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Surface Treatment and Comparative Analysis for the Performance Assessment of Crushed Brick Aggregates as Coarse Aggregate Substitutes in Concrete

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Abstract: This research paper investigates the feasibility of utilizing recycled bricks as an alternative to traditional aggregates in concrete mixtures. Various mix designs were developed with a variable-water-to-cement (w/c) ratio for the and fine aggregate, while the composition of coarse aggregates was modified to examine the effects on the physical and mechanical properties of fresh and hardened concrete. The study focuses on evaluating parameters such as compressive strength, splitting strength, and flexural strength at different ages of curing. Additionally, the impact of different treatment methods on the performance of recycled brick aggregates is examined. The results indicated that incorporating crushed bricks into concrete mixtures significantly affects the workability of the mixture, resulting in a notable reduction. Furthermore, when recycled bricks are added to the concrete mix, along with various treatments, there is a negative impact on the compressive strength of the hardened concrete. The irregular shape and size distribution of the crushed brick particles contribute to stress concentrations and weak zones within the concrete, leading to a decrease in compressive, tensile, and flexural strength properties.

Keywords: Recycled Bricks, Mechanical Properties, Compressive Strength, Flexural Strength, Workability

1. Introduction.

During the early part of the last century, there was a significant increase in global population and urbanization, leading to a substantial rise in factory productivity. This trend necessitated the exploration of reusable materials as a means to preserve the environment and reduce construction costs. In the United States, for instance, Franklin Associates reported that the waste generated from construction operations reached 136 tons of building and demolition materials. This amount continued to rise, reaching 170 million tons by 2003 [1]. According to previous studies, it was found that 39% of construction waste is generated from residential buildings and 61% is generated from non-residential buildings. The increasing need to use concrete in various civil engineering applications such as buildings, bridges, dams, etc., concrete has made concrete the most widely used material in the field of construction around the world. According to Ramtin Movassaghi [2], the concrete industry around the world requires ten billion tons annually, making it one of the largest industrial processes consuming earth resources around the world. On the other hand, the concrete industry requires a high cost in terms of mining raw materials and producing cement [2]. Although many countries have called for the need to preserve the environment and to recycle and reuse materials once, this does not mean providing facilities with low quality [3]. Reducing the consumption of the earth’s natural resources is one of the most important goals that all countries call for, and it can be achieved through recycling and using materials and reducing the natural extraction of rubble, which leads to a positive impact on the environment [4]. One of the reasons why countries around the world call for the use of reusable materials or the recycling of waste and used materials is the economic crisis that many countries suffer from, but the used materials must provide performance and behavior similar to the originally used materials and not less than them even though the recycled materials need additional improvements that make them eligible to replace many construction materials [4]. In the past two decades, there has been significant

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progress in the development of recycling methods for construction and demolition wastes (CDW). These methods have aimed to effectively manage and reuse the waste generated from construction and demolition activities. One prominent example is the recycling of concrete rubble, which is a major component of CDW. Concrete rubble, after undergoing appropriate treatment, can be used as a replacement for natural aggregate (NA) in new concrete. This recycled form of concrete rubble is known as recycled concrete aggregate (RCA). RCA offers a sustainable alternative to the use of NA in concrete production and helps in reducing the demand for virgin aggregates. However, it's important to note that concrete rubbles from demolished buildings often contain not only concrete materials but also crushed clay bricks (CBA). These bricks are mixed with the concrete debris, adding to the complexity of the recycling process. To efficiently recycle such construction and demolition waste, it becomes necessary to separate and sort the concrete rubble from the crushed clay bricks. Separation techniques, such as sieving, magnetic separation, or air classification, can be employed to isolate the concrete rubble and bricks from each other. Once separated, the concrete rubble can be further processed and treated to produce RCA, while the crushed clay bricks can be utilized in other applications. The utilization of RCA and crushed clay bricks in concrete production contributes to resource conservation, waste reduction, and environmental sustainability. It also helps in reducing the environmental impact associated with the extraction and processing of natural aggregates. The crushed clay bricks used in the mixture of recycled concrete aggregate (RCA) may originate from various sources, including load-bearing masonry walls, cladding, or party walls. However, separating the CBA from the RCA is both financially burdensome and technically unfeasible. As a result, the combined mixture of RCA and CBA, known as recycled bricks concrete (RBC), is commonly utilized without separation. This practice has become widespread, with extensive utilization of both RCA and CBA in construction projects.

