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Performance of self-compacting concrete containing recycled coarse aggregate.

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ABSTRACT

This study aims to evaluate the performance of self-compacting concrete when replacing natural coarse aggregate with recycled aggregate at varying ratios (20%, 40%, 60%, 80%, and 100%), in the context of promoting sustainability in the construction sector and reducing dependence on natural resources. Natural aggregate from the Jufrah region in Libya was used as the primary source, while the recycled aggregate was obtained from crushed concrete, addressing the issue of waste disposal from demolished buildings. The compressive strength of the mixes was measured at different ages (3, 7, 21, 28, and 60 days). The results showed that the fresh properties of the mixes remained within EFNARC standards. Moreover, replacing 20% of natural aggregate with recycled aggregate resulted in a 6% reduction in compressive strength at 3 days and 15% at 28 days, while a 40% replacement led to a 10% reduction at 3 days and 25% at 28 days. These findings indicate that the use of recycled aggregate negatively affects compressive strength, especially at higher replacement levels. However, it can still be successfully used in specific applications within well-defined limits, contributing to environmental goals without significantly compromising concrete performance.

أداء الخرسانة ذاتية الدمك المحتوية على الركام الخشن المعاد تدويره.

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الكلمات المفتاحية:

الخرسانة
الخرسانة ذاتية الدمك
الركام الخشن المعاد تدويره

المخلص

تهدف هذه الدراسة إلى تقييم أداء الخرسانة ذاتية الدمك عند استبدال الركام الخشن الطبيعي بركام معاد تدويره بنسب متفاوتة (20%، 40%، 60%، 80%، و100%)، وذلك في سياق تعزيز الاستدامة في قطاع البناء وتقليل الاعتماد على الموارد الطبيعية. تم استخدام الركام الطبيعي من منطقة الجفرة في ليبيا كمصدر رئيسي، في حين تم الحصول على الركام المعاد تدويره من خرسانة مكسّرة، لمعالجة مشكلة التخلص من مخلفات المباني المهدامة، تم قياس مقاومة الضغط للخلطات في أعمار مختلفة (3، 7، 21، 28، و60 يوماً). أظهرت النتائج أن خصائص الخرسانة في الحالة الطازجة بقيت ضمن المعايير المحددة من قبل EFNARC كما أن استبدال 20% من الركام الطبيعي بركام معاد تدويره أدى إلى انخفاض في مقاومة الضغط بنسبة 6% عند عمر 3 أيام، و15% عند عمر 28 يوماً، بينما أدى الاستبدال بنسبة 40% إلى انخفاض بنسبة 10% عند 3 أيام، و25% عند 28 يوماً. تشير هذه النتائج إلى أن استخدام الركام المعاد تدويره يؤثر سلباً على مقاومة الضغط، لا سيما عند نسب الاستبدال العالية. ومع ذلك، يمكن استخدامه بنجاح في تطبيقات محددة ضمن حدود مدروسة، مما يساهم في تحقيق الأهداف البيئية دون التأثير الكبير على أداء الخرسانة.

1. Introduction

In recent decades, the concrete industry has witnessed significant advancements, among which the development of Self-Compacting Concrete (SCC) stands out as one of the most important innovations. SCC is a modern type of concrete known for its high flowability and ability to consolidate under its own weight without the need for mechanical vibration. It was first developed in Japan in the late 1980s to address quality issues related to improper compaction, particularly in complex structures or those with dense reinforcement

[1]. SCC is characterized by its ability to flow freely and fill formwork while fully encapsulating reinforcement, without segregation or loss of homogeneity. Chemical admixtures (such as superplasticizers) and mineral additives (such as silica fume or fly ash) are often used to achieve the desired properties such as viscosity, flowability, and resistance to segregation [2]. The growing interest in using SCC stems from the significant benefits it offers, including improved concrete quality, reduced labor

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and construction time, minimized noise from vibration equipment, and better working conditions on-site. SCC has also demonstrated excellent structural performance and high durability, making it suitable for complex engineering applications such as bridges, tunnels, and high-rise buildings [3].

Despite its many advantages, designing a proper SCC mix requires precise control to balance flowability with resistance to segregation. Therefore, ongoing research continues to focus on enhancing its mechanical and rheological properties and expanding the use of alternative or recycled materials in its composition.

