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RESEARCH

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# Studying the usability of recycled aggregate to produce new concrete

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## Abstract

One of the most significant environmental issues worldwide is garbage, particularly waste from construction materials, which is generated in substantial numbers. However, in the building industry, the significant extraction of natural resources such as cement, natural sand, and natural gravel poses a critical environmental challenge, depleting these resources at an alarming rate. There are some solutions that developed countries are resorting to, namely the division of construction waste into groups, where it is reused under the name of recycling construction waste to produce new, environmentally friendly building materials. The aim of this research includes a laboratory process study as it includes the use of the following ratios: 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%, under the process of replacing coarse plain aggregates including coarse recycled aggregates and studying the most important mechanical properties of concrete. This research was carried out using fresh concrete properties such as workability tests and hardened concrete properties such as compressive strength, splitting, and flexural tensile strength examined at the durations of 7, 14, and 28 days. The research includes the investigation of the three main properties of concrete. After conducting the tests, the results have shown that the main property of recycled concrete is lower strength than that of conventional concrete, but it can be said that it is within the limits that can be used for construction. The results also showed that compared to normal aggregates, development in the recycled aggregate percentage rates reduces the operational workability of concrete. The research proved that the maximum decrease in compressive, flexural, and tensile strength, density and the slump were 19.4, 18.3, 19.6, 19.5, and 25.0% respectively compared to the control concrete samples.

**Keywords:** Compressive strength, Flexural strength, Tensile strength, Natural aggregate, Concrete, Recycled material, Waste materials

## Introduction

As time has progressed, the production, methods, and processes for manufacturing concrete have developed considerably. The most important construction material used in the realization of many large projects is concrete, as it is considered one of the most important materials that is most readily available and easy to work with. With the evolution of production and execution methods, the types of concrete have also changed in terms of ingredients, production methods, and additives, depending on the concrete used for the work, as concrete varies for different areas of construction [1–3]. Conservation of the environment and natural resources is found to be one of the most important features of any country's development and is considered the main pillar of construction projects, but some problems arise because of industrial and technological development. There is a method that is currently being followed internationally, which is the recycling of waste, especially construction waste, as it is considered a fundamental plan to reduce construction waste [4–6]. The most important environmental problems arising from the development of construction around the world are the demolition or reconstruction of old buildings, which generates large amounts of construction waste in order to build or develop buildings and create or modernize them [7–9]. A significant and distinctive step is the recycling of construction waste and its use in the construction of modern buildings. The disposal of construction waste involves the accumulation of rubble in the vicinity of buildings, where it causes numerous environmental problems and accumulates in large quantities that are difficult to remove afterward. In addition, the natural depletion of construction resources subsequently leads to an imbalance of environmental resources [10, 11]. Numerous studies and research have been carried out, albeit with different waste materials, and all of them emphasized the possibility of using construction waste with new concrete for buildings. Utilizing recycled aggregates in construction results in substantial energy, financial, and natural resource savings. Utilizing recovered aggregates directly reduces the environmental impact of waste resources. By using recycled aggregates in the manufacturing of concrete and continuously monitoring the process, we can ensure exceptional performance. The quality of the recycled aggregate is vital in determining the strength of the mixture. This feature is determined by many elements, including the age of the original concrete, the recycling technology used, the grade of crushed concrete utilized for the recycled aggregate, and the meticulous consideration of all aspects in formulating and preparing the concrete mixture for this particular composition [12–14].

So far, among the technologies developed for the recycling of concrete waste, the use of a crushing machine to reduce the waste into particles of recycled aggregates is currently widely used to produce recycled aggregates. In addition, despite the various ecological and economic benefits of using recycled aggregates, their use in the manufacture of structural concrete remains very restricted. The issue might perhaps be attributed to the substandard characteristics of recycled aggregates. Prior research has shown that recycled aggregates had certain unfavorable characteristics, such as inadequate grading, increased water absorption, porous structures, and reduced density caused by the leftover concrete adhering to their exterior surface. Furthermore, research has shown that the quality of recycled aggregate concrete (RAC) is contingent upon the characteristics of the original concrete, including its strength, water absorption, form, and size. The water absorption of recycled aggregate is directly correlated with the strength of the original concrete it originates from. Consequently, when the original concrete becomes stronger, the recycled aggregate's water absorption likewise increases. In contrast, the water absorption of recycled aggregate diminishes as the aggregate's maximum size grows. Nevertheless, Gómez-Soberón J [15] conducted research to experimentally examine the mechanical properties of concrete produced with different amounts of recycled aggregate as replacements. The research test findings revealed variations in the properties of the new concrete compared to conventional concrete. The study focused on the key features of recycled concrete, specifically examining the effects of the curing period (ranging from 7 to 90 days) and the replacement of natural aggregates. According to another study by Kou and Poon [16] investigated the durability of recycled concrete aggregate and approach it to original concrete, where old concrete was used as aggregate instead of natural aggregate. The increase in the use of old concrete can be developed but with the incorporation of new materials like fly ash at rates of 25–35%, which are the main conclusions of this study. The results of the research showed some differences in the characteristics of the new concrete associated with normal concrete, as the research studies the most important characteristics of concrete for recycled concrete with works curing duration of 7–90 days, as natural aggregates were replaced. According to Kumar R [17] achieved that there are many materials that can be used, such as bricks, recycled aggregates, sawdust, rice husk ash, and other materials as they are the main component of this research, but they were used as an alternative to cement and aggregates. The ratio of 70–80% is the result obtained from the research for compressive strength compared to concrete without waste. Soroushian P [18] concluded that there are materials that can be used as they cause many changes in concrete, especially with cement, as they increase the strength of the bond between cement and recycled aggregates such as glass waste materials, which were used in this research as a partial substitute for cement. Seo T and Lee M [19] presented that one of the features observed in this research is the increased dry shrinkage rate of recycled concrete. Where the research examined the main characteristics in addition to drying shrinkage of concrete. Zhang H and Zhao Y [20] illustrated that the research includes the use of (0, 50, and 100%) as alternative proportions for aggregates with three groups of recycled concrete. Hamad, B. S., and Dawi, A. [21] reported that in the high-performance concrete mix, the researchers utilized the crushed tested cylinders with crushed natural lime-stone as recycled aggregates with partial or full substitution for natural aggregate to study the fresh and hardened mechanical properties. Moreover, Afizah Ayob et al. [22] presented that by using 20%, 50%, and 100% of RCA the researcher examined the effect of recycled concrete aggregates on concrete durability and engineering behavior. Bheel N et al. concluded that under different examination times of 7–56 days for curing, the mechanical characteristics of the concrete were examined under the influence of the process of replacing the cement with the waste cement concrete. Waseem S and Singh B [23] presented that the research concluded that it is possible to use recycled concrete with ratios (0, 50, 100%) in the concrete's resistance to shear, as it proved to be very effective in resisting shear forces using push-off samples. Velay-Lizancos M [24] presented that the effectiveness of employing recycled concrete in manufacturing of self-compacted concrete with replacement ratios (0, 20, 35, 50%) and replacing both coarse and fine aggregates and studying the main characteristics of concrete. Chaitradip S et al. [25] the results of this study demonstrated that the age and grade of the concrete that was demolished to produce the recycled aggregate both affect the strength of concrete by using a variety of methods to investigate the characteristics of both natural and recycled aggregate in concrete. Dhiyaa M et al. [26] experimental research has been done by using silica fume additive to determine how employing recycled aggregate affects the compressive strength of concrete. Liu B et al. [27] studied the bond through steel-reinforced and recycled aggregate concrete in terms of computer programs (ABAQUS) with finite element models. Ben Nakhi, A., and Alhumoud, J. M. [28] studied two aggregate particle sizes with different percentages of recycled aggregate (0–100%, with increments of 10%) in the chloride diffusion of saturated concrete. Wang Q et al. [29] reported that one of the characteristics of the concrete that was investigated in this examination is autogenous shrinkage, as the results proved that it is possible to reduce shrinkage by using recycled aggregates, as the researchers studied many ratios of aggregate with different ratios of (w/c). Sadowska B. and Małgorzata G.'s [30] study demonstrates that substituting recycled aggregate for conventional aggregate in high-performance concrete results in a loss of concrete strength, modulus of elasticity, and tensile resistance. Salgado F. and Silva F. [31] in this one, three types of recycled aggregate were used: construction aggregate, concrete aggregate, aggregate, and a mixture of the two types. The research showed that concrete consisting of a mixture of two types shows mechanical, physical, and geometric properties and a decrease in the modulus of elasticity and compressive strength similar to recycled aggregate. CH Karthik and A Nagaraju [32] with adopting a fly ash and alccofine, this paper's primary goal is to determine the strength characteristics of recycled aggregates' in order to utilize them as a sort of substitute for natural aggregates. Madhu, K. A., et al. [33] with three cycles of demolition waste aggregate and 25%, 50%, 100% percentages as coarse aggregate and to achieve long sustainability, the research concentrated on the use of concrete demolition waste. Joseph, H. S., et al. [34] at substitution percentages of 0, 30, 60, and 100%, examined the microstructural and the hardening properties behavior of using combined coarse recycled aggregate in comparison for natural aggregate.

