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Research Article

Performance Analysis of Recycled Concrete Aggregates Derived from Construction Waste

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Abstract

This paper highlights the potential advantages of incorporating aggregates derived from construction debris, particularly in the context of Libya, where the use of recycled concrete aggregate (RCA) is not yet widespread. This research aims to integrate recycling into state laws and procedures while demonstrating the practical applications of RCA. Three types of aggregates were examined such as natural aggregate (NA) as the reference, recycled concrete aggregate (RCA) from crushed old concrete blocks, and recycled terrazzo tiles (RTT). The characteristics of these aggregates were determined using various tests, including weight, volumetric, relative density (specific gravity), granular gradation, and Los Angeles abrasion (LA) tests. Results indicated a 15% reduction in specific gravity and a 20% decrease in volumetric weight for RCA compared to NA. The LA test revealed a higher abrasion percentage for the recycled aggregates, consistent with previous studies. To ensure a fair comparison, the same aggregate gradation and component proportions, based on the reference design mix, were used across all three mixes. The compressive strength of concrete made with these different aggregates was assessed through compression tests on cubes measuring 15 x 15 x 15 cm. A total of 12 specimens, with a combined volume of 0.0405 m^3, were cast and cured by submerging them in water at 25°C for 3, 7, 14, and 28 days. The findings showed that the compressive strength of the NA mixture was higher than that of the mixes containing recycled materials. However, the compressive strength of the recycled aggregates is promising, with only a 21% decrease compared to the NA mixture, indicating potential for their use in construction.

Keywords: Natural aggregate, recycled aggregate, physical and mechanical properties, compressive strength.

INTRODUCTION

The use of recycled aggregate has gained significant traction in many developed nations, not only due to its environmental benefits but also its economic advantages. Figure 1 illustrates the percentage of recycled concrete waste in various European countries, demonstrating the widespread adoption of this method. This process involves collecting construction and demolition waste, processing it, and converting it into a reusable material for new or alternative projects. By reducing the overall volume of waste, this practice helps conserve landfill space, which is beneficial for the environment.

Moreover, it contributes to the preservation of natural resources by minimizing the demand for raw materials.

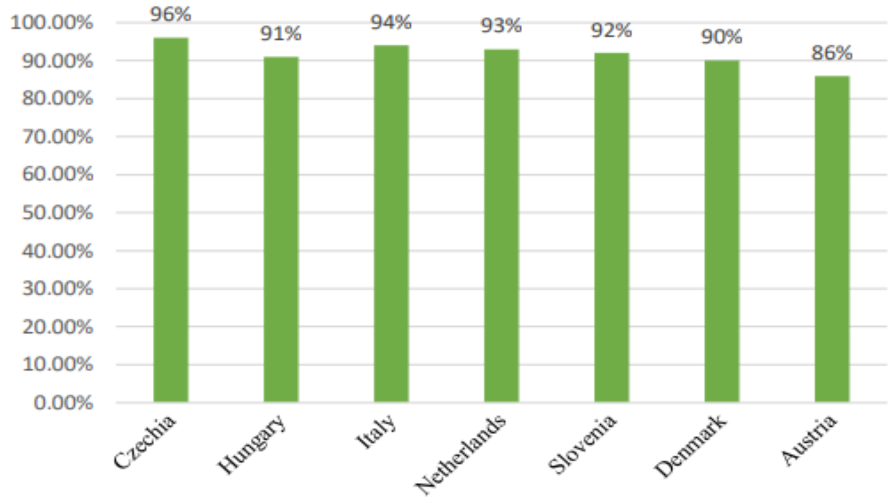


Figure 1. Recycling rate of Construction and Demolition Waste (C&DW) used in different world countries [1].

Recycled Concrete Aggregate (RCA) offers several advantages over Natural Concrete Aggregate (NCA) in terms of unit weight, absorbency, mechanical strength, and chemical durability, as noted by Awoyera et al. (2022) [2]. However, RCA typically requires more water, although improvements in the quality of RCA can reduce this demand. The design of RCA concrete mixes is largely based on the linear relationship between the water requirements of RCA and its mechanical, chemical, and physical properties. The shortage of natural materials, such as coarse and fine aggregates, coupled with the significant amount of waste generated from construction activities, has led to the development of simple-crushed coarse aggregate (SCRCA) and simple-crushed fine aggregate (SCRFA) from building debris. Through particle-shaping processes, SCRCA and SCRFA are converted into particle-shaping fine aggregate (PSRFA) and particle-shaping coarse aggregate (PSRCA), while the recovered powder (RP) is also collected.