With the growing focus on environmental sustainability and the circular economy in the construction sector, the use of Recycled Coarse Aggregate (RCA) has emerged as a viable alternative to natural aggregate in concrete production. RCA is obtained from construction and demolition waste, such as crushed concrete debris, and is processed through crushing, separation, and cleaning. This approach aims to reduce the consumption of natural resources, minimize construction waste, and lower the environmental impact of building activities [4].

Construction and Demolition Waste (CDW) derived from deconstructed edifices can be repurposed and utilized as aggregates in the fabrication of new concrete [5]. Typically, CDW undergoes processes of crushing, sieving, and classification into distinct fractions: coarse aggregate, fine aggregate, and powder. Research has demonstrated that recycled concrete aggregate can effectively substitute for natural coarse aggregate in concrete production without considerably compromising the mechanical properties [6, 7]. Although the incorporation of recycled coarse aggregate in concrete applications is on the rise, the application of the fine fraction lags behind [8]. Given that recycled fine aggregate exhibits heightened porosity and water absorption relative to conventional aggregates (such as quartz) [9], this phenomenon results in an escalated requirement for water, consequently diminishing the mechanical and durability characteristics of the mixtures [10, 11]. Additionally, the potential reactivity of recycled concrete powder—attributable to the presence of unreacted cement particles—poses a significant impediment to its utilization as an inert filler material [12].

Although RCA differs from natural aggregate in several physical and mechanical properties—such as higher water absorption, increased porosity, and the presence of adhered mortar on its surface—numerous studies have shown that it can be used in specific proportions without significantly compromising concrete performance, especially in non-structural or low- to medium-strength applications [13].

To ensure the proper performance of concrete containing RCA, mix designs are often adjusted by reducing the water-to-cement ratio, using chemical admixtures, or pre-treating the recycled aggregate. Recent studies have even reported promising results with higher replacement levels (up to 100%) in certain applications, particularly when combined with self-compacting or high-performance concrete [14].

Therefore, incorporating recycled aggregate into concrete production is not only an environmentally responsible choice but also a practical step toward achieving more sustainable infrastructure, provided it is used within well-studied technical limits.

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1.1 Significance of Research

The primary objective of this research is to evaluate the performance of Self-Compacting Concrete (SCC) when Recycled Coarse Aggregate (RCA) is used as a partial or full replacement for natural coarse aggregate. The study focuses on analyzing the fresh and mechanical properties of the resulting concrete, such as workability, segregation resistance, and compressive strength, while also investigating the impact of different replacement ratios on the behavior and durability of SCC.

2. Literature Review

Some studies indicate that the use of RCA in SCC affects workability due to increased surface roughness and water absorption, requiring

the use of larger amounts of plasticizers to achieve the same level of thixotropy [15]. On the other hand, studies have shown that mechanical properties such as compressive strength gradually decrease as the percentage of RCA substitution increases, but partial substitution (up to 30 %) does not significantly affect the performance of concrete [16]. Another study shows that the results of fresh concrete (rheological properties and self-compacting ability) and hardened concrete properties (compressive strength, density, and dynamic modulus of elasticity) show only slight differences at small replacement ratios of 0 %, 10 %, 20 %, 30 %, and 40 % [17]. Other studies addressed the effect of RCA on durability, showing an increase in permeability and shrinkage, but recommended the use of pozzolanic materials such as fly ash and silica foam to improve the overall properties [18].

On the other hand, recent research has indicated that optimization of RCA processing methods, such as pre-washing or removal of suspended mortar, improves the performance of self-compacting concrete containing RCA. Life cycle assessment studies have also shown that the use of RCA contributes to reducing the carbon footprint and environmental emissions associated with conventional concrete production [19].

3. Methodology

3.1 Materials

3.1.1 Cement

Cement is the main component in concrete, because it works as a link between the rest of the concrete components and plays an important role in improving the mechanical and physical properties of concrete, whether it is fresh or solid. In the case of self -blood concrete, the concrete composition requires specific specifications that ensure an easy flow without affecting strength or stability and the self-blood concrete is characterized by its sensitivity to the percentage of water to the cement, as cement is the primary component of this mixture with auxiliary materials. In this study, the regular Portland cement of the first type, which is manufactured locally, was used by the Burj Cement Factory in Zliten in the mixtures and the table (1) is built by the physical and mechanical specifications of cement, which is one of the most common types of construction in Libya, and is characterized by the stability of its characteristics and its suitability for Libyan and international specifications.

