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Evaluation of Recycled Brick Waste Aggregates as a Sustainable Substitute in Cement Treated Base

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Abstract

Recycling industrial waste to obtain secondary raw materials is a key focus of environmental policy and circular economy strategies. One such industrial waste, recycled brick waste (RBW), is characterized by high pollution and low recycling rates. This paper evaluates the effects of graded replacement of various RBW sizes as a substitute for coarse and fine natural aggregate (NA) on the mechanical properties and durability of cement treated base (CTB). The novelty of this study lies in the durability evaluation of four types of CTB, including natural, recycled, and mixed CTB. RBW and NA materials are characterized and compared, and the mechanical properties and durability of CTB with RBW materials are analyzed and compared to CTB with 100% NA. The results show that the mixes containing waste bricks exhibit comparable mechanical characteristics and could be used in layers of pavement foundations. Additionally, the durability of the mixes containing RBW yields better results compared to blends containing NA.

Keywords: cement treated base (CTB), recycled brick waste (RBW), mechanical properties, durability, abrasion test

1 Introduction

The building industry, which consumes over 3 billion tons of virgin materials annually, is the largest consumer of such materials worldwide [1]. In recent years, there has been a growing emphasis on sustainable pavements that utilize recycled materials to help conserve natural resources. Instead of discarding construction and demolition waste in landfills, it is being considered as a valuable source of recycled materials for replacing natural aggregates, thereby reducing potential environmental impacts and enhancing the economic value of recycling [2]. In many developing countries, brick construction is still prevalent alongside concrete construction, resulting in a significant amount of demolition waste comprised of brick aggregates. This presents an opportunity for utilizing recycled brick aggregates as a building material, particularly in countries like South Africa [3].

Several researchers have explored the idea of recycling brick waste. Hou et al. [4] investigated the effects of incorporating cement-stabilized crushed brick aggregates (CBA) in asphalt pavement base and subbase applications. The results have shown that as the content of CBA increases, the maximum dry density of the cement-stabilized CBA decreases, while the optimal water content increases. Additionally, the unconfined compressive strength, splitting strength, and resilient modulus at different ages all decrease with an increase in CBA content. Other studies have also examined the use of recycled concrete aggregates and crushed clay brick as substitutes for natural aggregates in unbound base materials, showing similar trends in terms of moisture content, dry density, and CBR values [5]. Furthermore, structural- and pavement-grade concrete mixtures using recycled brick aggregates have been developed, demonstrating comparable mechanical properties and durability performance to conventional concrete mixtures [6]. Additionally, investigations on the microstructure and durability of concrete with varying levels of replacement of sand aggregate with recycled brick aggregate have shown changes in water absorption, pozzolanic reactivity, and porous structure [7].

Atyia et al. [8] showed that the replacement of NA by RBW as coarse and fine aggregates in the concrete induce the compressive strength to be less. In addition, the total porosity is increased, and the thermal conductivity was less than the conventional concrete. Christen et al. [3] developed a more sustainable 3D printable concrete by the replacement of NA with RBW. An existing 3D printable concrete mix is used as reference and adjusted by replacing rate of 64%. The results show a decrease of compressive strength by 25%. Furthermore, studies have explored the use of waste clay bricks as substitutes for sand in roller-compacted concrete pavement, revealing that up to 25% substitution of brick waste for sand does not significantly affect the properties of concrete, but higher substitution ratios can result in increased water absorption [9]. Additionally, investigations on the pore structure and morphology characteristics of recycled fine aggregates from clay bricks as substitutes for sand in green concrete have shown a significant increment in porosity, pore volume, and pore size, indicating the impact of pozzolanic activity and internal curing [10]. SEM results showed that the mechanical interlocking of the interfacial transition zone and the compactness of reaction rim strengthened effectively with the incorporation of RBW.

Moreover, the use of crushed clay bricks as substitutes for natural fine or coarse aggregates in durable concrete has been shown to affect dry density and compressive strength [11]. Geotechnical applications of recycled brick aggregates have also shown favorable characteristics in terms of compaction and shear strength [12]. The values of maximum dry density (MDD) and optimum moisture content (OPM) are evaluated as 2.03 g/cm^3, 11.52 % respectively. Lastly, the design of cement-stabilized macadam mixtures with varying replacement ratios of recycled brick aggregates is being investigated to improve the content of recycled materials. Results showed that mixtures of recycled brick stabilized by cement with different replacement ratios had good mechanical properties, and the 7 days strength of the 55% replacement ratios mixtures reached 7.11 MPa, which exceeded the requirements of 3 MPa and 5 MPa for the pavement sub-base and base of the Chinese specification, respectively [13].
In this paper, we aim to further explore the potential of utilizing RBW in pavement construction, in the manufacture of CTB through providing a comparison of a several mechanical properties. The objective of this research is to analyze the effect of graded replacement of varying granular fractions of (0/3) mm and (3/8) mm, as well as 100% of RBW, on the durability properties in

road construction. Modified Proctor tests were conducted to evaluate the fresh state characteristics, while compressive strength, tensile strength, porosity, water absorption by immersion, thermal conductivity, and abrasion resistance were measured. The findings of this study could potentially have significant implications for sustainable construction practices, particularly in developing countries where brick construction is still prevalent.