Various studies have examined the mechanical properties of concrete made with recycled materials to ensure the performance of products derived from RCA (see Table 1). A comparison of the flexural strength between natural aggregate (NA) and RCA is provided in Table 2, highlighting RCA's potential applications in the construction industry.

In Libya, the accumulation of waste from buildings destroyed by recent wars presents a significant challenge, particularly in cities like Benghazi, Derna, and Sirte, where entire neighbourhoods, such as Al-Sabry, have been severely impacted. The environmental disaster caused by Hurricane Daniel in September 2023 further compounded these issues, causing widespread destruction to infrastructure in the Green Mountain areas and the city of Derna. The scale of damage has made reconstruction a pressing issue, disrupting the environmental and social systems of these cities. Moreover, the demolition and transportation of debris occupy vast areas, distorting the aesthetic appearance of the cities and further harming the ecosystem.

Table 1. The characteristics of RCA and NA's compressive strength in certain reviews.

Ref	Compressive strength RCA	Remarks
[3]	0 to 24% lowers than that of NCA for coarse RCA only. 15-40% lower than that of NCA for coarse and fin RCA.	Concrete using coarse and/or fine recycled concrete aggregate (RCA) can be produced with enough compressive and flexural strength for paving and other applications. In some circumstances, RCA can even replace virgin aggregate in the concrete entirely.
[4]	Increased air content, which is common in concrete mixes containing RCA, can also lead to decreased strength values.	If RCA concrete comes from an old concrete source that was made with a lower water to cement ratio than the new concrete, then RCA concrete may have a compressive strength that is comparable to, or occasionally higher than, NCA concrete.
[5, 6]	A 20–30% decrease in compressive strength with high-performance concrete	Because of the application of RCA
[7, 8]	Insert N.A. into concrete and mortar.	The primary element influencing the aggregate's performance deterioration is the mortar that bonds to the recycled aggregate. The secondary recycled aggregate that is recovered from the recycled concrete can have a mortar adhesion rate that is more than twice as high as the original recycled aggregate.
[9]	Use RCA instead of NCA to concrete a gradient of 7%, 14%, 21%, and 28%.	Recycled concrete's mechanical qualities could still be able to satisfy design specifications.
[10]	Steel fiber-based SFRFA for recycled concrete	A noticeable improvement in performance as compared to concrete made with RFA.

[11]	RCA replaces NA with a loss in compressive strength. The porosity of the concrete as a whole rises when RCA replaces NA. However, adding silica fume (SF)—either 5 or 10%—reduces mechanical strength by an additional ~11%. This indicates that the performance drop related to SF is only around 4% when the influence of RC is removed.	In general, for reference mixes, mechanical performance rises with concrete age (hydration process) and falls with increasing coarse RCA content. The failure at the ITZ and fracture propagation through the cement paste itself appears to be the causes of the larger strength drop in non-structural concrete.

Table 1. The characteristics of RCA and NA's flexural strength in certain reviews

Ref	Flexural strength RCA	Remarks
[12]	Flexural strength differences between RCA and NCA concrete typically range from 0 to 10%.	Compared with NCA concrete, the flexural strength of RCA concrete was shown to be greater after three days; however, it fell after 28 days. At a later age, the NCA concrete exceeded the RCA concrete in terms of flexural strength, having gradually increased in strength.
[13, 14]	There was no apparent adverse effect of RCA on the flexural strength of the concrete. However, RCA concrete with sufficient flexural strength may be made for a variety of uses, occasionally even completely replacing NCA.	It indicates that the interfacial connection is more effective along the specimen length. As a result, there is less flexure (bending) constraint, counteracting the negative impact of the RCA's weakness on the modulus of rupture (flexural strength) of the concrete. Consequently, it was discovered that the flexural strengths of concretes with and without RCA were equal.

Several researchers and scientific organizations have studied the potential for reusing construction and demolition debris. While recycling remains relatively new in Libya, both local and international experiences have demonstrated the viability of reusing such materials. This research aims to highlight the environmental, economic, and technological benefits of recycling building and demolition waste. Additionally, the study seeks to integrate recycling protocols within the legal and institutional frameworks of the Libyan state.

This research explores the potential for recycling construction waste and reusing it as new building materials, contributing to a healthy environment and aligning with sustainability principles. This research work investigates the use of recycled concrete aggregate (RCA) derived from crushed old concrete cubes and recycled terrazzo tile aggregate (RTT) as alternatives to natural coarse aggregate (NA) in concrete production. It also compares the performance of mixtures containing RCA with those made exclusively with natural aggregate. The results of the mechanical and physical tests will help to determine the feasibility and wider adoption of RCA in meeting industry requirements. Additionally, the study examines how the mechanical and physical properties of the recycled materials correlate with compression test parameters to assess their suitability for use in construction.

