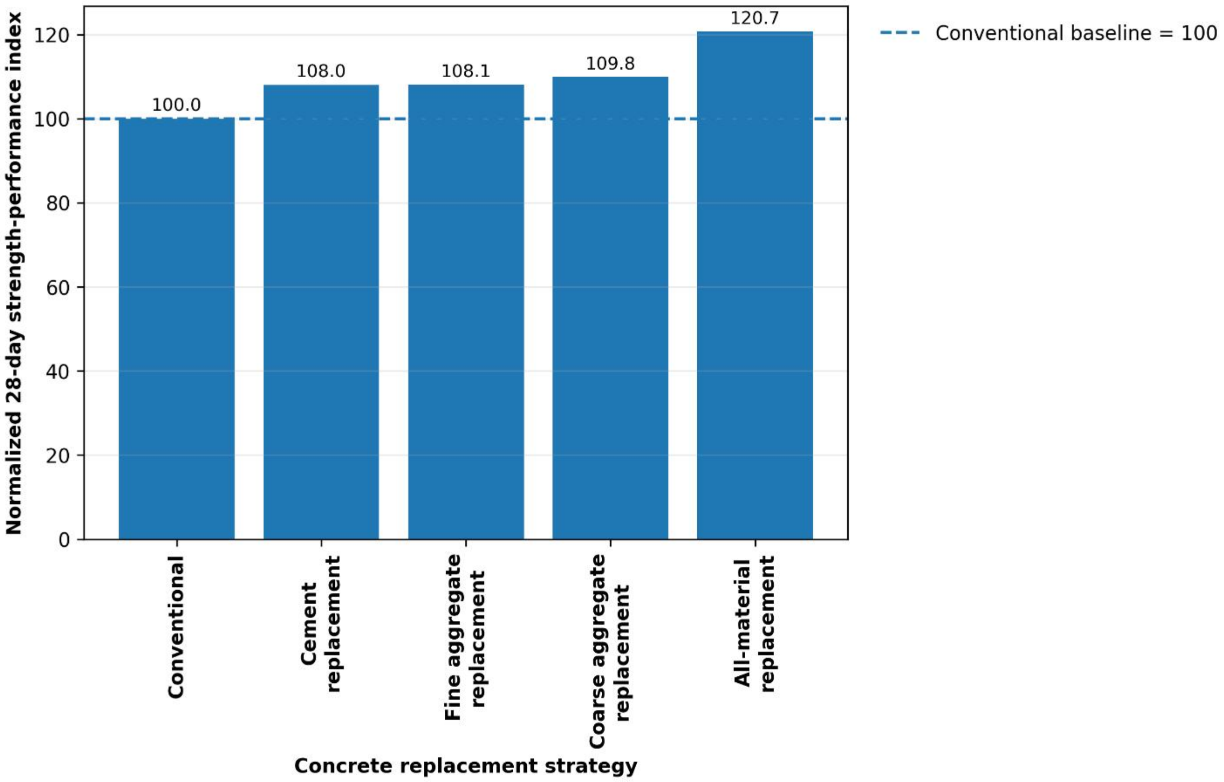

Figure 4. Normalized 28-day overall strength-performance index of the different replacement strategies

4. Discussion

The results have shown that the materials can be used to increase the compressive strength and split tensile strength compared to the conventional concrete. The best overall performance was achieved by the combined/all-material replacement strategy with compressive strength of 26.10 MPa and split tensile strength of 4.46 MPa at 28 days. The results presented herein corroborate the feasibility of incorporating RC and supplementary constituents into SC (Revilla-Cuesta et al., 2022). The findings are also in line with sustainable guidelines that prioritize both mechanical performance and resource efficiency in the production of recycled aggregate concrete (Shmlls et al., 2023).
All the replacement concrete in the cement showed an increase in compressive strength compared to the conventional concrete, including a 12.13% improvement at 28 days. This improvement can be related to additional cementitious reactions and evolution of the cementitious matrix. Similarly, the use of supplementary materials in recycled aggregate systems (RAS) has been reported to provide improvement (Chen et al., 2022). In addition, the use of limestone calcined clay cement has also shown the ability to enhance the properties of recycled aggregate concrete by changing the composition of the binder (Guo et al., 2022).
The results showed that using fine-aggregate replacement enhances the mechanical properties with an increase of 10.58% in 28-day compressive strength and 5.58% in split tensile strength. The use of alternative fine aggregates can lead to changes in the properties of the particle packing and characteristics of the matrix if used at the correct proportions. Waste foundry sand (WFS) is suitable alternative to natural river sand (NRS) and experimental results have demonstrated that it can