2 Materials

The materials used in this study included Portland cement (CEM II 42.5) in accordance with EN 197-1, natural crushed aggregates (sand of size 0/3 mm and coarse gravels of fractions 3/8, 8/15, and 15/20 mm), and recycled brick waste (RBW) were obtained from the waste of fired bricks originating from the brick factory in Medea, located in the northern region of Algeria and included (sand of size 0/3 mm and coarse gravels of fractions 3/8, 8/15, and 15/20 mm). The physical and chemical properties of the cement and all aggregates are presented in Tables 1, 2 and 3. The recycled brick waste used in this study is shown in Figure 1. The grading curves of the aggregates used are shown in Figure 2.

Table 1: Chemical composition of Portland cement

SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	SO_3	L.I	K_2O	CaO_{Free}	Na_2O
23.83	56.35	6.06	4.66	2.44	2.37	2.23	0.83	0.66	0.58

Table 2: Physical properties of aggregates

Test items		**Fractions (mm)**			
		0/3	**3/8**	**8/15**	**15/20**
	Specific density (kg/m^3)	2690	2590	2610	2650
	Water absorption (%)	3.45	1.96	1	0.46
	Los Angeles (%)	/	32.4	25.95	24.88
	Sand equivalent (%)	78	/	/	/
	Fineness modulus	3.04	/	/	/
NA	Methylene blue value (%)	0.5	/	/	/
	Specific density (kg/m^3)	2340	2280	2150	2000
	Water absorption (%)	18.2	16.8	14.03	10.21
RA	Los Angeles (%)	/	34.16	23.72	30.23
	Sand equivalent (%)	69.11	/	/	/
	Fineness modulus	2.63	/	/	/
	Methylene blue value (%)	0.5	/	/	/

Table 3: Fluorescent Chemical analysis of aggregates

Component	**Al_2O_3 (%)**	**SiO_2 (%)**	**Fe_2O_3 (%)**	**CaO (%)**	**SO_3 (%)**
NA	6.77	0.59	2.50	90.14	/
RBW	18.73	49.28	9.56	20.08	2.45



Figure 1: Recycled brick waste used in this study

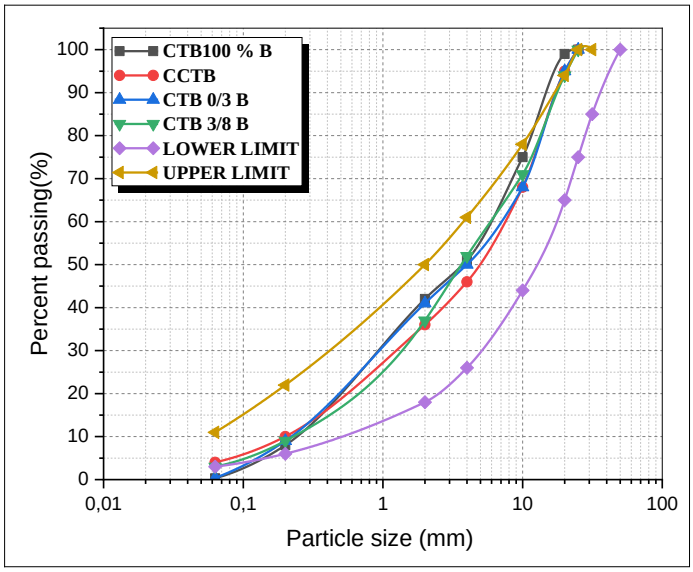


Figure 2: Gradation curves for the CTB

3 Experimental Program

The experimental program in this study aimed to investigate the impact of replacing recycled brick waste (RBW) as a fraction of fine and coarse (0/3 and 3/8 mm) and 100% RBW in CTB. The formulation of the control cement treated base (CCTB) followed the NF EN 14227-1 [14] standard, with a fixed cement percentage of 6% and optimal water quantity determined through proctor modifier tests. The variables in the study were the type of aggregate used. Four samples were produced for each CTB mixture, and the results were obtained as an average of three

readings. The CTB samples included: CCTB, consisting of natural aggregate treated with cement; CTB 0/3 B, with a recycled fraction of 0/3 and the remaining fraction of natural aggregate; CTB 3/8 B, with a recycled fraction of 3/8 and the remaining fraction of natural aggregate; and CTB 100% B, which used cement-treated recycled brick waste as the aggregate. Table 4 presents the quantities of materials used in the mixtures for performance evaluation.

Table 4: Chemical composition and characteristics of the materials used

Abbreviation	**Grain size-nominal dimensions (mm)**	**Proportion of mixtures (%)**
CTB	0/3	44
	3/8	21
	8/15	17
	15/20	18

A mixer with a capacity of 150 liters was used to manufacture the CTB mixtures in a laboratory environment with a temperature of 20°C and 50% relative humidity. After placing the mixed materials into molds on the vibrating table, they were vibrated for 1 minute after each layer. The specimens were removed after 24 hours and kept in water at 20°C until the testing age. The method for preparing the mixtures is illustrated in Figure 3.