According to BS EN Standards [1,2], when incorporating recycled concrete aggregate (RCA) and crushed clay bricks (CBA) into concrete, it is recommended to use the same mix design as conventional concrete up to certain percentage levels. For example, a typical recommendation is to use up to 30% RCA and 5% CBA in the mixture. Within these limits, there is usually no significant difference observed in the resulting concrete properties. Moreover, the use of recycled concrete is particularly recommended for secondary structural members that require lower-grade concrete, such as curbs, paving blocks, and ground-bearing floor slabs. This allows for the sustainable utilization of recycled materials in less critical applications. The exploration of the properties of recycled concrete aggregates (RCA) was first initiated by Gluzhge in Russia, as mentioned in [3]. Subsequently, numerous countries have undertaken extensive research and development in this field, with a focus on various aspects of recycled concrete. These studies have acknowledged that properties such as water absorption, shape and size of RCA particles, presence of impurities, and chemical composition can significantly impact the behavior and performance of recycled concrete. Numerous reports on RCA provide valuable insights into the early investigations in this field [4]. These studies have contributed to the understanding of the performance and characteristics of recycled concrete, facilitating its wider adoption in construction practices. In addition to recycled bricks concrete (RBC), crushed clay bricks (CBA) have also been acknowledged as a significant component in construction and demolition wastes (CDW). The influence of crushed brick aggregate (CBA) on the properties of recycled concrete has received relatively less attention in research studies. This is mainly due to the fact that CBA has not been widely recognized or considered as a highly recyclable material, in comparison to recycled concrete aggregate (RCA). In the past, RCA was commonly disposed of in landfills or used for low-value applications, primarily because of limited recycling facilities and concerns related to economic feasibility. As a result, there is a dearth of comprehensive research documenting the specific effects of CBA on the properties of recycled concrete. As a result, a substantial body of research has focused on understanding the properties and behavior of RCA in recycled concrete. On the other hand, the investigation into the impact of CBA on recycled concrete properties has been relatively limited. This is partially due to the prevailing perception that CBA is less desirable as a recyclable material compared to RCA. Consequently, there is a relative scarcity of studies examining the specific effects of CBA on the performance and characteristics of recycled concrete. In addition to recycled bricks concrete (RBC), crushed clay bricks (CBA) have also been recognized as a significant and often inseparable component in construction and demolition wastes (CDW). However, the specific impact of CBA on the properties of recycled concrete is not as extensively studied compared to recycled concrete aggregate (RCA). This is partly because CBA has not been widely regarded as a highly recyclable material in the past, unlike RCA.

RCA was initially used for low-value purposes or sent to landfill due to limitations in recycling facilities and concerns about economic efficiency. However, the situation has changed with the advancement of sustainable concrete technology and extensive research in this field. In recent years, significant progress has been made in the development of modern sustainable concrete technology, leading to a shift in the perception and utilization of RCA. Presently, RCA) is extensively employed in non-structural concrete applications, including its use as coarse material for road base, paving blocks, and embankment fills. Considerable research and studies have been conducted to examine the properties of RCA, and the findings have been widely reported in the literature [4–9]. Studies have revealed a notable distinction between recycled concrete aggregate (RCA) and natural aggregate (NA) in terms of water absorption, especially in the case of recycled fine aggregate. In an experimental study conducted by Topcu and Sengel [8], concrete specimens were examined, wherein the weight percentage of RCA was varied up to 100%. The test outcomes demonstrated that as the proportion of waste concrete materials increased, the density of the concrete decreased. However, the difference in density was not as significant as the variations observed in water absorption. Furthermore, in the research conducted by Limbachiya et al. [10], it was revealed that the inclusion of RCA at levels ranging from 7% to 9% led to a decrease in relative density and approximately twice the water absorption compared to NA when in the saturated surface dry state. In the study conducted by Molhotra [11], optical and scanning electron microscopy techniques were employed to examine recycled concrete aggregate (RCA). The findings indicated that the particles of RCA exhibited a more angular and smoother morphology compared to NA. Mukai and Kikuchi [12] further supported these observations by noting that in order to achieve a similar slump in concrete, it was necessary to use approximately 5% more free water when utilizing recycled coarse aggregate and natural sand compared to NA. To address this issue, several methods have been proposed by other researchers to improve the recycled concrete workability. Poon et al. [13] emphasized the need for specific measures to manage the moisture content of recycled concrete aggregate prior to its use in concrete casting. Furthermore, their research revealed that incorporating 25% fly ash as a partial replacement for cement in the concrete mixture generally resulted in an increase in the slump of the mixture. Researchers widely recognize that the compressive strength of recycled concrete tends to gradually decrease as the proportion of recycled material used as a substitute for natural aggregate increases. However, it is important to note that up to a certain percentage of RCA substitution, the impact on strength may not be significant. In the study conducted by Rao et al. [18], it was discovered that the strength of concrete using RCA and NA was comparable even at full replacement. However, it was observed that a higher water/cement ratio was necessary to achieve this level of strength. When the W/C ratio was reduced to 0.4, the strength of the concrete with RCA was only 75% of the control mix. Sanchez and Alaejos [19] highlighted that mortar content in recycled concrete unfavorably affected properties such as absorption, density, and Los Angeles abrasion. To address this issue, extensive research has been conducted to enhance the compressive strength of recycled concrete. Kou et al. [20] suggested that incorporating 25-35% fly ash in paving blocks was a practical approach to optimize their strength characteristics. Test results showed that compressive strength reached 49 MPa at 28 days by following this recommendation. Furthermore, there have been suggestions that the properties of recycled concrete can be significantly improved by incorporating admixtures such as superplasticizers and silica fume. It should be noted that most of previous studies focused on the recycled aggregate but few studies investigated the recycling of bricks as an alternative to the coarse aggregate. This paper presents a a novel investigation that aims to examine the physical and mechanical properties of concrete made with recycled bricks. The objective is to explore the potential and limitations of using recycled materials in primary concrete structures. This study encompasses a series of laboratory experiments aimed at investigating multiple aspects related to recycled aggregate. These aspects include the examination of physical properties of recycled aggregate, assessment of workability in fresh concrete, and evaluation of strengths in hardened concrete at different ages. The research aims to provide comprehensive insights into the behavior and performance of recycled aggregate in concrete mixtures. Through these experiments, the research aims to analyze how the inclusion of CBA at different percentage levels influences the properties of concrete. The findings will provide insights into the impact of incorporating CBA on the physical and mechanical characteristics of recycled concrete.