Table 1. Physical and Mechanical Specifications of Cement.

Test	result	L.S.S 3 -341 / 1997
Initial Uncertainty Time	80 minutes	>45 minutes
Final Uncertainty Time	15 minutes	<10 hours
Standard Texture %	25.5 %	As per need
Specific Surface Area	3251 g/cm	>2500 g/cm
Compressive Strength of Cement Mortar at 3 Days	25 N/mm ²	>21 N/mm ²
Compressive Strength of Cement Mortar at 7 Days	48 N/mm ²	>39 N/mm ²
Volume Stability	0. 833 mm	<10 mm

3.1.2 Coarse aggregate

Coarse aggregate is an important element in concrete, as it contributes significantly to the composition of the total volume of the mixture and directly affects the mechanical and rheological properties of concrete, especially in the case of self-compacting concrete (SCC), which requires a careful balance between rheology and segregation resistance. The source of natural and recycled coarse aggregate with a maximum nominal size of 10 mm was adopted and selected from the Al-Jafra region and recycled from the remains of crushed concrete cubes at the Department of Civil Engineering, Wadi Al-Shati University. The samples used were subjected to a set of physical, mechanical and chemical tests with the aim of evaluating and comparing their properties, as well as knowing their impact on the performance and effectiveness of self-compacting concrete, and Table (2) shows the results of the physical and mechanical tests of the aggregates and Figure (1) illustrates the gradations of the aggregates used.

Table 2. Physical and Mechanical Tests of Coarse Aggregate used.

Test Type	Recycled Aggregate	Natural Aggregate	Specification Limits
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Specific Gravity	2.14	2.67	2.75-2.5
Undisturbed volumetric weight	1.36	1.39	-
Disturbed volumetric weight	1.49	1.56	1.85-1.5
Absorption %	5.20	1.93	Less than 3%
Silt and clay %	-	1.2	Less than 4%
Brix (LA) %	29.17	21.55	Less than 50%
Crushing Modulus %	22.00	14.52	Less than 45%
Flattening %	-	15	Not more than 25%
Elongation %	-	19.6	Not more than 25%



Fig. 2: Shows of the plasticizer used.

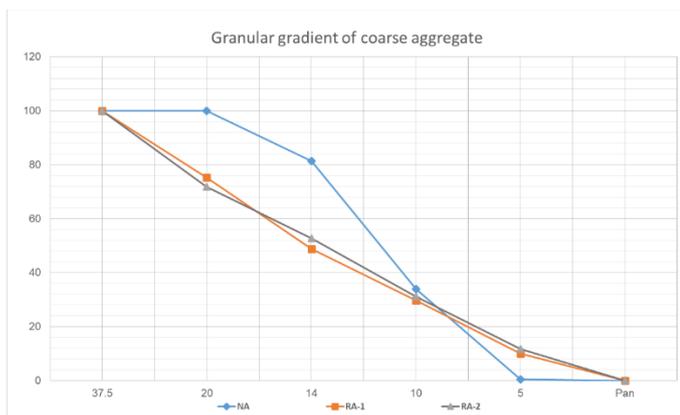


Fig. 1: Illustrates the granular gradients of the coarse aggregate used.

3.1.3 Fine aggregate

In this study, a natural aggregate from the Zalaf region was used, because it is a well-known and locally used source in concrete works in the south of the country, the type and source of fine aggregate was fixed in all concrete mixes used in the study, to ensure that the type of coarse aggregate is the only variable that affects the results.

3.1.4 Mixing water

Drinking water was used in all concrete mixes in this study, to ensure its compliance with technical standards and specifications in the field of concrete, and also because drinking water is considered free of impurities, organic substances or harmful salts, it was chosen as a reliable source to avoid any negative impact on the properties of new or hardened concrete, table (3) shows the chemical analysis of the water used.

Table 3. Chemical analysis of the water used.