All previous research that was adopted in this research confirms that using previously prepared concrete as coarse aggregate instead of the regular coarse aggregate reduces the characteristic of concrete despite the difference in the materials used in the concrete mix and the additives that may be added to the mix, as well as the difference in tests and the difference in results that occurred. Researchers have approved them, but they all confirm the decrease in the mechanical properties of new concrete, which contains previously prepared coarse aggregate. However, most researchers have confirmed that new concrete can perform compared to regular concrete and give acceptable results, in order to reduce harmful substances in the environment and also to constrain the exhaustion of natural resources. The aim of this research includes studying the effect of using construction waste as coarse aggregate with various replacement ratios (0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) instead of natural aggregate to find the three most important characteristics of concrete with curing age, and experimental test, which is considered a comprehensive study of all previous research. An experimental study was conducted to ascertain the characteristics of newly mixed and solidified concretes made from natural aggregates and recycled coarse aggregates. The workability and bulk density of the fresh concrete samples were assessed, while the compressive strength, flexural strength, and splitting tensile strength tests were performed on the cured concrete samples.

## Experimental program

### Materials

The cement of conventional class was employed, and its features (chemical and physical) are adapted to designations as reported by. As a fine aggregate, common sand was managed completely in the preliminary task, and its features were agreeable with the destination of Iraqi specification. Ten millimeters of coarse aggregate was applied with grading according to destination as reported by [35]. Table 1 represents the different characteristics of the aggregates used in the research. Figures 1 and 2 depict the partitioning of sand and coarse particles by the use of a sieve. The produced coarse recycled concrete aggregate (RCA) has a specific gravity ranging from 2.0 to 2.5, which is slightly lower than that of raw aggregates. This is primarily due to the strong adhesion of mortar to each particular aggregate particle. The density of recycled coarse aggregate may be influenced by many variables, such as the manufacturing method and the content of the recycled materials. However, recycled coarse aggregate has a lower density than natural coarse aggregate. Furthermore, a significant distinction between recycled aggregates and

**Table 1** Different properties of the types of aggregates used in the research

| Type/characteristics | Fine aggregate | Coarse aggregate (normal) | Coarse aggregate (recycled) |
|---|---|---|---|
| Specific gravity | 2.66 | 2.72 | 2.28 |
| Water absorption % | 0.78 | 1.38 | 5.77 |
| Fineness modulus | 2.28 | 5.8 | 6.02 |
| Bulk density kg/m$^3$ | 1682 | 1620 | 1348 |
| Sulfate content% | 0.06 | 0 | 0.09 |

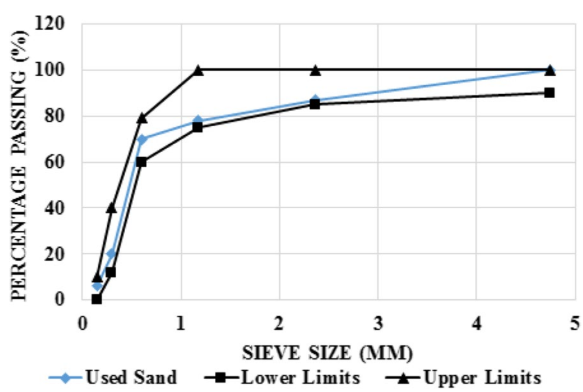



**Fig. 1** Lower and upper limit of sieve divisions of fine aggregate

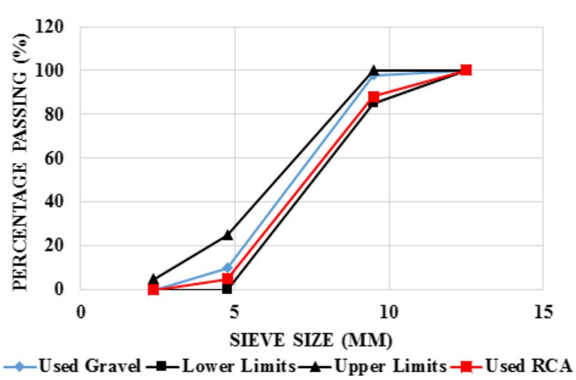



**Fig. 2** Lower and upper limit of sieve divisions of coarse aggregate

natural aggregates is their somewhat lower density compared to the original materials. The main cause of this phenomenon is the increased water absorption due to the presence of old cement concrete adhering to recycled aggregate particles. Natural aggregates usually have a density of 2400 kg/m$^3$, while recycled aggregates frequently have a density between 2150 and 2680 kg/m$^3$. The quality level of the recycled material used significantly impacts the concrete created with recycled coarse aggregate (RCA). The concrete cylinders that were analyzed and crushed during prior laboratory research studies are used to generate the recycled aggregate utilized in this study. To get the proper size and quality of RCA material, it is necessary to break, remove, and crush the existing concrete. A laboratory mold that had been tested before was crushed and graded to create 10 mm aggregates, which met the standards for both aggregates and recycled coarse aggregate. The materials used in the experimental study are shown in Fig. 3.

### Mixing and specimen preparation

Table 2 displays the quantities of each element, namely cement, fine aggregate, coarse aggregate, and recycled coarse aggregate. Moreover, Table 2 accurately computed the

**Fig. 3** Materials used in the experimental work for concrete production

**Table 2** Mix proportions (kg/m$^3$)

| Mix | Cement (kg/m$^3$) | Sand (kg/m$^3$) | Gravel (kg/m$^3$) | Recycled coarse aggregate % | w/c |
|---|---|---|---|---|---|
| MRCA(0) | 520 | 610 | 920 | 0 | 0.4 |
| MRCA(10) | 520 | 610 | 920 | 10 | 0.4 |
| MRCA(20) | 520 | 610 | 920 | 20 | 0.4 |
| MRCA(30) | 520 | 610 | 920 | 30 | 0.4 |
| MRCA(40) | 520 | 610 | 920 | 40 | 0.4 |
| MRCA(50) | 520 | 610 | 920 | 50 | 0.4 |
| MRCA(60) | 520 | 610 | 920 | 60 | 0.4 |
| MRCA(70) | 520 | 610 | 920 | 70 | 0.4 |
| MRCA(80) | 520 | 610 | 920 | 80 | 0.4 |
| MRCA(90) | 520 | 610 | 920 | 90 | 0.4 |
| MRCA(100) | 520 | 610 | 920 | 100 | 0.4 |