2. Concrete Mixes and Materials properties

The experimental section of the research paper investigates the feasibility of using crushed bricks as a substitute for coarse aggregate (gravel) in concrete. The concrete mix consists of natural gravel, cement, sand, water, silica fume, superplasticizer, and recycled bricks (crushed and crushed burned bricks), as presented in Table 1 and Fig. 1. Before the concrete components are mixed, comprehensive physical and chemical inspections of the materials were conducted. The cement is tested according to Iraqi standards, while sieve analysis, grading, and compressive strength tests are performed following ASTM C109, ASTM C-136, ASTM C191, and Iraqi standards No. 45/1984, respectively. The physical and chemical properties are evaluated based on Iraqi standard specification No. 45/1984. Grey condenser grade 920 D silica fume is included in the concrete mix. The superplasticizer additive used in the experiment is confirmed to meet the requirements specified in ASTM C494-99. For the experimental investigation, four different concrete mixes are prepared which the reference mixture serves as a baseline and does not include crushed bricks (NC). The proportions of the components are in a ratio of 1:1.5:3. The second one is crushed brick (CBAC) treated with cement solution which involve utilizing various weights of crushed bricks, based on a percentage of the coarse aggregate weight, are incorporated into the mix and treated with a cement solution. The third type is burned brick mixture (B-CBAC) which this mixture is made using burned bricks treated with cement. The last one is crushed brick treated with HCL that are treated with hydrochloric acid (HCL) at concentrations of 5% and 10%. It should be noted that the brick types investigated previously to choose the suitable type to produce recycled concrete.

Table 1 Concrete Mixes details.

Material /(kg/m3)	**Mix 1 (NC)**	**Mix 2 (CBAC)**	**Mix 3 (B-CBAC)**	**Mix 4 (BCBAC-HCL)**
Cement.	500	500	500	667.125
Sand.	750	750	750	667.125
Coarse aggregate kg/m$^{3.}$	1500	1350	1350	1267.53
Super PS.	0.5%	0.5%		0.5%
CBC Kg/m^3	-	105	105	126.753
Silica fume.	-	-	-	10%
w/c.	0.42%	0.38%	0.38	0.35

(a) Recycled bricks

(b) Cement

(c) Crushing bricks

(d) Cleaning bricks with water

(e) Cleaning bricks with HCL

(f) Aggregate

Fig. 1 Used Materials.

3. Casting procedure.

In the experimental program, surface treatment of the crushed bricks is performed using two different methods: cement solution treatment and sodium hypochlorite solution treatment. For the cement solution treatment, the bricks are crushed to obtain the desired aggregate size of 19-20 mm. The crushed brick aggregate is then sieved using a standard sieve series in compliance with Iraqi standard specification No. 45/1984. Next, the crushed brick aggregate is mixed with cement and water. The water used is twice the weight of the CBA and the mixture is stirred for 2-3 minutes. The CBA is then immersed in the prepared cement slurry for a duration of 24 hours. After the soaking period, the CBA is removed from the slurry and left to dry for 3 days at ambient temperature. Any excess loose materials on the hardened CBA are removed. As for the sodium hypochlorite solution treatment, the burned aggregate is subjected to immersion in a sodium hypochlorite solution for 24 hours. Subsequently, the aggregates are rinsed with tap water and dried for use in the experiments. These surface treatment methods are applied to modify the crushed brick aggregates and prepare them for incorporation into the concrete mixtures, allowing for the evaluation of their performance in comparison to conventional concrete mixes. Fig. 2 illustrates the fabrication of concrete4 mixture made with recycled bricks. RCA constituted the majority of the sample, accounting for approximately 84% of the weight fraction. Crushed brick aggregate made up 14.5% of the sample, while other waste impurities comprised 1.4%. Although the percentage of impurities was relatively small, it is important to note that they can create weak points within the concrete and potentially affect its mechanical properties [36]. To address this concern, BS EN 8500-2 [2] sets a maximum permissible limit for harmful impurities in recycled aggregate RA. It is worth mentioning that in this study, the impact of these impurities was not investigated extensively, as most of them were removed during the sorting process.

(a) Fabrication of mixture | (b) Casting process

Fig. 2 Fabricating and casting the specimens.