Figure 3: Method for preparing the mixtures of CTB

The experimental program in this study involved conducting tests for fresh and hardened properties in accordance with the standards listed in Table 5. The testing of fresh concrete included the dry density–water content relationships were determined by conducting modified compaction tests on CTB materials in accordance with the ASTM standard [15]. It is noted that the sample was compacted in five layers in a 102 mm diameter by 127 mm high mold with the application of 56 blows per layer for the compaction testing. The compaction was carried out with a 4.5 kg hammer dropped from a height of 450 mm.

The testing of hardened CTB included the compressive strength, tensile strength, water absorption, porosity, thermal conductivity, and abrasion test. The compressive strength was measured in cubic specimens of 10x10x10 cm^3 at 3, 7 and 28 days of curing, according with Standard EN 196-1 [16]. All CTB specimens are subjected to tensile strength test was measured on prismatic specimens of 7x7x28 cm^3 at 3, 7 and 28 days of curing, this test was performed in accordance with Standard EN 196-1 [16]. In regards to the porosity accessible to water test, three cubic specimens 7x7x7 cm^3 from the were used to evaluate their porosity in water up to 28 days, according to the NF P18-459 [17]. The water absorption by immersion test was determined on CTB prismatic specimens of 7x7x28 cm^3, as per ASTM C642 [18]. After 28 days of curing, the specimens were dried in 105± 5˚C. the specimens were cooled down by natural heat loss after 24 hours of oven drying period. For about 24 hours, the specimens were immersed in normal curing water. The water absorption of the mixes shows the difference between saturated mass and oven-dried mass. Thermal conductivity is one of the means that are generally used with the aim to assess with precision the thermal characteristics of CTB. The thermal conductivity test was performed using the technique of the hot wire by CT-meter on prismatic specimens of 7x7x28 cm^3 according to Standard (NF EN 933-15)[19]. The abrasion resistance of the CTB studied was measured using the Cantabro test. This test determines the mass loss of a cylindrical specimen of similar diameter and height ($D = H$ = 10 cm). The test specimens are rotated in Los Angeles drum for 300 revolutions according to Standard (ASTM C1747) [20].

Table 5: Tests protocol

	Tests	**Specimen (mm)**	**Standards**
Aggregate	Grain size distribution	/	EN 933-1
	Density	/	EN 1097-3
	Water absorption	/	EN 1097-6
	Los Angeles (%)	/	EN 1097-2
	Sand equivalent	/	EN 933-8
	Methylene blue value	/	EN 933-9
CTB	Proctor compaction	Cylinder	ASTM
	Compressive strength	Cube (10*10*10 cm3)	EN 196-1
	Tensile strength	Prismatic (7*7*28 cm^3)	EN 196-1
	Water absorption	Prismatic (7*7*28 cm^3)	NBN B15-215
	Porosity	Cubic samples of (7*7*7)	NF P18-459
	Thermal conductivity	Prismatic (7*7*28 cm^3)	NF EN 933-15
	Abrasion test	Cylinder ($D = H$ = 10 cm)	ASTM C1747

4 Results and Discussion

4.1 Proctor Compaction

The variation of the dry density and water content for estimation of optimum water content (OWC) and maximum dry density (MDD) of the different mixtures are presented in Figure 4.

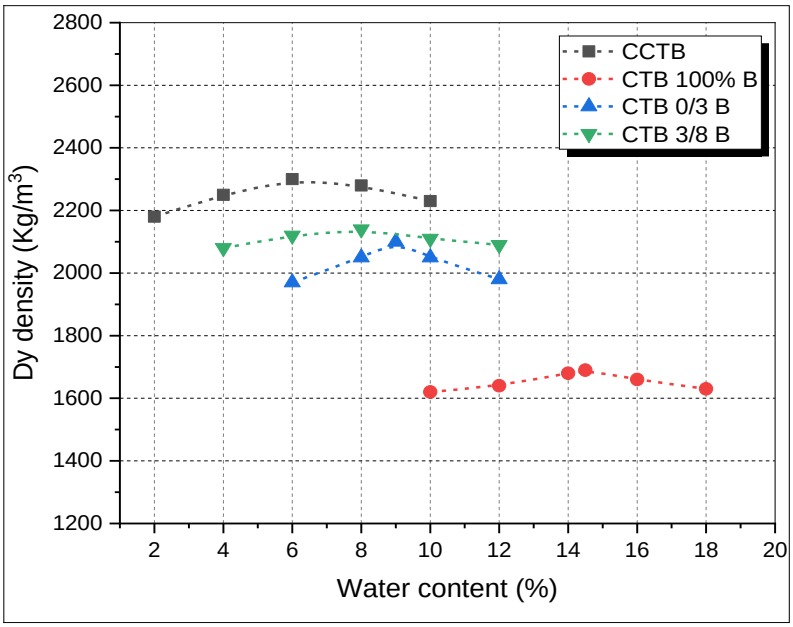


Figure 4: Variation of dry density with water content

The results of the compaction tests showed that the control mix (CCTB) had the highest MDD value of 2300 kg/m3 with the lowest OWC value of 6%. Partial replacement of NA with RBW resulted in a decrease in MDD, with CTB 3/8 B, CTB 0/3 B, and CTB 100% B showing approximately 7%, 9%, and 26% decrease in dry density, respectively, compared to CCTB. Conversely, the water content results showed an increase in OWC, with CTB 100% B showing the highest increase of about 59%, followed by CTB 0/3 B with a 33% increase, and CTB 3/8 B with a 25% increase, compared to CCTB. This suggests that the addition of crushed brick waste decreases MDD and increases OWC due to the lower density and higher water absorption capacity of crushed brick waste. Similar findings have been reported by other researchers [11, 12, 21], who have confirmed that the replacement of NA with RBW leads to an increase in OWC and a decrease in MDD. Additionally, Ajay et al. [22] showed that the incorporation of RBW content leads to the increase of porous crushed clay in the mixtures, which has significant water absorption capacity and may contribute to the slight increase in OWC with increased RBW content in the mixtures.