optimal blend ratios for casting each design, using the specified amounts of constituents in cubic meters. The concrete mixture specified in Table 2 is intended for grade 30 concrete, which is often used in construction for slabs, external walls, and structural piles in commercial concrete projects. This empirical investigation used 11 distinct concrete compositions, each using varied quantities of reused coarse material. The mixes were examined during periods of 7, 14, and 28 days. MRCA(0) represents the control mix, while the other mixes reflect MRCA with varying percentages of recycled coarse aggregate. These percentages include 10, 20, 30, 40, 50, 60, 70, 80, 90, and 100, which are used to replace the coarse aggregate [36–38]. The water quantity and water-to-cement ratios were consistent across all concrete mixtures. To achieve a homogeneous and standardized concrete mixture, the components were combined in a sequential manner. The concrete was produced using a concrete mixer that rotated at a speed of 60 revolutions per minute. The fines were added to the drum mixer and mixed for a period of 3 min, along with the cement and fine aggregate as stated in the mix design. Subsequently, the conventional coarse aggregate and the recycled aggregate are mixed together in accordance with their designated ratio, followed by an additional duration of about 3 min. The water was added incrementally and, once blended, the mixing process proceeded for an additional 3 min until the concrete mixture achieved homogeneity and uniformity. To achieve the best quality concrete that is ready for pouring. Following the completion of the mixing process, the next step is the molding process, in which the molds are filled and agitated using a three-layer laboratory vibrator. The workability (slump) test of the mixture was assessed subsequent to the mixing process and before casting. According to the standard specifications, the samples were cast into molds shaped like cylinders and prisms, with dimensions of 100 × 200 mm and 100 × 100 × 500 mm, respectively. These samples were then evaluated in accordance with the parameters given in the standard. [39–44]. To obtain the required overlay and uniform compaction, the samples were deaerated using a vibrating table. The specimens were extracted from the mold after a duration of 1 day and thereafter submerged in water until the testing time, according to the stipulated criteria outlined in ASTM C 511–03 [45]. The molds were stored at room temperature in a laboratory for 24 h before being taken out of the molds. The specimens were subjected to a curing procedure for periods of 7, 14, and 28 days in a water tank kept at a constant temperature of 27 ± 3 °C. Figure 4 illustrates the whole sequence of actions included in this experimental investigation. Figure 5 shows the mixing process and fresh concrete before putting the concrete in the molds and testing.

### Testing procedure

The workability (slump) of all combinations was evaluated by assessing the new concrete qualities using an inverted cone. In addition, additional characteristics such as the bulk density test were assessed. Furthermore, the study also examined the compressive, flexural, and splitting tensile strengths of different concrete mixtures. The intention of the slump test is to ascertain the consistency of classifying concrete in its initial stage. It is indirectly correlated with the yield stress of concrete, so facilitating the assessment of its susceptibility to deformation under stress, such as that induced by its own weight [40]. The slump test was used to assess the workability of fresh concrete mixes in accordance with ASTM C-140 [40]. The process of doing the slump test began by ensuring that the inside surface of the slump cone was well cleaned and moist, yet free from excess moisture. To ensure effective functionality, the slump cone should be placed on a level surface that is devoid of any vibrations. The concrete was then poured into the mold in a tripartite manner, with each stratum representing one-third of the overall height of the cone. Subsequently, a total of 25 imprints were applied to each layer of the concrete prior to the pouring of the subsequent layer. Subsequently, delicately and gradually elevate the cone in an upward trajectory from the concrete or ground. Subsequently, a measuring tape was used to document the vertical extent of the collapse. The concrete's fresh density was calculated in accordance with the specifications stated in ASTM C 29 [44]. The container is filled with concrete and then compressed in two stages. The time of compaction should be adequate and limited to avoid any indications of segregation or exudation. The concrete's bulk density is determined by measuring the amount of concrete present inside a certain volume The concrete's compressive strength was measured after 7, 14, and 28 days according to the ASTM C39 standard [41]. The loading rate was 0.7 megapascals per second. Each concrete mix used cylindrical dimensions of 100 × 200 mm, as seen in Fig. 6. The concrete's tensile splitting strength was measured after 7, 14, and 28 days according to ASTM C469 [43]. Subsequently, the process started by ensuring the specimen was devoid of moisture and the testing equipment was free of any contaminants. The specimen was thereafter oriented in a manner that the applied weight was at a right angle to the direction of the casting. A loading rate ranging from 0.2 to 1.0 MPa/s was selected. The load was steadily increased without sudden impact at a constant rate of 10% until the specimen reached its maximum load-bearing capacity. Each concrete mix used cylindrical specimens with dimensions of 100 × 200 mm, displayed in Fig. 6. The flexural strength of concrete was measured at 7, 14, and 28 days after following the ASTM C78 [46] standard. The loading rate was 0.8 megapascals per second. A prism with dimensions of (100 mm × 100 mm × 500 mm) was used for each concrete mixture.

## Results and discussion

In this section, the results of fresh and mechanical properties of concrete containing recycled coarse aggregates in concrete are presented in the following sections.

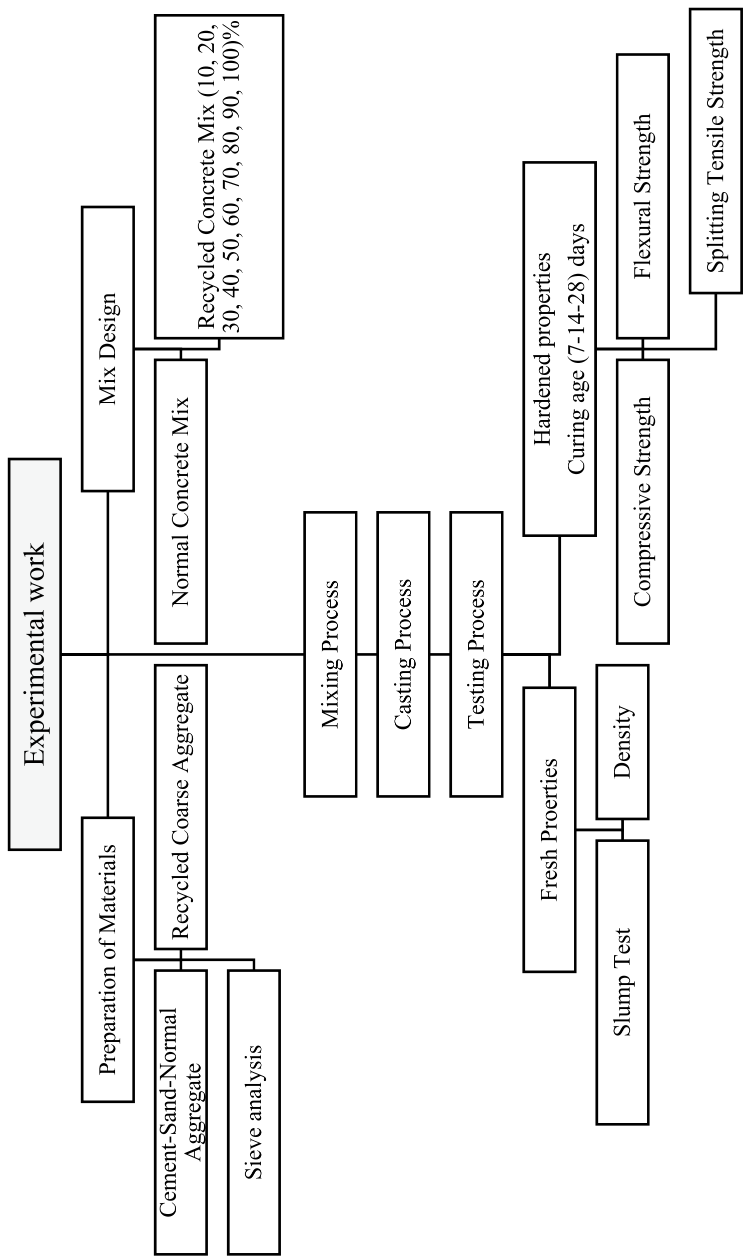



**Fig. 4** Research work plan according to the order of work

**Fig. 5** Mixing process for the experimental work and fresh concrete mixture

**Fig. 6** Samples of concrete for various testing such as fresh and mechanical properties

## Fresh properties of concrete

The properties of fresh concrete such as workability (slump), and bulk density are presented as follows:

### *Workability (slump) test*

The workability of freshly produced concrete is a crucial characteristic that greatly influences its ultimate strength. The workability of a concrete mix design is mostly determined by the characteristics of the raw material being utilized. The workability of new concrete with various proportions of recycled coarse aggregate for coarse aggregate in concrete production was evaluated using a slump test. The test results are presented in Table 3. The purpose of paying attention to and considering the concrete mixture is to obtain a regular, homogeneous, and workable concrete texture that is suitable for various construction works. There are three main methods for determining the strength of concrete, one of them is the slump test. Workability was tested through the slump [40]. Figure 7 depicts the slump values of concrete with varying proportions of recycled coarse aggregate in the manufacturing process. The designated value for the reference samples was 120 mm. The slump test findings for concrete containing recycled coarse aggregate particles demonstrated a reduction in the workability of the mixes as the quantity of recycled coarse aggregate increased, serving as an alternative to traditional coarse aggregate. The conclusion of the slump examination is given in Table 3. The slump conclusion specifies that the extreme slump estimation of 120 mm was estimated for the concrete with a 0% recycled aggregate ratio and the minimum slump value of 90 mm, which signifies a 25% reduction from the maximum value recorded for the concrete with 100% recycled coarse aggregate content. The level of slump for the mix created using natural coarse aggregate was 120 mm, slightly above the desired slump of 90 mm. This decrease in value was deemed to reflect a more accurate combination as the typical decrease in the ready mix business is around 90 mm. The increased water absorption of the recycled coarse aggregate was responsible for the decrease in slump levels. Increasing the recycled coarse aggregate from (0) normal aggregate to (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) recycled coarse aggregate reduces the slump by (0.8, 1.7, 4.2, 8.3, 11.7, 14.2, 19.2, 22.5, 25, and 25%). The reason for the decrease in workability is that the recycled coarse aggregate used in concrete as an alternative to regular aggregate consists of a rough surface, and as the surface area is larger than regular aggregate, the large surface area leads to increasing the absorption of more mixing water and higher water demand compared to regular aggregate.

**Table 3** Slump flow examination and ratio (%) with the activity of recycled aggregate

| Mix | Slump test (mm) | % |
|---|---|---|
| MRCA(0) | 120 | 0.0 |
| MRCA(10) | 119 | − 0.8 |
| MRCA(20) | 118 | − 1.7 |
| MRCA(30) | 115 | − 4.2 |
| MRCA(40) | 110 | − 8.3 |
| MRCA(50) | 106 | − 11.7 |
| MRCA(60) | 103 | − 14.2 |
| MRCA(70) | 97 | − 19.2 |
| MRCA(80) | 93 | − 22.5 |
| MRCA(90) | 90 | − 25.0 |
| MRCA(100) | 90 | − 25.0 |

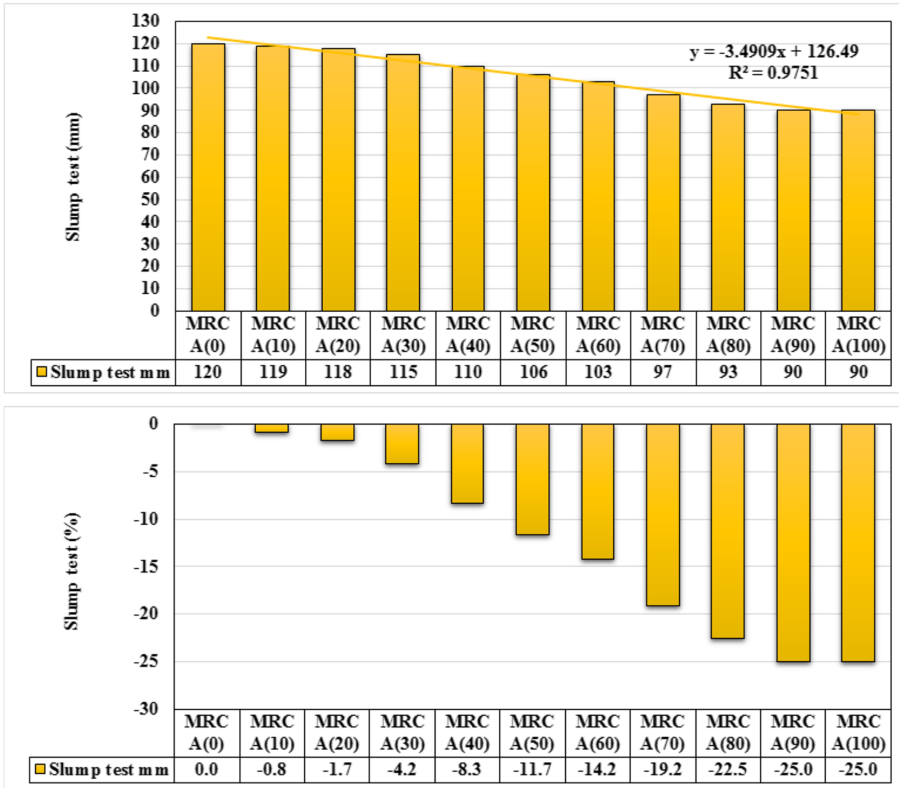



**Fig. 7** Slump flow examination and ratio (%) with activity of recycled aggregate

### *Bulk density of concrete*

The density values for the saturated concretes are shown in Fig. 8 and Table 4. The recycled coarse aggregate concrete exhibited a reduced density in comparison to the reference concrete. Moreover, the density declined as the ratio of mixed recycled aggregate rose, regardless of the existence of suspended particles in the aggregate. The drop in density was a result of the lower density of the recycled coarse aggregate in comparison to the natural aggregate. The study also discovered a clear association between density and the ratio of recycled coarse aggregate replacement, which is consistent with previous research done by Singh et al. [47]. Additionally, the increased porosity of recycled aggregate results in a higher air content in recycled coarse aggregate concrete. The density of concrete is influenced by factors such as porosity, texture, structure, and size of particles. According to the density test findings (Table 4), it was subsequently established that the coarser texture and less rounded shape of the recycled coarse aggregate caused air to get trapped in the mixture, which also impacted the density of the concrete. The density of natural coarse aggregate is greater than that of RCA particles, therefore replacing coarse aggregates with RCA granules may effectively reduce the density of concrete. The weak adhesion between recycled concrete aggregate (RCA) particles and cement paste in the concrete matrix might result in a reduced overall density due to the presence of voids created by the RCA granules inside the internal concrete matrix. The presence of voids leads to an increase in porosity, resulting in a decrease in density. The conclusion of the density examination is given in Fig. 8 and Table 4. Concrete that incorporates recycled