4. Laboratory tests

4.1. Slump test

In order to assess the workability of the fresh concrete, a slump test was conducted. The test was performed following the guidelines outlined in BS EN 12350-2 [30]. The slump test is a widely recognized method for measuring the workability of concrete in general and recycled concrete specially. For each batch of concrete mixes, the slump test was carried out to ensure consistency across different batches. The slump measurement provides an indication of the workability for each concrete mix. In the case of the normal traditional concrete (control) mixture, the expected range for the slump was set to be within 10-30 mm, as shown in Table 4. This range falls into the good workability category, indicating that the concrete mixture has a relatively a good level of workability. When the concrete mix included crushed bricks, the workability reduced significantly. The use of recycled bricks in concrete mixtures have a significant effect on workability, especially when considering different treatments applied to the recycled bricks which led to necessity of treating the recycled bricks to avoid the decrease in workability although of the less W/C ratio in modifying the concrete mixture. Two treatments commonly employed are cement treatment and hydrochloric acid (HCL) treatment. Additionally, the use of burned crushed bricks treated with cement can also impact workability. Regarding the cement treatment, when recycled bricks are treated with cement, it can lead to improved workability in the concrete mixture. Cement treatment helps to bind the loose particles of the recycled bricks together, enhancing their overall strength and reducing the porosity. This treatment improved the interlocking between the recycled bricks and the cement paste, resulting in better workability and easier compaction of the concrete mixture when compared with un treated bricks. Treating recycled bricks with hydrochloric acid (HCL) is typically done to remove any unwanted contaminants or impurities from the bricks. While this treatment help in cleaning the recycled bricks, it has a negative impact on workability. HCL treatment caused the surface of the recycled bricks to become rough and more porous, which reduced the flowability of the concrete mixture. This led to a decrease in workability and make the mixture more difficult to handle and compact. The use of burned crushed bricks that have been treated with cement can have a mixed effect on workability. Burned crushed bricks, when properly treated with cement, provide good bonding with the cement paste. This enhances the overall strength and stability of the concrete mixture. However, if the burned crushed bricks are not adequately treated or if the cement treatment is insufficient, it results in increased porosity and reduced workability. In such cases, the presence of unreacted or poorly bonded crushed bricks can hinder the flow of the concrete mixture, making it less workable. The slump test was conducted on all concrete batches, and the results are presented in Table 2. The control mix exhibited a slump measurement of 33 mm, while the CBAC showed a slump of 24 mm. The B-CBAC mixture had a slump of 20 mm, which was 40% lower compared to the control mix. The RCB-50 mixture had the lowest slump measurement of 10 mm. CBAC HCL with 5% and 10% recycled aggregated showed less workability when the replacement ratio increased. Thus, it can be inferred from the results that there was a tendency for the slump to decrease as the ratio of recycled bricks increased. This observation may be attributed to the high content of crushed bricks, which had a relatively weak and porous texture. During the blending process, some of the mortar particles might break, leading to an increase in the number of small-sized particles and the porous texture within the mixture. This, in turn, affected the particle size distribution of the aggregate and its absorption capacity. The impact was particularly significant which was more prone to breaking. Another factor that could have contributed to the decrease in slump was the relative density of the aggregate. The mixture calculations were based on the relative density of the natural aggregate (NA). Consequently, the volume of coarse aggregate in the concrete increased, leading to the "loss" of most of the free water and a reduction in the degree of cement hydration.

Table 2 Slump test results.

Specimen	Substitution ratio (%)	Slump (mm)
NC	5%	33
CBAC	5%	20
B-CBAC	5%	10
CBAC HCL	5%	24
CBAC HCL	10%	17

5. Test Results

5.1. Composition of Recycled Bricks Aggregate

The composition of the recycled aggregate sample obtained from the demolition plant is presented in Fig. 3. The main component of the recycled bricks, accounting for approximately 10% of the weight fraction. Natural aggregate constituted 88.7% of the sample, while other waste impurities made up 1.3%. These impurities could comprise various materials such as wood, metal, plastic, or other debris present in the demolished structures. Even though the percentage of impurities was relatively small, they have the potential to create weak points or introduce inconsistencies in the concrete mixture, which could impact its mechanical properties. These impurities might have different physical and chemical characteristics compared to the main components, leading to variations in strength, durability, and other performance aspects of the concrete, thereby affecting its mechanical properties [36]. To address this concern, standards such as BS EN 8500-2 [2] provide guidelines and specify the maximum allowable limit for harmful impurities in recycled aggregate. By adhering to these limits, the quality and performance of concrete made with recycled aggregate can be maintained within acceptable levels. It is worth noting that the study mentioned in the context did not specifically investigate the impact of these impurities on the mechanical properties of concrete. This was mainly because most of these impurities were already removed during the sorting process employed at the demolition plant. The sorting process helps to separate and eliminate unwanted materials from the recycled aggregate, ensuring a cleaner and more consistent product for concrete production.

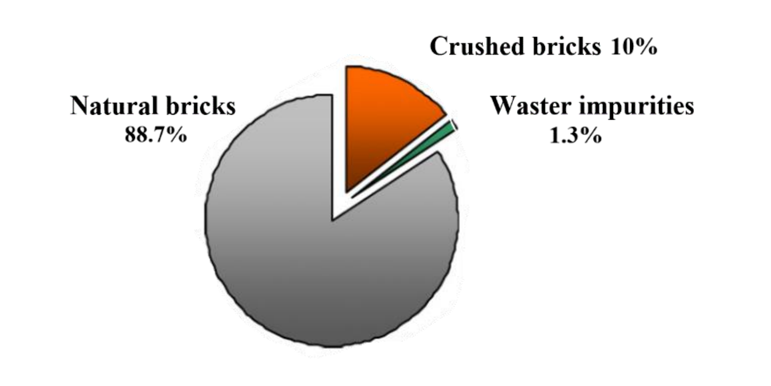


Fig. 3 Analysis of the internal component of concrete mixtures made with recycled bricks.

5.2 Compressive Strength

To evaluate the failure stress of the concrete specimens under uniaxial compression, the compressive strength test was performed. The testing procedure adhered to the guidelines outlined in BS EN 12390-3 [31]. An 'Avery-Denison' compression machine was utilized for conducting the test. In accordance with the specifications provided in BS EN 12390-1 [32], two 100 mm cube specimens were prepared for each batch of concrete mix. These specimens were used for the compressive strength testing. The cube specimens used in compressive strength testing are widely employed and provide a representative measure of concrete strength. The compressive strength test was conducted at two different ages: 7 days and 28 days. These specific time periods were selected to monitor the progress of compressive strength development over time.