Chemical element	Maximum specification limits grams/liter	Ratio grams/liter
TDS	120	2000
CL	23	500
SO4	10.7	1000
bicarbonates & carbonates	22.6	1000
PH	7	8 - 6

3.1.5 Chemical additives (superplasticizer)

In this experiment, a superplasticizer (Lipoment 163), a local product manufactured by the Libya Construction Chemicals Company, was used as a very effective material to significantly reduce the water content, conforming to the American Standard F Type C494 ASTM and British Standard 3 Part 5075 S. B. This plasticizer is characterized by its ability to improve workability without increasing the amount of water in the concrete mix. Therefore, it is ideal for use in self-compacting concrete (SCC) that needs high fluidity and stability at the same time. Lipoment 163 was used at a concentration of 2% by weight of cement, which is recommended by the manufacturer and ranges from 0.6-2.5% The same dosage was maintained in all mixes to determine the effect of aggregate type as the main variable in the study and Figure (2) shows the plasticizer used.

3.2 Self-compacting concrete

Self-compacting concrete (SCC) is a fresh concrete with high fluidity and flow. It can fill forms and pass through dense reinforcement without the need for external mechanical vibration. This is achieved through modifications to the mix, including special additives (such as superplasticizers), increased fineness, and reduced coarse aggregate. This technology saves time and labor, reduces noise, and produces a smoother finished surface. It is ideal for use in densely reinforced elements and in narrow, complex spaces.

3.2.1 Advantages

High flowability: Self-compacting concrete is characterized by its ability to flow and penetrate easily into every void within the formwork.

Better performance in dense reinforcement: It can pass through dense reinforcement easily without nesting or voids.

Time and labor savings: It reduces the need for manual or mechanical compaction using vibrators, saving time and effort.

High finish quality: It results in a smoother, more precise finished concrete surface, reducing voids and waste.

Solution for engineering problems: Ideal for work with complex concrete elements or those difficult to reach with vibrators.

Noise reduction: Reduces noise generated by the use of mechanical vibrators on construction sites.

3.3 Concrete mixes

In this experiment, a practical approach was used to design self-compacting concrete mixes by preparing a set of trial mixes using different proportions of recycled aggregate. The proportions of the components were maintained except for the type of coarse aggregate, which was modified to study its effect on the properties of concrete in its fresh and hardened state. Table (4) shows the components of the self-compacting concrete mix adopted in this study. Tests were conducted on the different mixes in terms of ease of use, such as flowability, fluidity, ability to pass through steel, and resistance to segregation, as shown in Figure (3). The compressive strength was also measured to reach the optimum proportions of components that achieve the required performance.



Fig. 3: Self-compacting plastic concrete tests.

Table 4: Weights of the self-compacting concrete mix materials used.

Mix ingredient	Quantity kg/meter 3	Specification Limits in the EFNARC Guide
cement	500	380 - 600
Coarse aggregate	818	Greater than 50% of the total aggregate volume
fine aggregate	818	750 - 1000
Water	210	150 - 210
superplasticizer	7.5	Depending on the manufacturer from 0.6 - 2.5

3.4 Mixing, pouring and curing concrete

The concrete mixing process was carried out using a 200-liter automatic mixer and the ingredients were mixed under similar conditions and according to systematic steps to ensure the balance of the ingredients and the quality of the resulting mixture. Once the mixing was completed, and to study the rheological properties of the concrete, tests were carried out directly on the fresh concrete to ensure that the results were accurate and not affected by time or initial uncertainty. After completing the fresh concrete tests, the

concrete was poured into cube-shaped steel molds, with dimensions (100X100X100 mm), then left at room temperature in the laboratory for 24 hours without any further transportation or treatment, in order to allow the initial doubt and consolidation of the concrete mixture, and the next day, the molds were carefully removed, and the specimens were transferred to curing tubs, where they were completely immersed in water and the curing process continued until the fracture tests were performed according to the curing ages (3, 7, 21, 60, 28, 60 days).

3.5 Self-compacting concrete tests

3.5.1 Concrete Plasticity Tests

Self-compacting concrete is characterized by its ability to flow and spread inside the molds and fill the voids around the reinforcing steel under the influence of its own weight only, without the need for any type of mechanical compaction, and the fresh properties of this concrete are among the most important criteria that determine the quality of its performance and efficiency in the utilization sites. To ensure the realization of these properties, a set of standard tests were developed for concrete in its fresh state, aiming to evaluate its performance in terms of workability and flowability, resistance to granular separation, the ability to pass between iron bars, and granular stability and Table (5) shows the results of these tests.