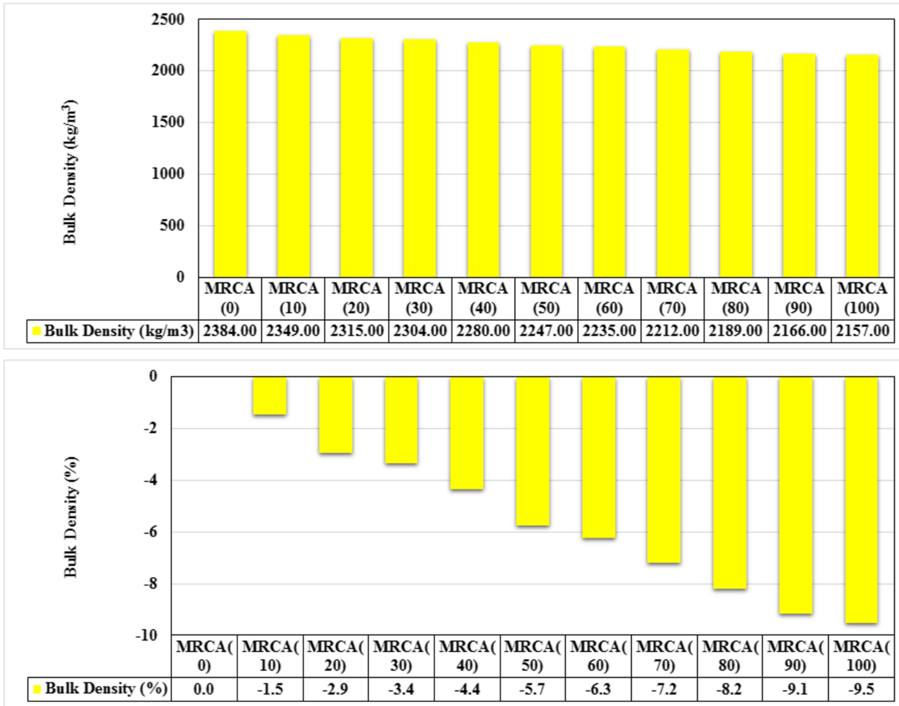



**Fig. 8** Bulk density examination and ratio (%) with activity of recycled aggregate

**Table 4** Bulk density (kg/m$^3$) examination and ratio (%) with activity of recycled aggregate

| Mix | Bulk density (kg/m$^3$) | % |
|---|---|---|
| MRCA(0) | 2384.00 | 0.0 |
| MRCA(10) | 2349.00 | − 1.5 |
| MRCA(20) | 2315.00 | − 2.9 |
| MRCA(30) | 2304.00 | − 3.4 |
| MRCA(40) | 2280.00 | − 4.4 |
| MRCA(50) | 2247.00 | − 5.7 |
| MRCA(60) | 2235.00 | − 6.3 |
| MRCA(70) | 2212.00 | − 7.2 |
| MRCA(80) | 2189.00 | − 8.2 |
| MRCA(90) | 2166.00 | − 9.1 |
| MRCA(100) | 2157.00 | − 9.5 |

aggregate is indeed regarded as cost-effective and eco-friendly. However, this practice also leads to a reduction in density. The decrease in density can be attributed to the utilization of recycled aggregate in various proportions, as recycled aggregate generally has a lower density compared to regular aggregate. The greater the proportion of recycled aggregate in the concrete, the lower the density. Increasing the recycled coarse aggregate from (0) normal aggregate to (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) coarse aggregate from recycled reduce the density by (1.5, 2.9, 3.4, 4.4, 5.7, 6.3, 7.2, 8.2, 9.1, and 9.5%) depending on [44] standard test. The findings align with the results of earlier studies, which also documented a decrease in density [48, 49].

## Mechanical properties of concrete

The properties of hardened concrete such as compressive strength, flexural strength, and splitting tensile strength are presented as follows:

### *Compressive strength*

The properties of concrete depend mainly on the properties and ratios of mixing the raw materials used in its production of aggregates of both types, cement and water, as well as the method of mixing materials, the process of transporting concrete to its location, the method of compaction and curing of concrete, the economic factor, the weather conditions surrounding the concrete, the type of building in which it is used, and the quality control at the work site. In sequence to control the quality of concrete manufacturing at the project site, a compressive strength test must be performed. Most other properties and resistances such as tensile, flexural, shear and cohesion with reinforcing steel improve and increase with increasing compressive strength and vice versa. One of the most important properties of hardened concrete is compressive strength. The most important resistance of concrete is compressive strength, as the concrete through it reflects the extent of its strength, suitability, and suitability for the work [41]. The basic considerations in the design of concrete mixtures are two important points, which are confirmed by all research, namely cost and the possession of concrete of the minimum specific properties with specification. The compressive strength of mixed specimens at the duration of 7, 14, and 28 days are displayed

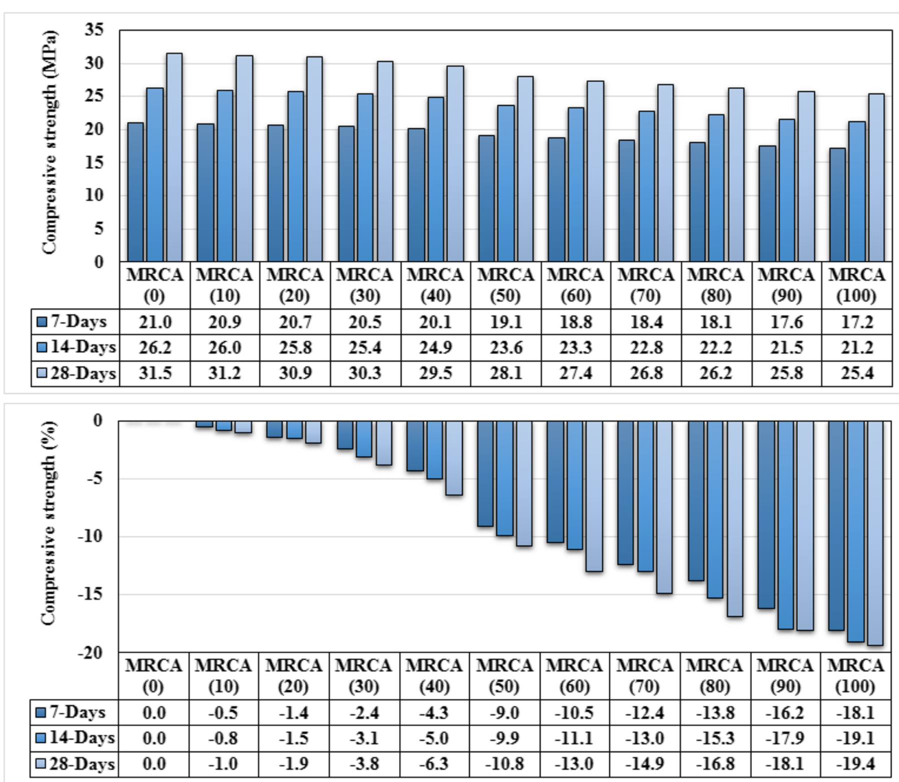



**Fig. 9** Compressive strength and ratio (%) with the activity of recycled aggregate

**Table 5** Compressive strength and ratio (%) with the activity of recycled aggregate

| Mix | Compressive strength (MPa) 7 days | % | Compressive strength (MPa) 14 days | % | Compressive strength (MPa) 28 days | % |
|---|---|---|---|---|---|---|
| MRCA(0) | 21.0 | 0.0 | 26.2 | +24.76 | 31.5 | +50.0 |
| MRCA(10) | 20.9 | −0.5 | 26.0 | −0.8 | 31.2 | −1.0 |
| MRCA(20) | 20.7 | −1.4 | 25.8 | −1.5 | 30.9 | −1.9 |
| MRCA(30) | 20.5 | −2.4 | 25.4 | −3.1 | 30.3 | −3.8 |
| MRCA(40) | 20.1 | −4.3 | 24.9 | −5.0 | 29.5 | −6.3 |
| MRCA(50) | 19.1 | −9.0 | 23.6 | −9.9 | 28.1 | −10.8 |
| MRCA(60) | 18.8 | −10.5 | 23.3 | −11.1 | 27.4 | −13.0 |
| MRCA(70) | 18.4 | −12.4 | 22.8 | −13.0 | 26.8 | −14.9 |
| MRCA(80) | 18.1 | −13.8 | 22.2 | −15.3 | 26.2 | −16.8 |
| MRCA(90) | 17.6 | −16.2 | 21.5 | −17.9 | 25.8 | −18.1 |
| MRCA(100) | 17.2 | −18.1 | 21.2 | −19.1+23.26 | 25.4 | −19.4+47.67 |