4.2 Compressive Strength

Figure 5 shows the variation on compressive strength of different CTB mixtures at 3, 7 and 28 days of curing.

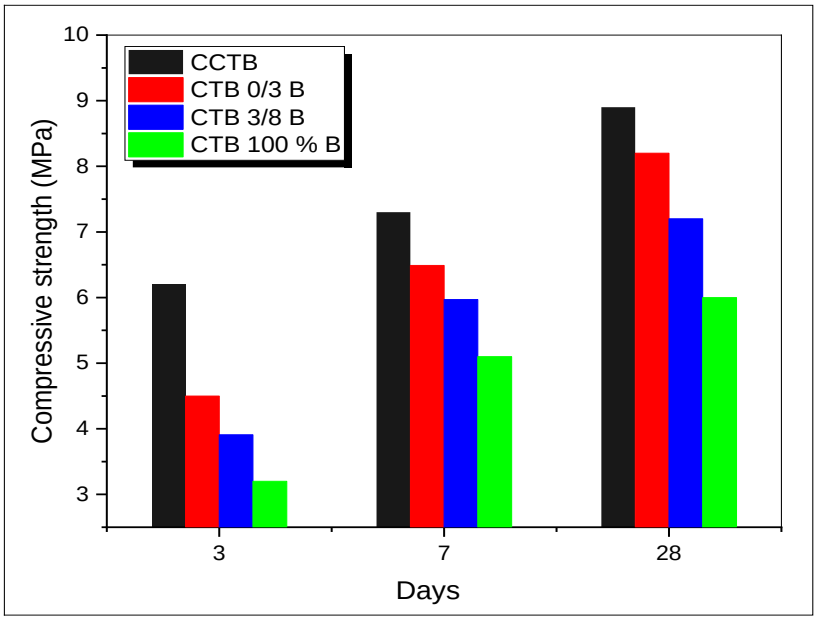


Figure 5: Compressive strength with CTB

The compressive strength results, as shown in Figure 4, revealed a decrease in strength for CTB 0/3 B, CTB 3/8 B, and CTB 100% B at all ages compared to CCTB. At 28 days, the decrease in compressive strength was approximately 8% for CTB 0/3 B, 19% for CTB 3/8 B, and 32% for CTB 100% B compared to CCTB. It was evident that the increase in size of recycled brick waste (RBW) materials had a negative effect on the strength values. This decrease in strength could be attributed to the higher porosity and water absorption of recycled aggregates, as reported by previous studies [23]. These findings are consistent also with other research [8]that showed a decrease in compressive strength of approximately 15% when RBW was used as a fine aggregate, 25% when used as a coarse aggregate, and 30% when used as both fine and coarse aggregate. According to the cement treated Base Guide [24], the minimum of the CTB compressive strength in 7 days is 2.1 MPa. The results indicate that all CTB mixtures achieved the minimum compressive strength, which allows them to be used.

The correlation between compressive strength values and porosity values was high (R^2 = 0.99) according to Figure 6, indicating that compressive strength of CTB mixtures was very sensitive to porosity, which increased with the use of RBW materials. This confirmed the relationship between porosity and compressive strength of CTB mixtures, with an increase in porosity leading to a decrease in compressive strength. This finding is consistent with the research by Christen et al. [3] that reported a decrease in resistance of concrete with increased porosity. The addition of highly porous RBW to the concrete mixture thus reduces its resistance, confirming the obtained results.

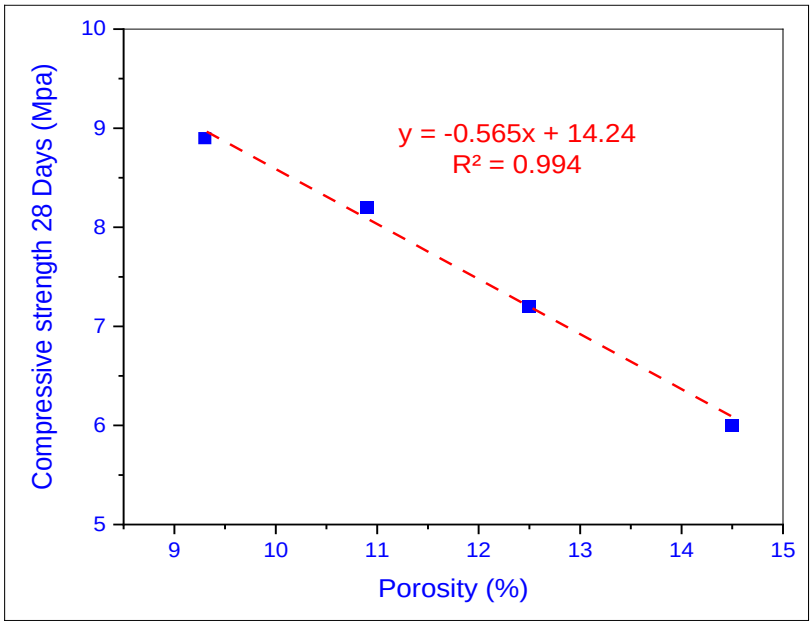


Figure 6: Correlation between compressive strength and porosity of CTB mixes

4.3 Tensile Strength

Figure 7 shows the variation on tensile strength of different CTB mixtures at 3, 7 and 28 days of curing.