Table 5. Test results of concrete mixes in their plasticized state.

Mix	Slump flow (mm) 650-800	T50 (sec) 2-3	J-Ring (mm) 0-10	V-Funnel test (sec) 6-12	L-Box test 0.8-1	Density (kg/m3)
RA0	750	2	9	5.91	0.80	2462
RA20	750	2	6	4.19	0.80	2429
RA40	730	2.1	6	4.19	0.80	2391
RA60	705	2.1	7	3.84	0.82	2350
RA80	700	2.2	8	4.82	0.85	2313
RA100	680	2.7	6	6.92	0.80	2292

3.5.1.1 Slump Flow and T50 testing

In general, most of the mixes recorded rheological values within the limits as in Figure (5), and the THRA0 RA20 mix recorded the highest rheological value (750 mm) with a perfect T50 time (2 s), indicating a medium viscosity and excellent rheology, which is similar to the characteristics of the low replacement ratio, showing excellent gradation, little absorption and medium resistance to fracture. R40 and R60 showed good results (700-730 mm), reflecting sufficient fluidity for practical use, while RA100 recorded only 680 mm, which is close to the minimum specification limit (650 mm), due to the high absorption ratio and high crushing ratio, which increases rolling resistance and leads to slower movement and thus a longer T50 time Figure (4) and (5) shown the results.

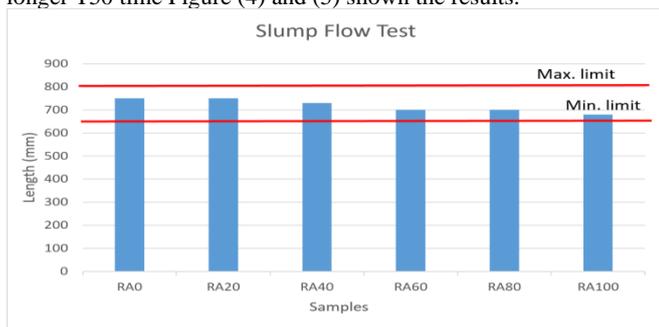


Fig. 4: Slump test results.

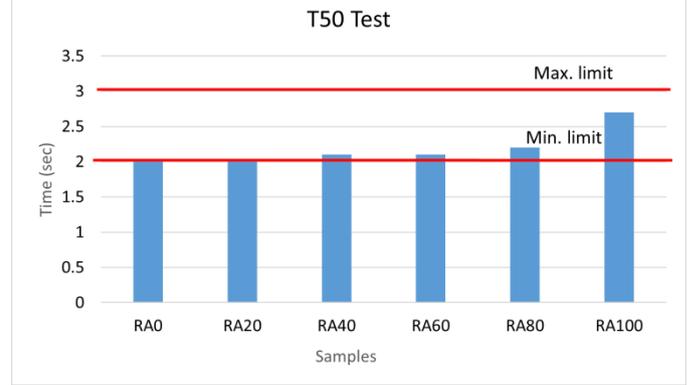


Fig. 5: T50 test results.

3.5.1.2 J-Ring test:

The clear difference between the Slump Flow test and the J-Ring test in the RA100 mixture indicates a good flow with the possibility of losing stability in the presence of dense rebar, and in this case, it is recommended to use a material that minimizes separation. While the RA20 to RA80 mixes showed a slight difference, RA0 showed an acceptable rheology with the ability to flow, indicating a relative balance in its properties despite the limited results in the other tests figure (6) shown J-Ring test results.

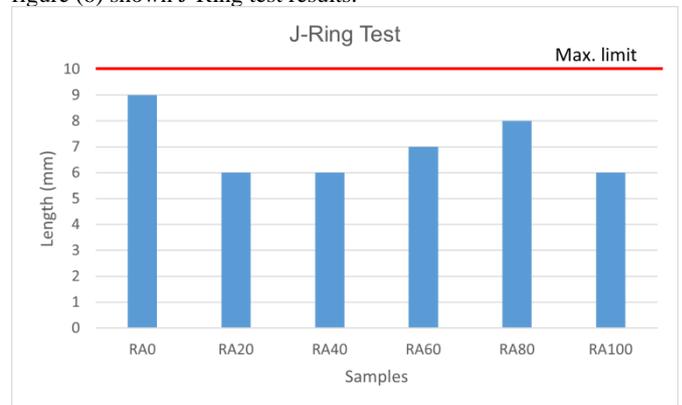


Fig. 6: J-Ring test results.