MATERIALS AND METHODS

Materials

The concrete debris was crushed into grades that matched the grades of natural aggregate used in the reference mix; the following three categories will be applied to the samples:

- Natural aggregate Natural aggregate (NA)
- Repurposed Concrete Aggregate, (RCA)
- Recycled Terrazzo Tile fragments, (RTT)

Mechanical Crushing Recycling Technology

No treatment recycling technology has been used due to the below three important levels:

- The first level: It is a mobile crushing station (Crusher) as shown in Figure 2, and it is equipped with some regular sieves. It is a suitable method for use in developing countries due to its low cost.
- The second level: includes the same mechanisms used in the first level with the addition of mechanisms for separating metals and a classification system for aggregates. This technology is fixed or mobile and has a higher production capacity than the first.
- The third level: the same technologies used in the second level with the addition of a mechanism for removing large pieces of wood, plastic, nylon, etc. This technology is used in medium and large capacity recycling stations as shown in Figure 2.

(a)

(b)

Figure 2. (a) On-site mobile crusher model, (b) fixed crusher for trash sorting equipped with separators.

The crushed concrete or terrazzo is sorted, and then either manually or mechanically sieved. Before the necessary amounts for testing are extracted from each size, each size is categorized in a separate container and gathered. The tests for specific weight, volumetric weight, absorption ratio, impact and wear resistance (Los Angeles test), and granular gradation shall be conducted independently on each sample belonging to the three preceding groups. The most intriguing aspects of the content seem to be the mechanical and physical characteristics of RCA, which were examined through testing and quality assessment. These characteristics allow us to compare the results of the NA and RCA mixes as well. RCA is required for their usage in the building of RCA mixes, in comparison to NA mixed, which enables us to assess the performance of the concrete. The results of the testing may cause RCA to be widely used to satisfy requirements.

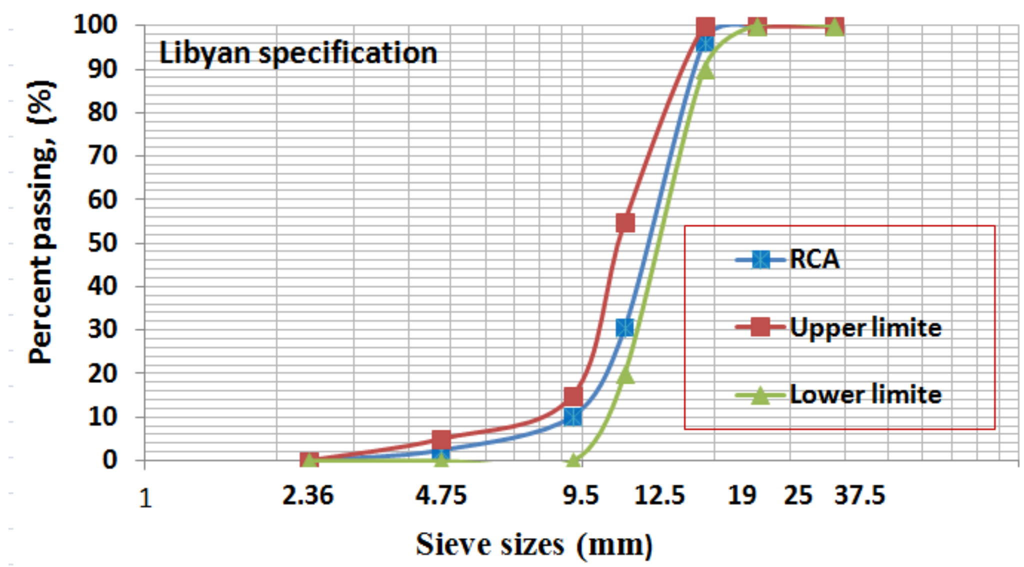
Additionally, the mechanical and physical properties of the research were linked to the compression test's characteristics. The same proportions of water and cement were used in each mixed, in addition to fine aggregate (sand) with a predetermined a specific gravity weight and absorption coefficient. The same granular gradation will be used in all three categories, and three concrete mixes will be created from them and assessed similarly. Test twelve cubes of concrete for each kind of aggregate used throughout the period of four periods (3, 7, 14, and 28 days) after pouring. Three cubes are examined each time, and the average results are determined.