Table 3 compressive strength results.

Mixture	Specimen's age (days)	Compressive strength				Variable/Control Ratio
		Cube 1	Cube 2	Cube 3	Average	
NC	7	37.8	38.8	40.8	39.13	-
	28	58	48.95	54.9	53.95	-
CBAC	7	21	32.4	28.4	27.27	69.68%
	28	36.36	37.9	35.2	36.49	67.63%
BCBAC	7	29.14	28.46	30.1	29.23	74.71%
	28	33.4	34.08	32.66	33.38	61.87%
BCBAC-HCL (5%)	7	35.3	33.4	37.4	35.37	90.38%
	28	45	52.8	53.4	50.40	93.42%

The curing duration significantly influences the hydration process and subsequent strength gain of concrete. By testing the specimens at these specific ages, the concrete's strength development can be assessed. During the test, the cube specimens were positioned in the compression machine, and a uniaxial compressive load was applied until failure occurred. The failure stress, which represents the maximum load the specimens could withstand before failure, was recorded during the test. This data provides valuable information about the concrete's compressive strength properties and its ability to withstand applied loads. Table 3 presents the results of compressive strength tests for four different mixes at 7 days and 28 days. The table indicates that concrete made with natural aggregate (NA) exhibited higher compressive strength compared to concrete containing crushed clay bricks (CBAC) or a combination of crushed clay bricks and recycled concrete aggregate (B-CBAC). Furthermore, the results shown in Fig. 4 demonstrate that as the substitution levels of recycled bricks increased, the compressive strength of the concrete decreased. It should be noted that the design strength specified in the mix design calculations was 50 N/mm^2 for the control mix. However, all of the mixes, including those with recycled materials, were able to achieve the expected design strength after 28 days of curing. The compressive strength for age of seven days revealed of an average compressive strength 39.1 MPa which increased to 53.95 MPa when the age reached 28 days. The addition of recycled bricks to the concrete mixture and in relation to the treatment method affected the compressive strength. Regarding the CBAC, the compressive strength of seven days scored only 27.27 MPa with a reduction by 31.7% when compared with traditional concrete mixture. The compressive strength at 29 days reached to 36.49 MPa lower than normal concrete by 32.4%. regarding the concrete mixture (B-CBAC), the compressive strength for age of seven days revealed of an average compressive strength 29.23 MPa which increased to 33.38 MPa when the age reached 28 days. The treatment effect was significant on the compressive strength of the concrete mixture which the age of seven days scored 35.37 MPa less the normal concrete by 9.4% only and for 28 days scored 50.4 which less than 6.6% when compared with normal concrete. The effect of recycled bricks, along with different treatments, on the compressive strength of concrete mixtures can vary with the impact of each treatment on the compressive strength. Regarding the cement treatment, treating recycled bricks with cement have a positive effect on the compressive strength of concrete mixtures. Cement treatment helps to bind the loose particles of the recycled bricks together, creating a stronger and more cohesive material. This treatment improves the interlocking between the recycled bricks and the cement paste, resulting in enhanced load transfer and improved compressive strength. The cement treatment enhances the overall bonding between the recycled bricks and the surrounding concrete matrix, leading to increased compressive strength. The effect of HCL treatment on the compressive strength of concrete mixtures is generally negative. HCL treatment is primarily used to remove impurities and contaminants from recycled bricks. However, the treatment caused the bricks to become more porous and chemically altered. These changes reduced the overall strength and structural integrity of the recycled bricks, which in turn can negatively impact the compressive strength of the concrete mixture. The increased porosity and weakened structure of the HCL-treated recycled bricks result in reduced load-bearing capacity and lower compressive strength of the concrete. The use of burned crushed bricks that have been treated with HCL have a positive effect on the compressive strength of concrete mixtures. The burning process helps to enhance the strength and durability of the crushed bricks. When treated with HCL, the burned crushed bricks form a strong bond with the surrounding cement paste, leading to improved load transfer and increased compressive strength of the concrete mixture. The proper treatment of burned crushed bricks with cement ensures improved compatibility and bonding, resulting in higher compressive strength.

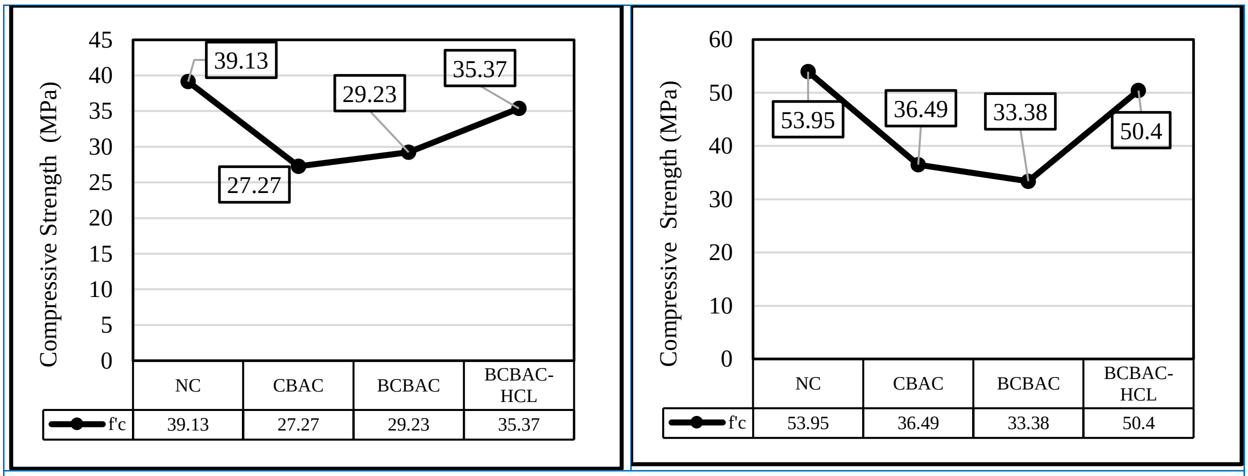


Fig. 4 compressive strength results for seven and twenty-eight days.