in Fig. 9 and Table 5. It can be noted from Fig. 10 that after examining the concrete cylinders under the force of compression to examine the compression strength of concrete, we will notice that when the percentage of recycled coarse aggregate that is used in higher proportions as a substitute for regular aggregate has effect the mode of failure of the hardened concrete and notice more cracking of the concrete cylinders, as well as more crushing and fragmentation of the concrete. Increasing the curing period leads to the development strength of concrete for all the mixed proportions. For 7 days of curing increasing the recycled coarse aggregate from (0) normal aggregate to recycled coarse aggregate (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) reduces the compressive strength by (0.5, 1.4, 2.4, 4.3, 9.0, 10.5, 12.4, 13.8, 16.2, and 18.1%). For 14 days of curing increasing the recycled coarse aggregate from (0) normal aggregate to recycled coarse aggregate (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) reduces the compressive strength by (0.8, 1.5, 3.1, 5.0, 9.9, 11.1, 13.0, 15.3, 17.9, and 19.1%). For 28 days of curing increasing the recycled coarse aggregate from (0) normal aggregate to recycled coarse aggregate (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) reduces the compressive strength by (1.0, 1.9, 3.8, 6.3, 10.8, 13.0, 14.9, 16.8, 18.1, and 19.4%). The effect of curing age increases the compressive strength by about (24.76 and 50%) for 14- and 28-day curing age according to the 7-day curing age for MRCA(0). The effect of curing age increases the compressive strength by about (23.26 and 47.67%) for 14- and 28-day curing age according to the 7-day curing age for MRCA(100).

Previous researchers, regardless of the variations in materials, additives, and testing methods, have consistently highlighted that incorporating recycled aggregate as a substitute for regular aggregate in concrete leads to a reduction in its compressive strength. This decline can be attributed to various factors. It is possible to enhance the compressive resistance or intensity of the concrete by extending the curing age of the concrete after utilizing recycled aggregate. This is because the longer the curing age, the stronger the compressive resistance of the concrete becomes. Hence, it is feasible to use recycled aggregate in concrete once again, but with stringent regulations in place for structural purposes. The use of recycled aggregate in concrete leads to a decline in its compressive strength due to several factors. The following are the reasons:

**Fig. 10** Shows the failure mode steps of concrete cylinders after being exposed to test in compression

- First, The irregular form of the recycled aggregate, as opposed to the standard aggregate, leads to a reduction in compressive strength.
- Second, the existence of cementitious substances or additives adhered to the recycled aggregate results in a reduction in the interlocking strength, surface roughness, and adhesion of the recycled concrete with the aggregates in the new concrete mixture.
- Third, the features and quality of the aggregates used are significant elements that influence the quality and strength of the concrete mixture. As the strength of the aggregate increases, the concrete exhibits greater compressive strength and enhanced resistance, durability, and stability against external forces.
- Fourth, another significant factor contributing to the reduction in the compressive strength of concrete is the existence of suspended materials on the reused aggregate, including cementitious materials, additives, clay, or other substances. These materials cannot be eliminated or cleansed, resulting in the detachment of the new concrete from the aggregate and the separation of the new concrete from the reused aggre-

gate. In addition, the new concrete absorbs significant quantities of mixing water that should be added to the concrete in accordance with the predetermined mixing ratios, because of the existence of these elements. The compressive strength of the new concrete will be compromised owing to the heightened permeability and porosity, resulting in reduced workability. However, these issues may be prevented by thoroughly cleaning the recycled aggregate.

#### *Flexural strength*

The flexural tensile strength of mixed specimens at the duration of 7, 14, and 28 days are presented in Table 6 and Figs. 11 and 12 depending on [42] standard test. As shown in Fig. 9, there were some aggregates crushed which indicate the strong bond between aggregate and paste but there were some aggregates separate from the paste during the test. Increasing the curing period results in the development strength of concrete for all the mix proportions. For 7 days of curing increasing the recycled coarse aggregate from (0) normal aggregate to (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) recycled coarse aggregate reduces the flexural tensile strength by (1.3, 2.3, 3.9, 5.6, 8.5, 9.8, 11.1, 12.1, 14.1, and 16.1%). For 14 days of curing increasing the recycled coarse aggregate from (0) normal aggregate to (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) recycled coarse aggregate reduces the flexural tensile strength by (2.0, 3.1, 4.6, 6.6, 9.2, 10.9, 11.7, 14.0, 15.0, and 16.0%). For 28 days of curing increasing the recycled coarse aggregate from (0) normal aggregate to (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) recycled coarse aggregate reduces the flexural tensile strength h by (2.3, 4.0, 5.9, 8.4, 11.2, 12.8, 14.7, 16.2, 17.3, and 18.3%). The effect of curing age increases the flexural strength by about (28.84 and 55.73%) for 14- and 28-day curing age according to the 7-day curing age for MRCA(0). The effect of curing age increases the flexural strength by about (28.9 and 51.56%) for 14- and 28-day curing age according to the 7-day curing age for MRCA(100). In the resistance of concrete to bending, we also notice here that the same reasons for the decrease in the compressive durability of concrete also cause a reduction in the flexural tensile strength of concrete with the use of recycled aggregate as an alternative to regular

**Table 6** Flexural tensile strength and ratio (%) with activity of recycled aggregate

| Mix | Flexural strength (MPa) 7 days | % | Flexural strength (MPa) 14 days | % | Flexural strength (MPa) 28 days | % |
|---|---|---|---|---|---|---|
| MRCA(0) | 3.05 | 0.0 | 3.93 | +28.85 | 4.75 | +55.73 |
| MRCA(10) | 3.01 | −1.3 | 3.85 | −2.0 | 4.64 | −2.3 |
| MRCA(20) | 2.98 | −2.3 | 3.81 | −3.1 | 4.56 | −4.0 |
| MRCA(30) | 2.93 | −3.9 | 3.75 | −4.6 | 4.47 | −5.9 |
| MRCA(40) | 2.88 | −5.6 | 3.67 | −6.6 | 4.35 | −8.4 |
| MRCA(50) | 2.79 | −8.5 | 3.57 | −9.2 | 4.22 | −11.2 |
| MRCA(60) | 2.75 | −9.8 | 3.50 | −10.9 | 4.14 | −12.8 |
| MRCA(70) | 2.71 | −11.1 | 3.47 | −11.7 | 4.05 | −14.7 |
| MRCA(80) | 2.68 | −12.1 | 3.38 | −14.0 | 3.98 | −16.2 |
| MRCA(90) | 2.62 | −14.1 | 3.34 | −15.0 | 3.93 | −17.3 |
| MRCA(100) | 2.56 | −16.1 | 3.30 | −16.0 +28.9 | 3.88 | −18.3 +51.56 |