Physical and Mechanical Properties of Aggregates

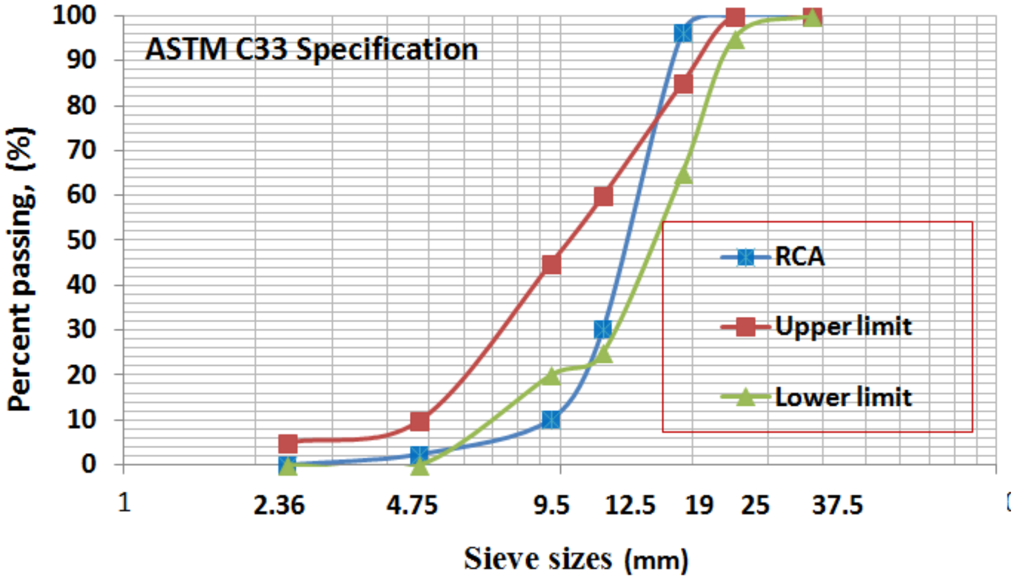
Three different aggregate mixes were utilized in the project: the reference mix, the second mix, and the third mix contained natural aggregate (NA), crushed concrete aggregate (RCA), and crushed terrazzo tile aggregate (RTT).

Sieve Analysis

Particle size distribution in an aggregate sample is ascertained by means of this test. Aggregate suitability for usage in concrete and other uses in construction should be considered, this test helps to ensure that it satisfies standard criteria. According to Libyan specification, this test was conducted. And we have compared the results with American specification standard type ASTM C136/C136M-19 [15], Granulates are obviously in the limit zone; with fineness modulus of 3.61, see Figure 3.



(a)



(b)

Figure 3. Gradation of coarse aggregate by sieve analysis. (a) Libyan specification standard, (B) ASTM C33 specification standard

Figure 4 illustrates how Libyan sand differs from that of other nations in some ways (Generally, Eastern Libyan sand is quite fine.), making it appear to deviate greatly from ASTM specifications (ASTM C136/C136M-19) [15], having a fineness modulus (FM) ranging from 2.3 to 3.1, compared to 2.12 for our sand, as shown in Figure 4.

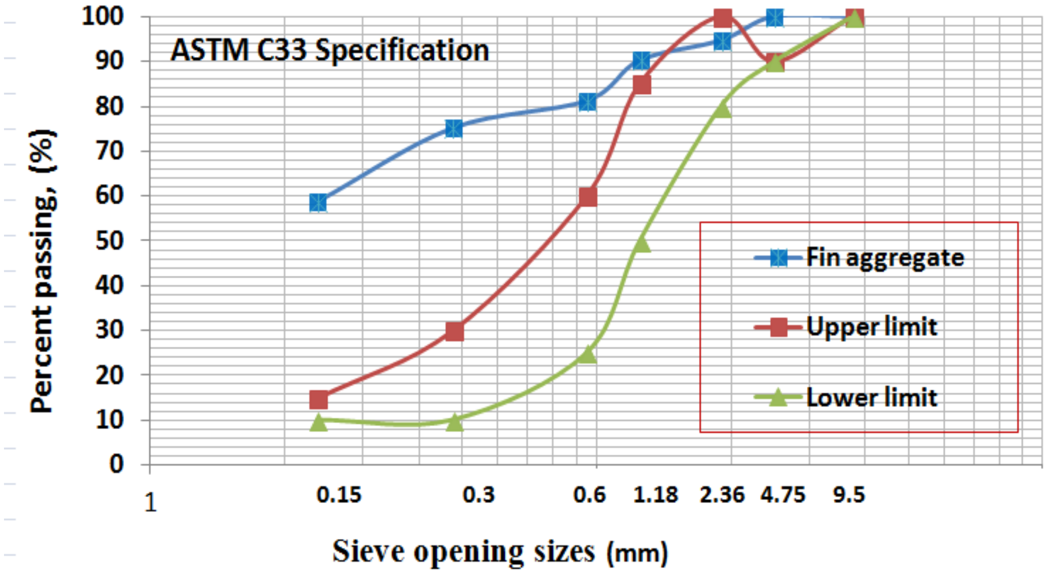


Figure 4. Gradation of fin aggregate by sieve analysis.