improve the strength and microstructural properties of concrete (Ahmad et al., 2022; Kumar et al., 2022). Foundry sand has also shown promise to be used in green concrete production (Priyadarshini & Giri, 2022).
A significant improvement in compressive strength of 16.22% was obtained for coarse-aggregate replacement while the improvement in tensile strength was relatively small. The geometry, physical properties, composition of recycled aggregate and the quality of the bonding at the interfacial transition zone (ITZ) between the fine recycled and the natural cement aggregate are vital factors affecting the mechanical performance of recycled aggregate concrete (RAC) (Mamirov et al., 2022). When supplementary materials like silica fume are used in the treatment, the microstructure and compressive strength of recycled coarse aggregate concrete can be further improved (Zhu et al., 2022).
The resultant replacement strategy gave the maximum of 24.26% and 17.10% increase in compressive strength and tensile strength after 28 days compared to the conventional concrete. The result indicates possible synergistic effects for the use of the alternative binders and the fine and coarse aggregates. The use of supplementary cementitious materials can enhance the properties of the matrix, whereas the use of recycled constituents can decrease the use of virgin materials. Similarly, the results suggest that the mix design of fly ash, GBFS, silica fume, and metakaolin can greatly affect the mechanical and pore properties of RAC (Wang et al., 2023).
The compressive and split tensile strengths generally increased with most of the replacement strategies from 7 to 28 days. This is the result of ongoing cement hydration and some further reactions involving the supplementary cementitious constituents. The age-dependent behaviour observed also highlights the need to consider age while estimating the compressive strength of conventional and recycled aggregate concrete (Munir et al., 2022).
The high strength of a few replacement mixtures is in agreement with earlier findings that concrete can be as strong or stronger with the effective use of recycled and supplementary material. However, the results are still influenced by the constituents and their mixture design. For instance, waste foundry sand can have good mechanical properties, and it has an impact on the behavior related to durability (Sandhu & Siddique, 2022).
Results showed potential to decrease Portland cement and natural aggregate dependence without sacrificing mechanical properties. The use of recycled aggregates can be a measure to promote more resource-efficient concrete production (Liu et al., 2024). The results are thus favorable for the incorporation of industrial by-products and recycled materials under controlled conditions in the production of sustainable structural concrete.
The study has only three replicates in each group and limited long-term performance indicators. No exact dosage optimization is possible because more than one replacement percentage was not available. Future investigations should address the durability, life-cycle environmental impact and long-term structural response.

5. Conclusion

The current research study has shown that with proper integration into the mix, the sustainable replacement of materials can be used to improve the mechanical performance of concrete. Combined/all-material replacement was the most effective strategy of the strategies analyzed because it obtained the best overall results with the highest 28-day compressive strength of 26.10 MPa and split tensile strength of 4.46 MPa. These values compared to those of conventional concrete were improvements of 24.26 and 17.10 respectively. Single cement, fine-aggregate and coarse-aggregate replacement strategies were also capable of generating quantifiable strength benefits but their performance was still less than the combined replacement condition. The development of strength gained steadily between 7 and 28 days and this showed the significance of the curing period in promoting further hydration and secondary pozzolanic processes. The statistical findings also revealed there to be important differences between replacement groups, especially in compressive strength and 28-day tensile performance. The results indicate that the synergistic application of supplementary cementitious materials, recycled aggregates, and alternative fine aggregates may decrease the reliance on conventional cement and virgin aggregates without compromising or worsening the structural performance. But since the dataset lacked several replacement percentages, the research finds the most effective replacement category, but not an optimal dosage. Research in the future must include more replacement levels, durability testing, life-cycle analysis and long-term structural performance to define optimal sustainable designs of concrete mixtures.

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