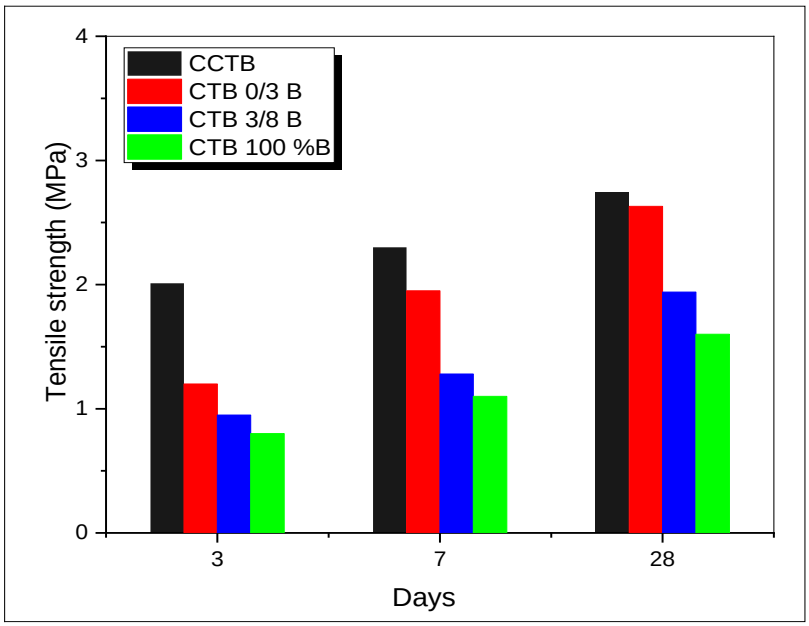


Figure 7: Tensile strength with CTB

The results of the tensile strength tests, as shown in Figure 7, revealed that CTB with 100% RAB materials experienced a significant decrease of approximately 42% compared to their reference CCTB. When RAB was used as a fine aggregate in the production of CTB 0/3 B, the

tensile strength decreased by about 5%. Similarly, when RAB was used as a coarse aggregate in the production of CTB 3/8 B, the tensile strength decreased by about 30%. Previous research [8] has attributed this degradation of resistance in mixtures with RBW to the low crushing resistance of RBW particles in comparison to natural aggregate particles.
The low resistance of RBW aggregates can be explained by their higher vacuum ratio and low solid ratio compared to natural aggregates, which weakens RBW aggregates in comparison to natural aggregates. According to the cement treated Base Guide [24], the minimum of the CTB tensile strength in 7 days is 0.7 MPa. The results indicate that all CTB mixtures achieved the minimum tensile strength, which allows them to be used.

4.4 Water Absorption by Immersion

Figure 8 illustrates the water absorption by immersion of various CTB mixtures after 28 days of curing.

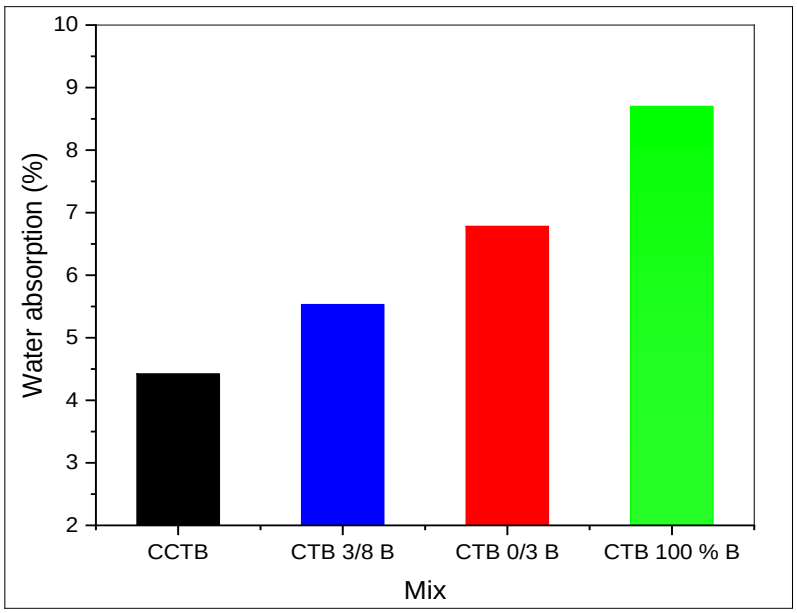


Figure 8: Water absorption by immersion of CTB at 28 days

The results show a gradual increase in absorption values with the use of RBW as gravel (3/8 mm), sand (0/3 mm), and total replacement of NA by RBW. The absorption values increased by 20%, 25%, and 45%, respectively, compared to the mixture using 100% natural aggregates. This trend can be explained by the increase in internal porosity caused by the use of RBW, which is characterized by its high porosity and greater water absorption compared to NA.
This finding is consistent with that of [7], who concluded that the porosity of RBW and its greater water retention will lead to greater water absorption in the RBW concrete.