All utilized aggregates' physical characteristics are listed in Table 3. According to ASTM C29/C29M [18], as seen in Figure 5, the estimated bulk density of aggregate is 1200–1750 kg/m3, and RCA is derived from this standard. The specific weight of recycled aggregate reached (2.21) in concrete waste aggregate, (RCA) and (2.25) in terrazzo waste aggregate, (RTT), as indicated in Table 3, demonstrating that its physical properties are clearly different from those of natural aggregate. Additionally, it can be observed that the specific and volumetric weights of recycled aggregate are lower than those of natural aggregate. while the specific weight of natural aggregate NA was (2.61). Furthermore, the water absorption rates of recycled aggregate from an old concrete cubic (RCA) and recycled terrazzo tiles (RTT) were 6.80% and 6.06%, respectively, greater than the 1.03% rate for natural aggregate (NA). The reason for the increase is the imperfectly removed cement mortar around the aggregate and the cracks it caused over the previous structure's lifetime. This indicates the large number of gaps in the recycled aggregate and the roughness of its surface as a result of the adhesion of mortar and impurities to it.

Table 3. Characteristics of the fin and coarse aggregates in the mixed concrete.

Testing	NA	RCA	RTT	Sand	Standards
Bulk specific gravity (SSD)	2.61	2.21	2.25	2.68	[16] [17]
Coefficient of absorption (%)	1.03	6.80	6.06	0.4	[17]
Bulk density (kg/m^3)	1525.7	1174.6	1200	1600	[18]
Los Anglese abrasion (%)	17	37.46	36.81	-	[19]

The Los Angeles test (LA) gave an abrasion value of 17% for natural aggregate, but 37.36% for recycled aggregate (such as concrete cube crushing aggregate) and 36.81% for terrazzo crushing aggregate in the case of natural aggregate. This indicates that the Los Angeles test had a significant impact on the abrasion value. Its density is lower, its absorption is higher, and its wear loss is greater than that of natural aggregate because of the recycled aggregate's lack of homogeneity and cohesiveness in its structure and the presence of old cement mortar, which was obtained by crushing old concrete and terrazzo tiles and remained attached to its surface. These results are reliable with many previous studies, as they came in proportions similar to the results we obtained. Note: Fine aggregate (less than 4.75 mm) resulting from crushing concrete waste and terrazzo tiles was excluded as an alternative to natural sand due to its very high absorption and the abundance of impurities and dust in it, which may affect the validity of the concrete mixture results.

Figure 5. Determine specific gravity for coarse and fin aggregate.

Mixed Design

Cement type CEM II-4-1 A-L 42.5 N for heavy concrete construction, conforming to Libyan Light (LSS NO: 340/2009) and conforming to European Standard (EN 197-1-2000) has been used. Specific surface of particles by Blain is 3300±100, specific gravity 3.15, initial setting time at 60 min. chemical composition as indicated by Libyan Cement Company (LCC) shows in Table 4.

Table 4. Chemical composition of cement as given by LCC.

Chemical Composition	Amount
C3S (%)	60 ± 2
C3A (%)	7.5 ± 1
Sulphate content SO3%	Max 3.5
Magnesium oxide content MgO%	Max 5
Chloride content Cl%	Max 0.1

A mix with W/C = 0.5 has been affected in laboratory, as shown in Table 5; 12 specimens Cube's volume (15 by 15 by 15 cm) (see Figures 7 and 8). Concrete has a total cubic volume of 0.0405 m^3. The reference mixture was designed to produce a compressive strength of up to 35 MPa, Specimens at 25°C were cured by submerging under water, whereas curing at 28 days. The British specification BS 8500 was used for the production of concrete mixes.

Figure 6. Add the ingredients to the prepared concrete mixture.

In order to compare the outcomes with the reference mixture, this mixture will be ad ministered in the identical amounts and proportions to the two samples of terrazzo tile br eakage RTA and old concrete cube RCA.

Table 5. Mixture proportions of concrete (kg/m³).