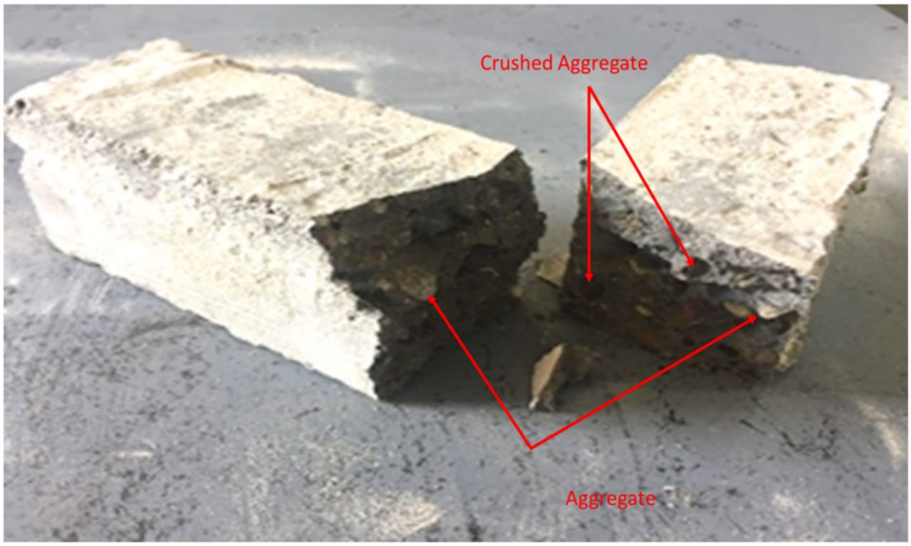
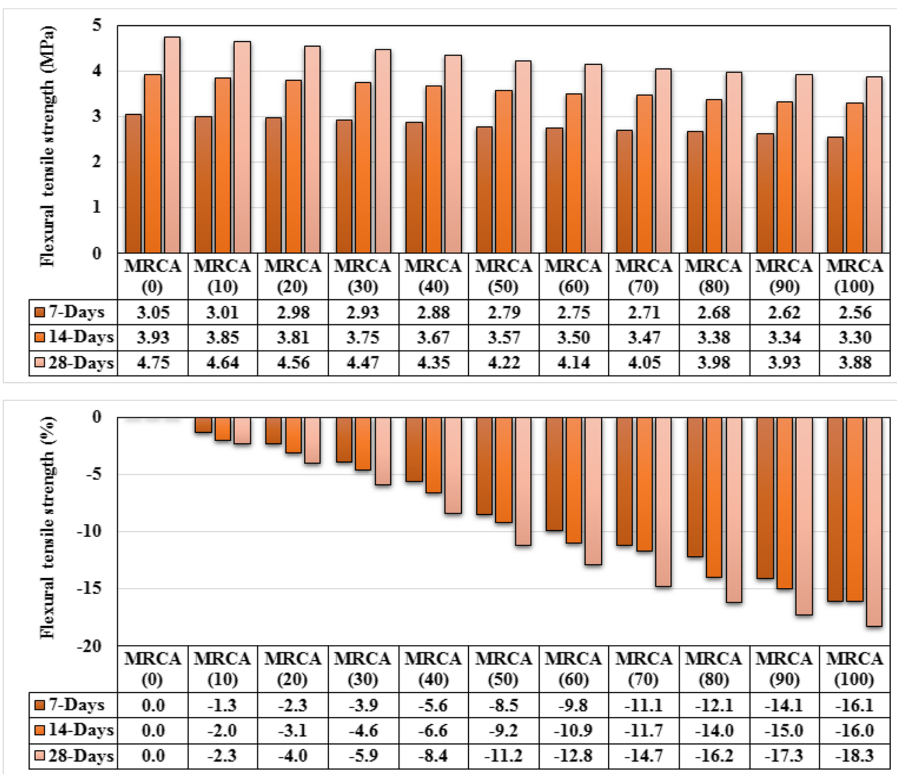



**Fig. 11** Shows the failure mode of concrete prism after exposed to test in flexure




| | MRCA (0) | MRCA (10) | MRCA (20) | MRCA (30) | MRCA (40) | MRCA (50) | MRCA (60) | MRCA (70) | MRCA (80) | MRCA (90) | MRCA (100) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7-Days | 3.05 | 3.01 | 2.98 | 2.93 | 2.88 | 2.79 | 2.75 | 2.71 | 2.68 | 2.62 | 2.56 |
| 14-Days | 3.93 | 3.85 | 3.81 | 3.75 | 3.67 | 3.57 | 3.50 | 3.47 | 3.38 | 3.34 | 3.30 |
| 28-Days | 4.75 | 4.64 | 4.56 | 4.47 | 4.35 | 4.22 | 4.14 | 4.05 | 3.98 | 3.93 | 3.88 |

| | MRCA (0) | MRCA (10) | MRCA (20) | MRCA (30) | MRCA (40) | MRCA (50) | MRCA (60) | MRCA (70) | MRCA (80) | MRCA (90) | MRCA (100) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7-Days | 0.0 | -1.3 | -2.3 | -3.9 | -5.6 | -8.5 | -9.8 | -11.1 | -12.1 | -14.1 | -16.1 |
| 14-Days | 0.0 | -2.0 | -3.1 | -4.6 | -6.6 | -9.2 | -10.9 | -11.7 | -14.0 | -15.0 | -16.0 |
| 28-Days | 0.0 | -2.3 | -4.0 | -5.9 | -8.4 | -11.2 | -12.8 | -14.7 | -16.2 | -17.3 | -18.3 |

**Fig. 12** Flexural tensile strength and ratio (%) with activity of recycled aggregate

aggregate. Regarding the form of failure, we note that there is almost one form of failure, which is the appearance of a fracture from the bottom of the prism and extending to the top. Sometimes the prism does not separate from one part to the other, but most of the time it is completely separated, but there is no shattering, breakage, or fragmentation in the mold.

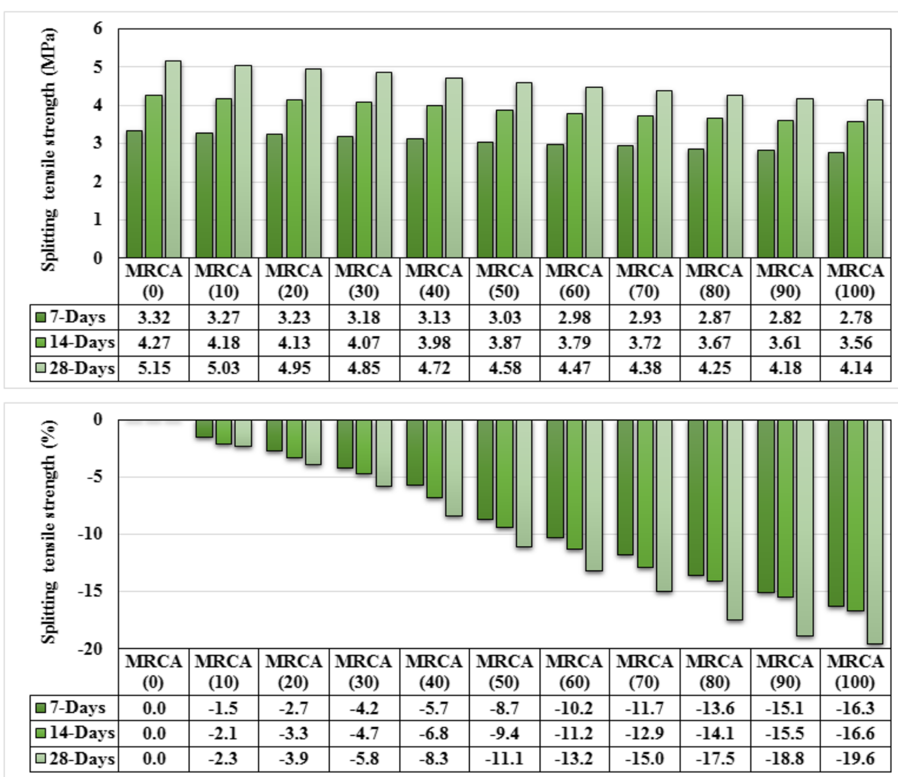
### Splitting tensile strength

The tensile strength of splitting of mixed specimens at the age of 7, 14, and 28 days are presented in Table 7 and Figs. 13 and 14. Increasing the curing period results in the development strength of concrete for all the mix proportions depending on [43] standard test. For 7 days of curing increasing the recycled coarse aggregate from (0) normal aggregate to (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) recycled coarse aggregate reduces the splitting tensile strength by (1.5, 2.7,4.2, 5.7, 8.7, 10.2, 11.7, 13.6, 15.1, and 16.3%). For 14 days of curing increasing the recycled coarse aggregate from (0) normal aggregate to (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) recycled coarse aggregate reduces the splitting tensile strength by (2.1, 3.3, 4.7, 6.8,9.4, 11.2, 12.9, 14.1, 15.5, and 16.6%). For 28 days of curing increasing the recycled coarse aggregate from (0) normal aggregate to (10, 20, 30, 40, 50, 60, 70, 80, 90, and 100%) recycled coarse aggregate reduces the splitting tensile strength by (2.3, 3.9, 5.8, 8.3, 11.1, 13.2, 15.0, 17.5, 18.8, and 19.6%). The effect of curing age increases the tensile strength by about (28.61 and 55.12%) for 14- and 28-day curing age according to the 7-day curing age for MRCA(0). The effect of curing age increases the tensile strength by about (28.05 and 48.92%) for 14- and 28-day curing age according to 7-day curing age for MRCA(100). In the resistance of concrete to splitting, we also notice here that the same reasons for the decrease in the compressive strength of concrete also cause a reduction in the splitting tensile resistance of concrete with the use of recycled aggregate as an alternative to regular aggregate. Regarding the form of failure, we note that there is almost one form of failure, which is the appearance of a fracture from the bottom of the prism and extending to the top. Sometimes the prism does not separate from one part to the other, but most of the time it is completely separated, but there is no shattering, breakage, or fragmentation in the mold. It was noticed here that the form of failure is similar to the form of failure in concrete under compression testing, where we notice that the concrete splits longitudinally. Sometimes the mold maintains its shape, but in most tests, the higher the percentage of recycled aggregate in