4.5 Porosity

Figure 9 shows the effect of RBW on the porosity of all CTB mixtures.

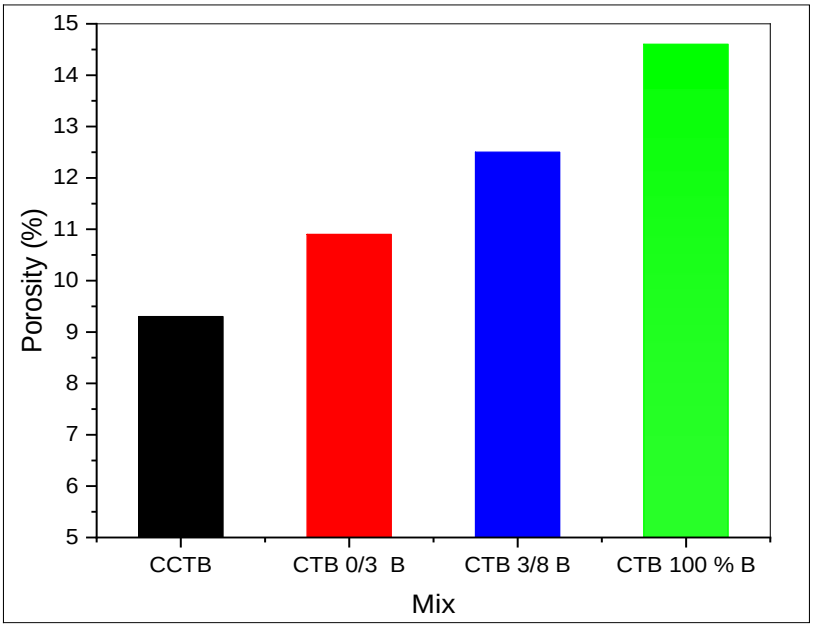


Figure 9: Porosity results of CTB samples at 28 days

The results indicate that porosity increased with the use of RBW. When RBW was used as sand (0/3mm) in CTB 0/3B, porosity increased by 17%. When RBW was used as gravel (3/8mm) in CTB 3/8B, porosity increased by 34%. The complete replacement of NA by RBA in CTB 100% B resulted in high porosity (about 56%) compared to the various mixtures of CTB. This increase in porosity occurred due to the use of recycled brick aggregates, which are characterized by a higher porosity than natural aggregates. This finding is consistent with the results reported by [3, 8] regarding the high porosity of RBW, which increases the overall porosity of the concrete mixture containing RBW.

Figure 10 shows Relationship between porosity and compressive strength of CTB mixtures.

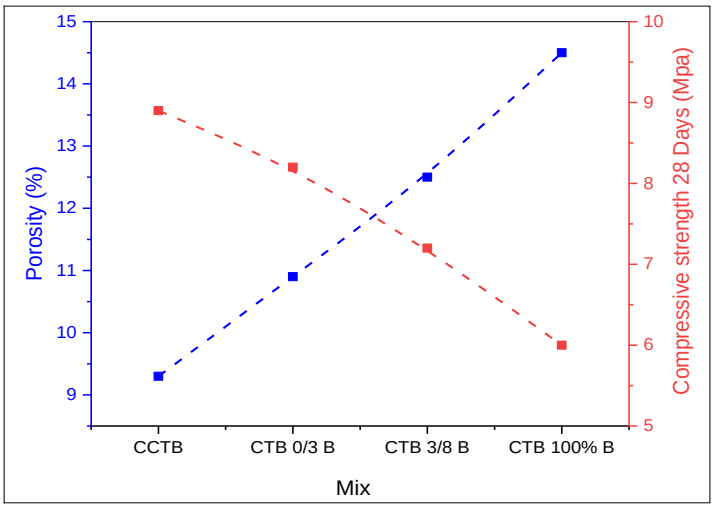


Figure 10: Relationship between porosity and compressive strength of CTB mixes

It can be observed that the compressive strength of CTB is highly sensitive to the porosity induced by the use of RBW materials. The tendency of compressive strength decreased as porosity increased.

4.6 Thermal Conductivity

The thermal conductivity results of the produced CTB are shown in Figure 11.