Cement	water	sand	NA	Entrained Air	Total
354.1	177	712.25	1007	0	2250.4

Figure 7. Moulding of specimens**.**

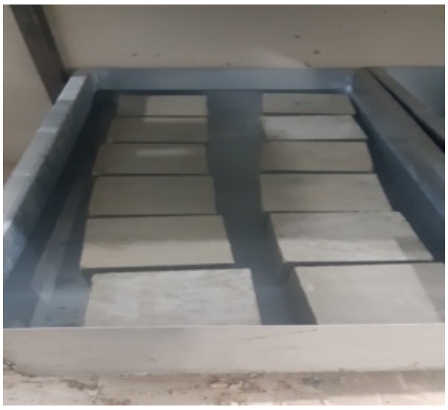


Figure 8. Curing of specimens in the water.

The slump for the test cone was estimated for each of the three mixes after they were directly mixed, and the findings were as indicated in Figure 9. It is evident from the test findings that the two combinations using recycled aggregate had fewer slumps, as shown in Table 6. This can be attributed to both its rapid absorption rate and the mortar's high porosity adherence to its surface. Moreover, the mixture could contain small particles with a high surface area to volume ratio, which raises the mixture's effective water consumption and lowers its operational effectiveness. Compared with specification, [20] it seems that RCA, RTT aggregate type's slump values have produced mixtures with a medium workability. The NA aggregate's slump values exceeded 100 mm, allowing for the production of high workability concrete that satisfies this criterion (100-175).mm.

Figure 9. Slump test measured.

Table 6. The workability of concrete mixtures is determined by the concrete slump test.

Mix Type	NA	RCA	RTT	Specification requirements
Slump (mm)	115	65	75	[20]

EXPERIMENTAL RESULTS

According to ASTM C109 [21], compressive strength of mixed concrete has determinate. Figure 10 shows compression test setup. We note from the charts that the compressive strength results of the three samples are close in the first seven days with a slight advantage for the standard mix sample NA, and the differences begin to widen after two weeks until the compressive strength of the samples using recycled aggregate (RTT) and (RCA) reaches approximately 25% less than the compressive strength of the standard mix (NA) at the end of the fourth week.

Figure 10. Configuration of a compressive strength test.

The compressive strength of the cubes of the mixture prepared from recycled aggregate from concrete waste (RCA) reached values of 15.72, 23.42, 28.43 and 31.73 MPa during the periods of 3, 7, 14 and 28 days respectively (see Table 7), which gives an indication of the quality of the concrete and the possibility of using it in construction works that do not require high compressive strength provided that the mixture is adjusted and the concrete waste is sorted from impurities. Equation (1) was used to determine the compressive strength of samples in MPa, where F_{max} is the maximum load applied in cross-sectional area A, and average compressive strength ($\sigma_{avr.}$) of the concrete cube at age 3, 7, 14 and 28 days in MPa is given in equation (2) as follows [22]:

$$\sigma_c = \frac{F_{max}}{A} \quad (1)$$

$$\sigma_{avr.} = \frac{\sum \sigma_c}{N} \quad (2)$$

These results' of standard deviation (STVD) provides a variety of N number of measurement as shown in equation (3):

$$\sigma = \sqrt{\frac{1}{N}} \left(\sum_{i=1}^{N} x_i^2 - N\overline{x}^2\right. \quad (3)$$

Table 7. Compressive strength of concrete mix values at different ages.

Type of mix	NA			RCA			RTT		
Age (days)	σ_c (MPa)	Aver.	STVD	σ_c (MPa)	Aver.	STVD	σ_c (MPa)	Aver.	STVD
3	16.73 18.12 17.12	17.32	0.7	15.1 16.1 15.95	15.1	0.54	13.75 14.40 12.82	13.66	1.61
7	24.15 23.21 26.9	24.74	1.9	22.64 24.01 23.6	23.42	0.71	20.63 22.3 22.9	21.93	1.16
14	32.57 31.68 33.92	32.72	1.1	27.24 29.64 28.41	28.43	4.6	25.34 25.09 25.61	25.35	0.26
28	38.39 36.99 38.87	38.08	1.0	30.62 31.23 33.34	31.73	1.0	30.29 29.41 30.49	30.06	0.57

The cubes of the mixture made from the remaining fragments of broken terrazzo tiles (RTT) had compressive strengths that were nearly identical to those of the cubes of the mixture made from recycled aggregate from concrete waste (RCA), with average values of 13.66, 21.93, 25.35, and 30.06 MPa at age 3, 7, 14, and 28 days, respectively, as is indicated in the Figure 11.