3.5.1.3 V-Funnel Test:

It was observed that the flow time gradually increases as the replacement ratio of natural aggregates with recycled aggregates increases. Mixtures from RA0 to RA100 were within acceptable limits (6-12 s), indicating good flowability of the concrete. At RA80 the time started to approach the upper limit, while RA100 recorded 11 seconds, indicating a clear decrease in flowability. This is attributed to the surface roughness of the recycled aggregate and its high water absorption, which leads to an increase in the viscosity of the mix. Therefore, the use of recycled aggregates negatively affects their rheological performance.

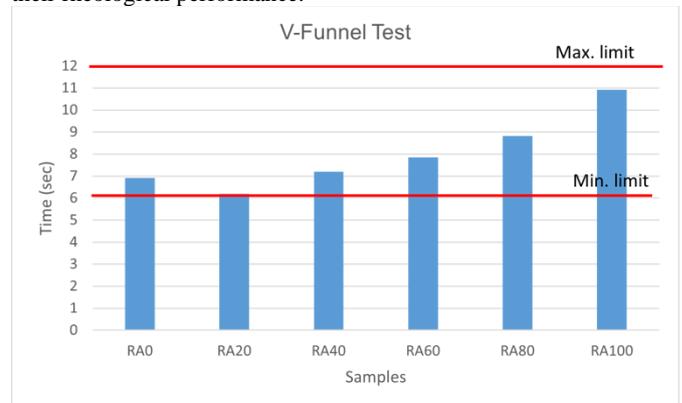


Fig. 7: V-Funnel test results.

3.1.1.1 L-Box Test:

The results showed that all values fell within the acceptable range of 0.80 to 1.00, with RA0 recording the lowest acceptable value and RA40 the highest, indicating that the use of recycled aggregates did not cause a decrease in the ability of concrete to pass through narrow voids, and even improved performance in some mixes. It is noted

that RA100 performed better than RA0, reflecting good cohesion and balanced flow of concrete despite the increased replacement ratio.

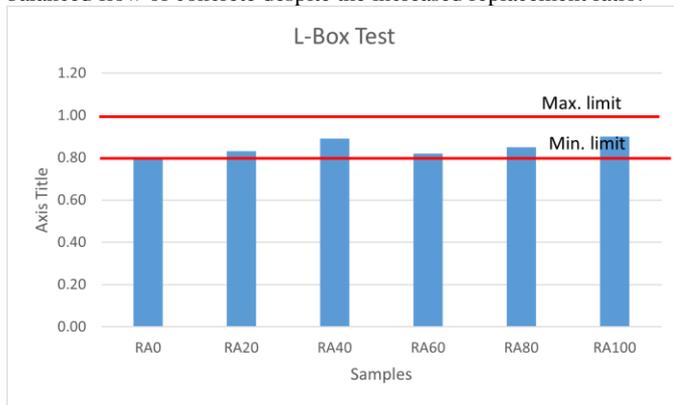


Fig. 8: L-Box test results.

3.1.2 Hardened state tests:

Compressive strength test results for self-compacting concrete using recycled coarse aggregate showed a clear variation according to the replacement ratios. The reference mix RA0 (without recycled aggregate) achieved the highest resistance at all ages, reaching about 57 MPa after 60 days. When 20 % of the natural aggregate was replaced with recycled aggregate (RA20), a slight decrease in resistance was observed, reaching 43 MPa, indicating that this percentage can be used without a significant impact on performance. The RA40 mix recorded a lower resistance of 36 MPa, which is a relatively acceptable performance. In RA60, the resistance started to drop more clearly, reaching 33 MPa on day 60. The RA80 mix showed poor performance in the early days, but then improved significantly, achieving 37 MPa. RA100, in which all the natural aggregate was replaced, recorded the lowest resistance, reaching only 33 MPa. It can be seen that increasing the proportion of recycled aggregates gradually reduces the compressive strength. However, some blends such as RA20 show promising behaviour at longer ripening times. In general, a replacement ratio of 20 % can be considered a good choice to balance mechanical performance and sustainability.