(a) NC (b) CBAC (c) B-CBAC (d) B-CBAC-HCL

Fig. 5 Failure mode of different concrete mixture specimens.

5.3 Tensile splitting strength test

The tensile splitting strength tests conducted on the cylindrical specimens provide valuable information about the RCA tensile strength properties. By applying a splitting force along the length of the specimens, the tests simulate the tensile stress that the concrete may experience in real-world applications. This is important because recycled bricks concrete is generally dissimilar in behavior when compared with the conventional concrete Following the guidelines outlined in BS EN 12390-6 [33] ensures standardized testing procedures, allowing for reliable and comparable results. The choice of two different curing periods, 7 days and 28 days, is significant as it allows for the evaluation of the concrete's strength development over time. The curing period plays a vital role in the hydration process, which directly influences the concrete's strength gain. The results obtained from the tests, as presented in Table 4, offer a comprehensive overview of the tensile splitting strength of the concrete specimens at the specified curing periods. These results enable comparisons between different concrete batches and provide valuable data for assessing the concrete's structural performance in terms of tensile strength. This information can be used to determine the suitability of the concrete for various applications where tensile forces are expected to be encountered.

Table 4 Tensile strength results**.**

Mixture	**Specimen's age (days)**	Tensile strength				Variable/Control Ratio
		Cylinder 1	**Cylinder 2**	**Cylinder 3**	**Average**	
NC	7	6.04	5.88	6.125	6.02	-
	28	7.097	7.246	7.516	7.29	-
CBAC	7	1.7	2	1.9	1.87	0.31
	28	2.7	2.635	2.1	2.48	0.34
BCBAC	7	1.9	1.36	1.79	1.68	0.28
	28	2.9	2.6	2.75	2.75	0.38
BCBAC-HCL	7	2.9	3	2.85	2.92	0.48
	28	3.31	3.36	3.24	3.30	0.45

The obtained results reveal a consistent trend where an increase in the content of recycled constituents in the concrete mixture leads to a decrease in cylinder splitting strength. This finding aligns with the observations reported by Evangelista and Brito [37], who attributed the strength reduction to the more porous structure of recycled aggregate. As depicted in Fig. 6, the influence of recycled brick content on the cylinder splitting strength at both 7 and 28 days is illustrated. The figure clearly demonstrates a clear relationship between the proportion of recycled bricks and the concrete strength, indicating a decrease in splitting strength as the content of recycled bricks increases. This further supports the understanding that incorporating a higher amount of recycled constituents negatively affects the strength performance of the concrete. This information emphasizes the importance of considering the content of recycled constituents when designing concrete mixtures, particularly in applications where tensile strength is a critical factor. It highlights the need for appropriate quality control measures and optimization of the mix design to compensate for the potential reduction in strength associated with increased recycled content. The results indicated that the concrete with NA (presumably natural aggregates) exhibited higher strength compared to CBAC (Concrete with Brick Aggregate) or B-CBAC (Concrete with Recycled Brick Aggregate) included concrete. It was observed that as the substitution levels of recycled bricks increased, the tensile strength decreased. In terms of the control mix, which had a design strength of 7 N/mm2, all of the mixes met the expected design strength after 28 days. The tensile strength at seven days averaged 6.02 MPa and increased to 7.29 MPa at 28 days. The addition of recycled bricks to the concrete mixture, along with the treatment method, had an impact on the tensile strength. For CBAC, the tensile strength at seven days was only 1.87 MPa, representing a 69% reduction compared to traditional concrete. At 28 days, the tensile strength reached 2.48 MPa, which was 66% lower than normal concrete. For the concrete mixture with B-CBAC, the tensile strength at seven days averaged 1.68 MPa, increasing to 2.75 MPa at 28 days. The treatment method had a significant effect on the tensile strength, with the seven-day strength being 2.92 MPa, 52% lower than normal concrete. At 28 days, the tensile strength was 3.3 MPa, which was 55% lower than normal concrete. These results highlight the influence of recycled brick aggregates and treatment methods on the tensile strength of the concrete mixtures. It is evident that the use of recycled bricks had a negative impact on tensile strength compared to traditional concrete, and the treatment method played a role in determining the strength levels at different ages. The effect of recycled bricks, along with different treatments, on the tensile strength of concrete mixtures can vary according to the replacement ratio and treatment of the recycled bricks. Treating recycled bricks with cement have a positive effect on the tensile strength of concrete mixtures. Cement treatment helps to enhance the overall bonding between the recycled bricks and the surrounding concrete matrix. This improved bonding result in better load transfer and increased tensile strength. The treated recycled bricks form a stronger interface with the cement paste, contributing to improved resistance against tensile stresses. However, it's important to note that the tensile strength of concrete is generally lower than its compressive strength. The effect of HCL treatment on the tensile strength of concrete mixtures is typically positive. While HCL treatment may remove impurities and contaminants from recycled bricks, it can also decrease their porosity and alter their chemical composition. These changes can enhance the structure of the recycled bricks, leading to higher tensile strength of the concrete mixture. The increased porosity and potential chemical alterations can create weak points within the material, making it more susceptible to cracking and lower tensile strength. Regarding the burned crushed bricks, the use of burned crushed bricks that have been treated with cement have a positive impact on the tensile strength of concrete mixtures. The burning process increases the strength and durability of the crushed bricks. When treated with cement, the burned crushed bricks create a strong bond with the surrounding cement paste, resulting in improved load transfer and increased tensile strength. The proper treatment of burned crushed bricks ensures better compatibility and bonding, leading to higher tensile strength.