Based on these findings, we may conclude that recycled aggregate can be used with ease in concrete projects that don't require a high compressive strength, including casting floors, sidewalks, and roads—all of which are among the engineering projects that utilize the most material. Previous findings, however, indicated that the RCA source and quantity had a major influence on the laboratory performance of RCA combinations, with NA outperforming RTT because RCA-prepared concrete mixtures had a greater optimum cement-binder quantity than RTT-prepared mixes. The variations were more noticeable after two weeks, and at the end of the fourth week, the compressive strengths of the samples constructed with recycled aggregates RCA and RTT were about 14% and 22% lower, respectively, than those of the standard mix NA. Furthermore, compared to old concrete, the recycled aggregates designed from terrazzo had a porosity that was significantly larger than that of natural aggregates (NA). This implies that there were a lot of voids in the recycled aggregates.

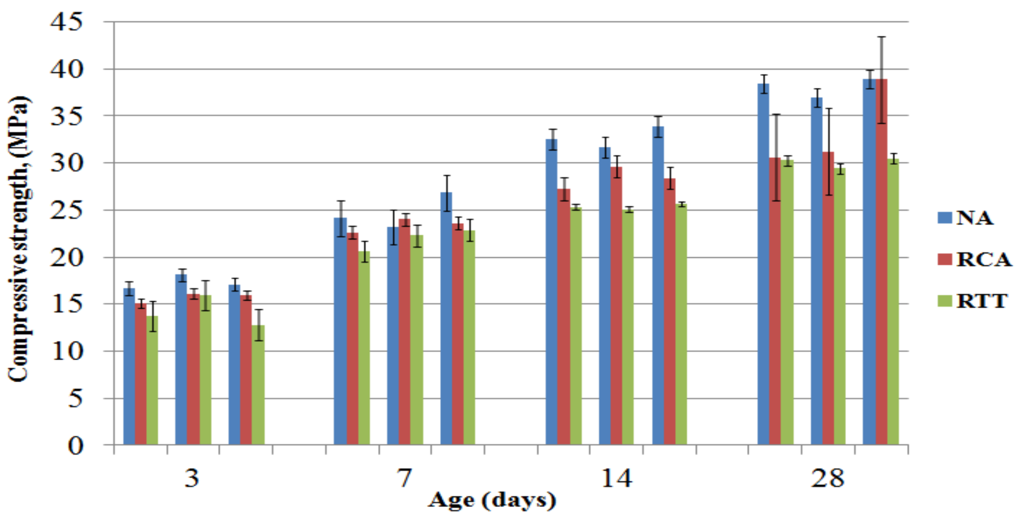


Figure 11. Compressive strength for cubes 150 x 150 x 150 (N/mm^2) at 3, 7, 14 days and 28 days for concrete mix NA, RCA, RTT.

SUMMARY AND DISSCUSION

The results show that replacing natural coarse aggregate (NCA) with recycled concrete aggregate (RCA) may successfully handle the issue while maintaining the environment. Furthermore, the social and economic problems caused by concrete waste may be addressed by employing RCA (particularly in Libya, where old structures in various towns should be rebuilt since 1950). The potential distinctions in the mechanical behavior of concrete under compression stress between natural coarse aggregate (NCA) and recycled coarse aggregate (RCA). The results of this study show that as sorting, recycling, and quality control techniques have advanced, recycled aggregate's qualities have significantly improved. To find out how the aggregate responds to them and study the results, this field needs to continue expanding, adjust the water or mixing ratios, or add additional premium additives. Recycled coarse aggregate (RCA) can be utilized to build concrete buildings, depending on the source and quality of the aggregate. Another way to safeguard the environment in green buildings is to use recycled concrete construction aggregate as coarse aggregate for concrete. As shown in Figure 11, the strength at 28 days, as a comparative results.

Figure 12 illustrates the highest difference in compressive strength (Δσc) between the NA concrete mix and the RCA and RTT concrete mix at 7 and 28 days. Nevertheless, at 28 days, NA's Δσc varies from RCA's by around 6 MPa. Figure 13 demonstrates that concrete mixes containing RTT and NA aggregates can provide results comparable to this at the same age.