**Table 7** Splitting tensile strength and ratio (%) with activity of recycled aggregate

| Mix | Tensile strength (MPa) 7 days | % | Tensile strength (MPa) 14 days | % | Tensile strength (MPa) 28 days | % |
|---|---|---|---|---|---|---|
| MRCA(0) | 3.32 | 0.0 | 4.27 | +28.61 | 5.15 | +55.12 |
| MRCA(10) | 3.27 | −1.5 | 4.18 | −2.1 | 5.03 | −2.3 |
| MRCA(20) | 3.23 | −2.7 | 4.13 | −3.3 | 4.95 | −3.9 |
| MRCA(30) | 3.18 | −4.2 | 4.07 | −4.7 | 4.85 | −5.8 |
| MRCA(40) | 3.13 | −5.7 | 3.98 | −6.8 | 4.72 | −8.3 |
| MRCA(50) | 3.03 | −8.7 | 3.87 | −9.4 | 4.58 | −11.1 |
| MRCA(60) | 2.98 | −10.2 | 3.79 | −11.2 | 4.47 | −13.2 |
| MRCA(70) | 2.93 | −11.7 | 3.72 | −12.9 | 4.38 | −15.0 |
| MRCA(80) | 2.87 | −13.6 | 3.67 | −14.1 | 4.25 | −17.5 |
| MRCA(90) | 2.82 | −15.1 | 3.61 | −15.5 | 4.18 | −18.8 |
| MRCA(100) | 2.78 | −16.3 | 3.56 | −16.6+28.05 | 4.14 | −19.6+48.92 |


**Fig. 13** Shows the failure mode of concrete prism after exposed to test in split




| | MRCA (0) | MRCA (10) | MRCA (20) | MRCA (30) | MRCA (40) | MRCA (50) | MRCA (60) | MRCA (70) | MRCA (80) | MRCA (90) | MRCA (100) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7-Days | 3.32 | 3.27 | 3.23 | 3.18 | 3.13 | 3.03 | 2.98 | 2.93 | 2.87 | 2.82 | 2.78 |
| 14-Days | 4.27 | 4.18 | 4.13 | 4.07 | 3.98 | 3.87 | 3.79 | 3.72 | 3.67 | 3.61 | 3.56 |
| 28-Days | 5.15 | 5.03 | 4.95 | 4.85 | 4.72 | 4.58 | 4.47 | 4.38 | 4.25 | 4.18 | 4.14 |

| | MRCA (0) | MRCA (10) | MRCA (20) | MRCA (30) | MRCA (40) | MRCA (50) | MRCA (60) | MRCA (70) | MRCA (80) | MRCA (90) | MRCA (100) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 7-Days | 0.0 | -1.5 | -2.7 | -4.2 | -5.7 | -8.7 | -10.2 | -11.7 | -13.6 | -15.1 | -16.3 |
| 14-Days | 0.0 | -2.1 | -3.3 | -4.7 | -6.8 | -9.4 | -11.2 | -12.9 | -14.1 | -15.5 | -16.6 |
| 28-Days | 0.0 | -2.3 | -3.9 | -5.8 | -8.3 | -11.1 | -13.2 | -15.0 | -17.5 | -18.8 | -19.6 |

**Fig. 14** Splitting tensile strength and ratio (%) with activity of recycled aggregate

the concrete, the more the form of failure tends toward shattering, cracking, and fragmentation in the concrete cylinders.

## Conclusions

The construction industry is one of the most rapidly evolving industries worldwide in terms of its use of natural resources. The harmful effects on the environment of processing and transporting essential components from the place of production of the substance to the construction location are widely recognized. Moreover, these natural resources are becoming increasingly scarce and difficult to obtain. It is therefore important to consider alternative approaches that promote a sustainable balance between the natural resources used in the construction industry. Concrete production using coarse aggregates as opposed to recycled coarse aggregates (RCA) is one approach to solving the above problem. The following findings are the result of the current investigation:

- Around the world, the increase in construction projects, infrastructure modernization, and demolition operations are causing many problems, including the accumulation of building waste, as these problems can be eliminated through a process called recycling. Until now, there are no specific ways to dispose of building materials other than leaving them and collecting them in large quantities, as they cause many environmental problems, as well as other environmental problems in return, which as the depletion of natural resources.
- The workability of recycled coarse aggregates (RCA) decreased as replacement ratios for coarse aggregates increased due to the rough surface, and as the surface area is larger than regular aggregate, the large surface area leads to increasing the absorption rate of more mixing water and higher water demand compared to regular aggregate in the concrete production.
- The density of recycled coarse aggregates (RCA) decreased as the amount of substitute material increased due to a significant disparity in density between the RCA and the other main ingredients in the concrete mix. Another contributing aspect to this problem is the permeability of the recycled coarse aggregate material and the existence of weakly connected or bound natural aggregates in the concrete. As a result, the water absorption rate is greatly enhanced.
- The presence of concrete on the aggregate surface leads to many issues, one of which is an increased absorption of mixing water. It has been shown that recycled aggregate absorbs water at a higher rate compared to natural aggregate.
- The compressive strength exhibited a decline as the replacement amount of recycled coarse aggregate increased, regardless of the age of the concrete sample. The increased absorption capacity of the material may have contributed to improved mechanical performance as a result of its coarser texture and internal curing. These effects were more noticeable with longer curing times.
- The flexural tensile strength exhibited a reduction as the amount of recycled coarse aggregate increased, regardless of the curing age.
- The splitting tensile strength decreased as the replacement amount of recycled coarse aggregate increased, regardless of the curing duration.

- The compressive, flexural, and tensile strengths increased when the curing times were prolonged.

In summary, the investigation has shown that once the optimal substitute ratio for coarse aggregate is determined, it could potentially be used in construction. Tests have confirmed the efficacy of recycled aggregate, despite the lower strength of concrete in comparison to standard concrete. Moreover, the results of this experimental study could provide insights into the viability of using recycled coarse aggregate (RCA) as a substitute for coarse aggregate in concrete production. Nevertheless, more research is necessary to evaluate the microstructure and endurance properties of these concrete blends for widespread use in practical settings. In addition, future research could investigate methods to improve the attributes of strength, including compressive, flexural, and tensile strengths, which provide the foundation for various characteristics of concrete.

**Authors' contributions**
O A Q: writing—original draft preparation, writing reviewing, and editing. N H (corresponding author): planning; experimental work done; validation; resources; data curation; review and editing for this manuscript. N H S: planning; validation; resources; data curation for this manuscript. M I. ALB: idea of concept, writing—review and editing for the manuscript. T A.T: review and editing for the manuscript. All authors read and approved the final manuscript.

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**Availability of data and materials**
Data will be provided upon request.

## Declarations

**Competing interests**
The authors declare that they have no competing interests.

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## Publisher's Note