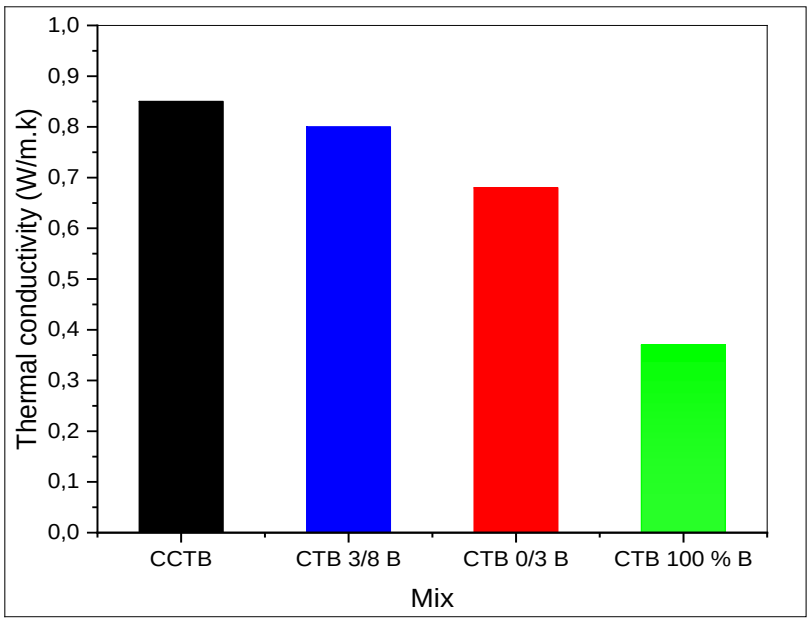


Figure 11: Thermal conductivity of CTB

The replacement of natural aggregates by recycled brick aggregates leads to a decrease in the thermal conductivity of CTB mixes, where when using RBW as gravel (3/8mm) and sand (0/3mm), the thermal conductivity values of CTB 3/8B and CTB 0/3B was less than CCTB by 6% and 20% respectively compared by CCTB, Thermal conductivity is reduced by more than 55% for a complete substitution of NA by RBW.

This result demonstrated that the type of aggregate has an important influence on the thermal conductivity of the CTB. This improvement in the thermal conductivity with the introduction of RBW is explained by low density and high porosity of RBA compared to NA [8, 25].

Atyia et al [8] reported the dry density and porosity is directly linked to the thermal conductivity of the concrete.

They are the main factors influencing the thermal properties of concrete. With increasing density, the porosity decreases, and thermal conductivity increases and vice versa.

Figure 12 shows the evolution of thermal conductivity and porosity as function of CTB mixtures.

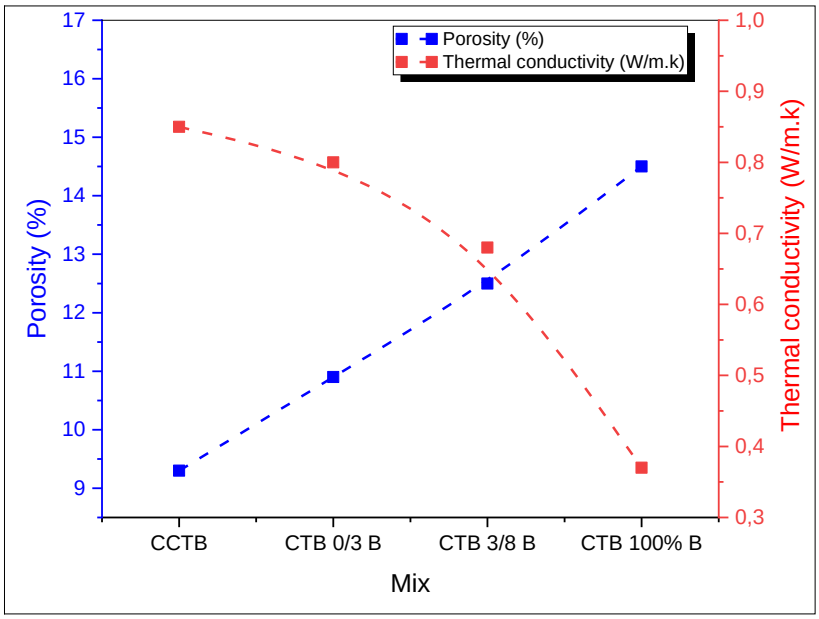


Figure 12: Relationship between porosity and Thermal conductivity of CTB mixes

Where the greater the porosity, the lower the thermal conductivity values and vice versa, which indicated that there is a direct relationship between them. The results also show that there is an equilibrium point between thermal conductivity and porosity for the CTB 3/8 B mixture.

4.7 Abrasion Tests (CANTABRO Loss)

The abrasion resistance test or Cantabro test was performed to estimate the internal cohesion among the particles. The samples were submitted to the Los Angeles drum without any balls, and the device was set to rotate for 200 cycles, in accordance with [20]. The variation in abrasion resistance evaluated by the Cantabro test of the different CTB mixtures studied is shown in Figure 13.

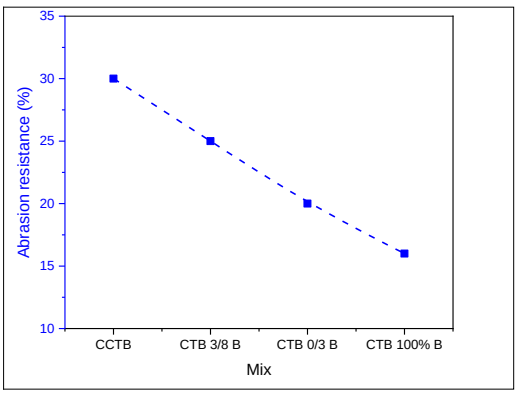


Figure 13: Abrasion test of CTB mixes

The CTB 3/8 B mix showed a reduction in abrasion loss of approximately 17% compared to the CCTB mix. However, the CTB 0/3 B and CTB 100% B mixes showed a reduction of 33% and 47%, respectively, in comparison to the CCTB mix. The abrasion resistance was affected in our case by the nature of the aggregates used. The mixes containing RBW showed higher abrasion resistance compared to the mixes containing NA. It can be concluded that good quality lightweight aggregates have better abrasion resistance.