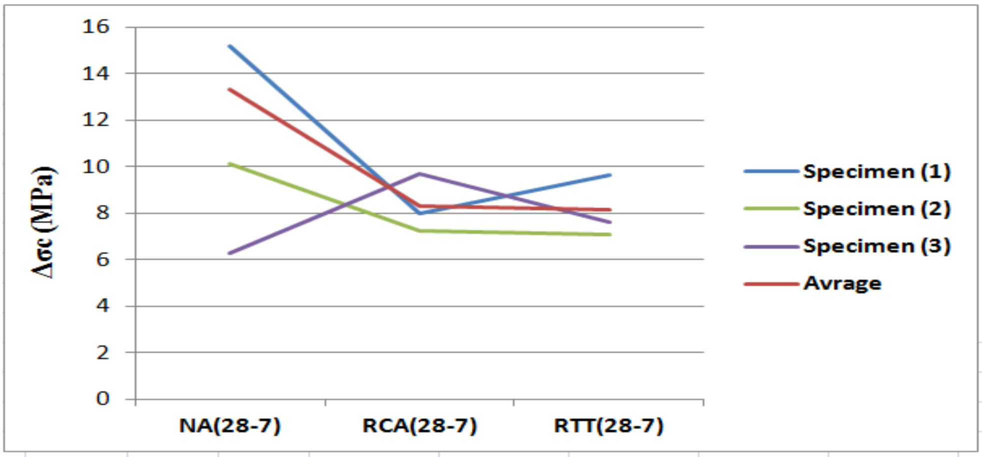


Figure 12. Compressive strengths results for concrete samples: NA, RCA, and RTT at 7 and 28 days.

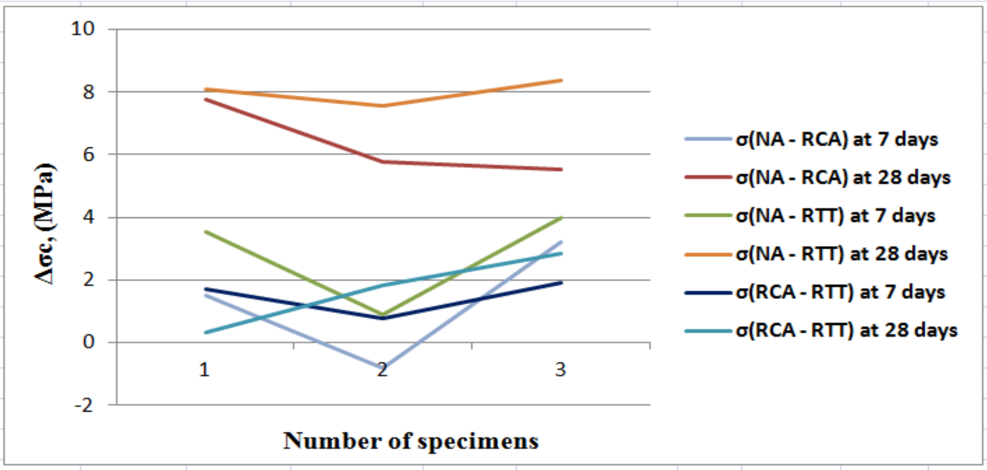


Figure 13. Compressive strengths results for concrete mix at 7 and 28 days for: (NA-RCA); (NA-RTT); and (RCA, RTT).

SUMMARY AND CONCLUSION

This research aims to enhance awareness of the environmental and economic value of recycling, particularly among professionals in construction and demolition organizations in Libya. It also demonstrates how building waste can be effectively recycled or reused to benefit society. Integrating recycling concepts into technical and engineering education is critical for equipping future architects and engineers with the knowledge necessary for sustainable practices. A key finding of this research work is the importance of performance monitoring to ensure the wider acceptance of recycled concrete aggregates (RCA). Long-term research is essential to measure material performance under various conditions, supporting broader industry adoption. The economic advantages of reusing and processing demolition waste are evident, as these activities often incur lower costs than extracting and transporting new materials. Furthermore, recycling also helps preserve natural resources, such as gravel and sand, by reducing demand for raw aggregates.

The results of this study, in line with previous research, confirm that recycling demolition waste is a viable and effective approach for reducing pollution caused by landfill waste. Specifically, the physical and mechanical properties of RCA-mixed concrete, compared to natural aggregate (NA)-mixed concrete, suggest its suitability for broader applications. Recycled aggregate concrete is appropriate for non-structural uses, such as road construction and block manufacturing. Moreover, when combined with specific chemicals or in the right proportions with natural aggregates, RCA can be employed in structural applications as well. The results showed that the compressive strength of the NA mixture was higher than that of the mixes containing recycled materials. The compressive strength of the recycled aggregates shows promise, exhibiting only a 21% reduction compared to the natural aggregate mixture, which indicates their potential for use in construction. Additionally, this research supports the growing recognition of recycled concrete as a sustainable, cost-effective, and environmentally friendly option in modern construction practices.

CONFLICT OF INTERESTS

The authors would like to confirm that there is no conflict of interests associated with this publication and there is no financial fund for this work that can affect the research outcomes.

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