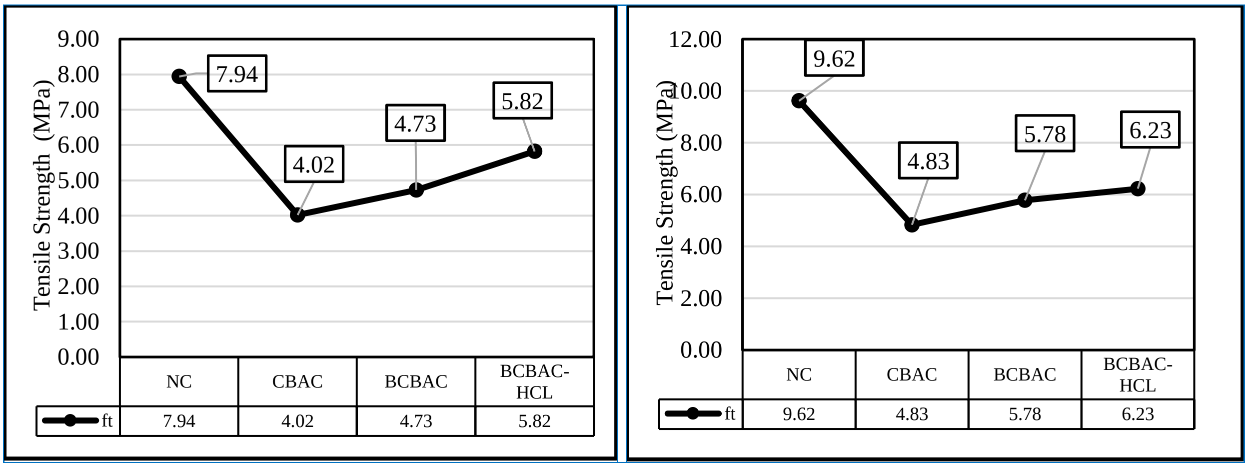


Fig. 6 Tensile strength results foe seven and twenty eight days.

(a) NC (b) CBAC (c) B-CBAC (d) B-CBAC-HCL

Fig. 7 Cylinder failure mode of different concrete mixture specimens.

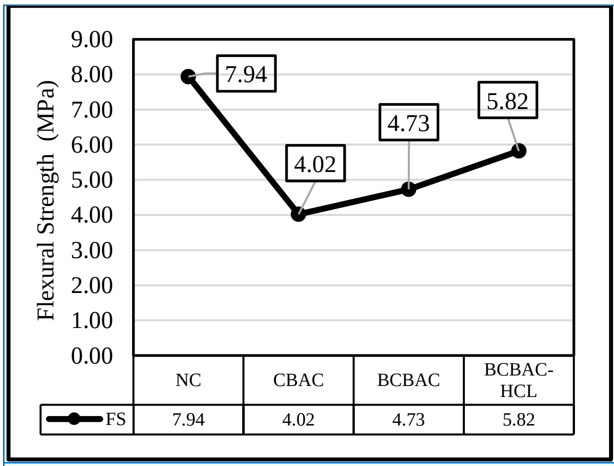
5.4 Flexural strength test

The results indicate that the use of natural aggregates (NA) resulted in stronger concrete compared to concrete containing crushed brick aggregate (CBAC) or a combination of crushed brick aggregate and natural aggregates (B-CBAC). This observation is supported by the data presented in Fig. 8. Specifically, as the level of recycled brick substitution increased in the concrete mixture, there was a decrease in flexural strength. This means that higher proportions of crushed brick aggregate in the mix led to a reduction in the concrete's ability to resist bending or flexural stresses. It is worth noting that the design strength for the control mix, which did not include any recycled brick aggregate, was specified as 50 N/mm² in the mix design calculations. This value represents the intended strength requirement for the concrete. The comparison of the flexural strength results between the different mix compositions suggests that the use of crushed brick aggregate, either alone or in combination with natural aggregates, adversely affected the flexural strength of the concrete. The decrease in flexural strength with increased levels of recycled brick substitution indicates that the presence of crushed brick aggregate had a detrimental impact on the concrete's ability to withstand bending forces as depicted in Table 5. These findings highlight the importance of considering the type and proportion of aggregates used in concrete mixtures, as they can significantly influence the resulting strength properties. In this case, the use of natural aggregates yielded stronger concrete compared to incorporating crushed brick aggregate.

Table 5 Flexural strength results.