4.8 SEM Analysis

To support the mechanical performance, scanning electron microscopy (SEM) analyses of CTB mixtures were performed, and the results are presented in Figure 14.

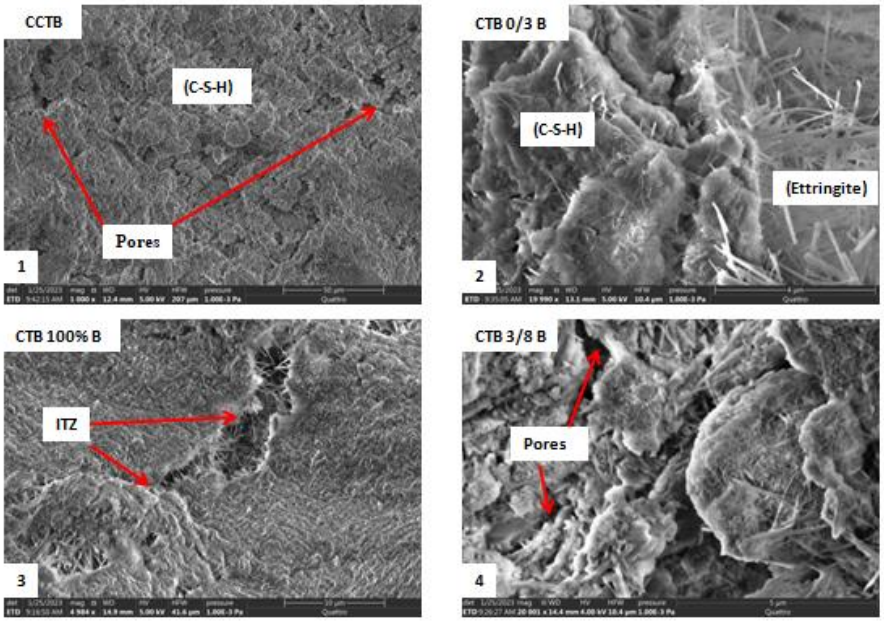


Figure 14: SEM images of CTB mixes : (1) CCTB; (2) CTB 0/3 B; (3) CTB 3/8 B; (4) CTB 100 % B

As shown in Figure 12 (1), the CCTB mix had a denser matrix with minimal porosity. However, when RBW was used as the fine aggregate (sand) in the CTB 0/3 B mix, as depicted in Figure 13 (2), new CSH hydrates were created due to the high pozzolanic impact of RBW particles. The use of RBW as a coarse aggregate in the CTB 3/8 B mix, as shown in Figure 13 (3), resulted in more pores compared to the CCTB mix due to RBW's effect on the internal bonding of particles. The CTB 100% B mix, produced by replacing NA entirely with RBW, revealed a smoother, looser surface and more pores in the microstructure, as depicted in Figure 14 (4).
These findings are consistent with the mechanical characteristics of the CTB mixtures and can be used to explain their performance. This result is in line with previous studies conducted by [4, 10, 26].

5 Conclusion

This study demonstrated that the use of recycled brick waste not only has a significant impact on road engineering but also contributes to global environmental protection. In addition, based on the analysis of the experimental results, the following conclusions can be drawn:

- The size of recycled brick waste particles significantly affects the characteristics and mechanical properties of the maximum dry density-optimum water content. The RBW (recycled brick waste) materials have lower densities and higher water absorption capacities than NA (natural aggregates).
- The compressive strength results indicate good performance for all CTB (cement treated base), highlighting the suitability of RBW to replace NA. The incorporation of recycled brick aggregates in the form of sand (0/3 mm) and gravel (3/8 mm) in CTB slightly decreases their mechanical performance.
- The use of RBW in the preparation of CTB considerably increases its ability to absorb water. CTB blends containing RBW are characterized by high porosities compared to CCTB.
- In addition, replacing natural aggregates with recycled aggregates improves thermal conductivity in the CTB.
- The incorporation of RBW significantly increases the porosity and total pore volume of CTB. The pozzolanic activity of fine RBW contributes to the improvement in the satisfactory compactness of ITZ between the fine RBW and cement matrix.
- CTB with RBW showed improvement in abrasion resistance compared to that in CTB made with 100% NA. Incorporating RBW in the form of gravel (3/8 mm), sand (0/3 mm), and 100% RBW in CTB led to increased abrasion resistance of 17%, 33%, and 47%, respectively.
- RBW is an interesting alternative as results indicate that all CTB mixtures containing RBW achieved minimum compressive and tensile strength, allowing them to be used in the field of road construction.

Overall, the results show that the mixes containing waste brick exhibit comparable mechanical characteristics and could be used in layers of pavement foundations. Additionally, the durability of these mixes yields better results compared to blends containing natural aggregates.

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