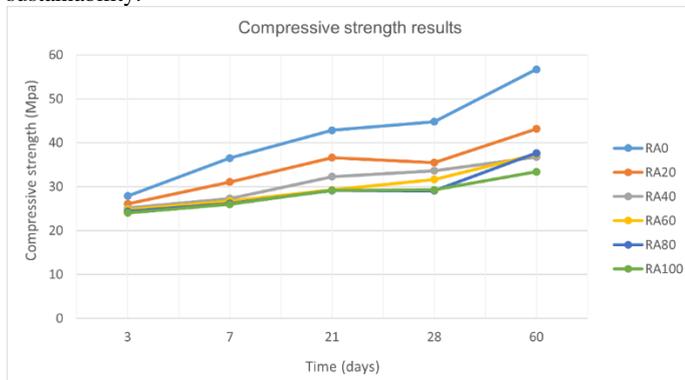


Fig. 9: Compressive strength results.

4. Result and discussions

RA0 (0% recycled aggregate) recorded the highest compressive strength and is the ideal reference mix, while RA20 achieved excellent performance with a slight reduction in strength, making it a suitable and sustainable choice.

The inclusion of recycled aggregates negatively impacts the fresh properties of SCC. Acceptable self-compacting behavior was observed up to RA40, while mixes with higher replacement levels exhibited impaired flow and passing ability, making them unsuitable without further mix design modifications (e.g., increased paste content, use of superplasticizers).

The density of the concrete mixes decreased steadily with increasing RA content. This trend is expected due to the lower specific gravity of recycled aggregates compared to natural aggregates, and the higher porosity of RA. This lower density can lead to lower mechanical performance and durability if not addressed during mix design.

SCC with up to 40% RA can achieve compressive strength values close to conventional concrete, making it a viable sustainable option for structural applications. Beyond that, mechanical performance

deteriorates unless compensated by enhanced mix design or treatment of RA.

A direct correlation has been observed between the physical properties of aggregates (e.g. crushing and absorption) and the final performance of concrete in both fresh and hardened states.

RA Replacement above 60% leads to reduced flowability, increased blocking, lower density, and reduced compressive strength, which may render the mix unsuitable for critical structural use without modification.

Thus, RA40 (40% replacement) appears to be the optimal balance point in this study, offering sustainable material use without compromising the essential qualities of SCC.

5. Conclusions

1. SCC mixes with up to 40% RA satisfied the EFNARC criteria for self-compacting behavior, while higher replacements compromised workability.
2. Concrete density decreased with increasing RA content due to the lower specific gravity and higher porosity of recycled aggregates. This trend affects both fresh and hardened concrete properties.
3. Compressive strength at 2 and 28 days decreased as RA content increased. Mixes with up to 40% RA retained compressive strength values close to the control mix (RA0), while replacements beyond 60% resulted in significant strength loss.
4. Based on a balance of workability, density, and compressive strength, 40% recycled aggregate (RA40) is identified as the optimal replacement level for SCC in this study.
5. The use of recycled aggregates in SCC is a viable sustainable approach for reducing environmental impact and promoting circular construction practices—provided that RA replacement does not exceed 40% without further mix design enhancements.

6. Recommendations

1. Limit recycled aggregate (RA) replacement to a maximum of 40% in self-compacting concrete (SCC) to ensure adequate workability and mechanical performance without significantly compromising quality.
2. Consider pre-saturating or treating RA (e.g., washing, surface coating) to reduce water absorption and improve consistency in fresh properties.
3. Incorporate SCMs such as fly ash, silica fume, or GGBS to offset strength reductions and enhance durability when using higher RA contents.
4. Adjust superplasticizer dosage to improve flow and reduce viscosity, especially in mixes with more than 40% RA content.
5. Conduct durability testing (e.g., chloride penetration, shrinkage, freeze-thaw resistance) for mixes containing RA to assess long-term serviceability in various environmental conditions.
6. Promote the use of recycled aggregates in SCC as part of sustainable construction practices, particularly in regions with limited access to natural aggregates or high construction waste generation.

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