Mixture	Specimen's age (days)	Flexural strength				Relative
		Prism 1	Prism 2	Prism 3	Average	Strength Reduction
NC	7	7.97	7.76	8.09	7.94	-
	28	9.37	9.56	9.92	9.62	-
CBAC	7	3.90	3.95	4.21	4.02	0.67
	28	5.21	4.58	4.71	4.83	0.66
BCBAC	7	4.59	4.65	4.95	4.73	0.79
	28	6.13	5.39	5.82	5.78	0.79
BCBAC-HCL	7	5.65	5.72	6.09	5.82	0.97
	28	6.45	5.96	6.22	6.23	0.85

All of the mixes were found to meet the expected design strength after 28 days. The flexural strength for age of seven days revealed of an average flexural strength 7.94 MPa which increased to 9.62 MPa when the age reached 28 days. The addition of recycled bricks to the concrete mixture and in relation to the treatment method affected the flexural strength. Regarding the CBAC, the flexural strength of seven days scored only 4.02 MPa with a reduction by 33% when compared with traditional concrete mixture. The flexural strength at 28 days reached to 4.91 MPa lower than normal concrete by 34%. Regarding the concrete mixture (B-CBAC), the flexural strength for age of seven days revealed of an average flexural strength 4.73 MPa which increased to 5.78 MPa when the age reached 28 days. The treatment effect was significant on the flexural strength of the concrete mixture which the age of seven days scored 5.82 MPa less the normal concrete by 3% only and for 28 days scored 6.23 which less than normal concrete by 15%.



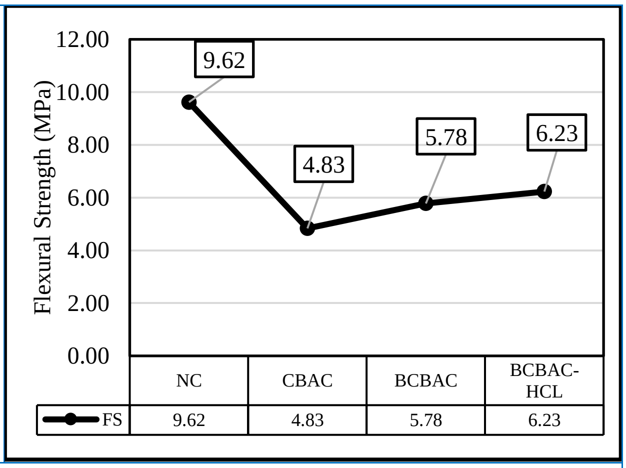


Fig. 8 Flexural strength results.

(a) NC (b) CBAC (c) B-CBAC (d) B-CBAC-HCL

Fig. 9 Prism failure mode of different concrete mixture specimens.

6. Summary

The investigation focused on examining how the use of recycled bricks instead of aggregates impacts the physical and mechanical properties of fresh and hardened concrete. Mix designs were employed with consistent water-to-cement (w/c) ratio and fine aggregate, but varying compositions of coarse aggregates. Based on this study, the following conclusions were drawn:

1. The inclusion of crushed bricks in concrete mixtures has a notable impact on workability, resulting in a significant reduction. The use of recycled bricks, along with different treatments, further affects workability. Two commonly employed treatments are cement and HCL treatment. Additionally, the incorporation of burned crushed bricks treated with cement can also influence workability. Specifically, when recycled bricks are treated with cement, it can lead to an improvement in workability within the concrete mixture.
2. The addition of recycled bricks to the concrete mixture, along with different treatments, has an impact on the compressive strength. Normal concrete (NA) generally exhibited higher compressive strength compared to concrete mixes that included crushed bricks (CBAC) or burned crushed bricks treated with cement (B-CBAC). As the substitution levels of recycled bricks increased, the compressive strength decreased.
3. The treatment method applied to the recycled bricks affected the compressive strength. Cement treatment generally improved compressive strength, while HCL treatment had a negative impact. The treatment method significantly influenced the compressive strength, with HCL-treated B-CBAC showing a decrease of 9.4% at seven days and 6.6% at 28 days compared to normal concrete.
4. The substitution of recycled constituents in the mixture led to a reduction in cylinder splitting strength. CBAC mixes showed significantly lower tensile strength, with a reduction of 69% at seven days and 66% at 28 days compared to traditional concrete. B-CBAC mixes exhibited lower tensile strength as well, with an average of 1.68 MPa at seven days and 2.75 MPa at 28 days.
5. Cement treatment enhanced bonding between the recycled bricks and the surrounding concrete matrix, resulting in better load transfer and increased tensile strength. HCL treatment generally had a positive effect on tensile strength by reducing porosity and enhancing the structure of recycled bricks. However, potential chemical alterations may create weak points within the material, making it more susceptible to cracking.
6. Burned crushed bricks treated with cement exhibited a positive impact on tensile strength. The burning process increased the strength and durability of the crushed bricks, and cement treatment further enhanced the bonding between the burned crushed bricks and the surrounding cement paste.
7. CBAC mixes exhibited lower flexural strength compared to traditional concrete. At seven days, the flexural strength was 4.02 MPa, representing a reduction of 33% compared to normal concrete. At 28 days, the flexural strength reached 4.91 MPa, which was 34% lower than normal concrete. B-CBAC mixes showed an average flexural strength of 4.73 MPa at seven days, increasing to 5.78 MPa at 28 days.

8. The treatment method significantly influenced the flexural strength. For CBAC mixes, the flexural strength at seven days was 5.82 MPa, only 3% lower than normal concrete. At 28 days, the flexural strength was 6.23 MPa, which was 15% lower than normal concrete.

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