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Orginal Article

Impact of recycled aggregate brick on the physical-mechanical and environmental characteristics of cement treated bases

Youcef Toumi [1], Samy Mezhoud [2], Otmane Boukendakdji [3], Moussa Hadjadj [4]

[1] Department of Civil Engineering; Laboratory of Materials and Durability of Construction (LMDC); Faculty of Technology; University of Mentouri Constantine I; BP, 325 Route de Ain El Bey, Constantine 25000, Algeria; youcef.toumi@doc.umc.edu.dz ORCID: 0009-0004-3050-3642
[2] Department of Civil Engineering; Faculty of Technology; University of Mentouri Constantine I; BP, 325 Route de Ain El Bey, Constantine 25000, Algeria; mezhoud.sami@umc.edu.dz ; ORCID: 0000-0003-0441-8773
[3] Department of Civil Engineering; Laboratory Materials and Environment (LME); Faculty of Technology; University of Médéa; Hai Enacer; Urban Pole, Médéa 26000, Algeria; boukendakdji.othmane@univ-medea.dz ; ORCID: 0000-0003-1360-8149
[4] Department of Civil Engineering; Faculty of Technology; University of Médéa; Hai Enacer; Urban Pole, Médéa 26000, Algeria; hadjadj.moussa@univ-medea.dz ; ORCID: 0009-0007-2304-2712

Abstract: Recycled aggregate brick (RAB) constitutes a significant waste stream in developed countries, originating from brick manufacturing and demolition processes. This paper investigates the potential utilization of various sizes of RAB as replacements for natural aggregate (NA) in cement-treated bases (CTB), along with an assessment of their mechanical and environmental properties. The study includes a life cycle analysis to evaluate the environmental impacts of different CTB formulations. The novelty of this study lies in the environmental evaluation of four types of CTB, including natural, recycled, and mixed CTB. The physical and mechanical properties of the recycled brick and natural materials are characterized and compared. Results indicate that recycled brick aggregates, when combined with a cement mixture, can be used as a base and sub-base layer with good mechanical performance. Moreover, environmental analyses demonstrate that recycled aggregate generates fewer impacts than natural aggregates. Consequently, this study suggests that the utilization of recycled aggregates brick in CTB offers a sustainable waste management solution while simultaneously contributing to the reduction of environmental impacts associated with construction activities.

Keywords: Cement Treated Base, Life Cycle Analysis, Recycled Aggregate Brick.

1. Introduction

Pavements are an essential component of transportation infrastructure [1]. However, the construction and maintenance of pavements typically require significant amounts of virgin materials, leading to a depletion of natural resources. Consequently, there is a growing need to find efficient and sustainable ways to recycle and reuse waste materials in pavement construction [2].

The development and implementation of sustainable pavement practices can help reduce the environmental impact of construction and maintenance activities, while also promoting resource conservation [3]. The use of recycled materials, such as Reclaimed Asphalt Pavement and Recycled Concrete Aggregate, in pavement construction has shown promising results in terms of both mechanical performance and environmental benefits [4]. In the pursuit of pavement sustainability, researchers have explored the use of various recycled materials as replacements for conventional pavement materials. These materials include fly ash, bottom ash, recycled asphalt shingles, lignin, waste plastic, crushed brick, recycled glass, and crumb rubber [5]. While much of the research on recycled materials in pavement construction has focused on asphalt layers, the base and sub-base layers have greater potential to incorporate sustainable materials due to their larger thickness [6].

Recycled aggregates, including brick waste, have been investigated as viable options for waste utilization in road base and sub-base layers over the past two decades. Despite being the second most important building material after concrete, brick waste has been underutilized in the road field [7]. Previous studies have explored the use of crushed clay brick as aggregates in unbound sub-base materials. The results showed that the replacement of recycled concrete aggregates with crushed clay brick further increased the optimum moisture content and decreased the maximum dry density, leading to reduced CBR values [8]. Several other studies have investigated the potential use of crushed brick as a substitute for natural aggregates in concrete and pavement sub-base applications. Debieb and Kenai [9] found that concrete containing up to 25% and 50% crushed brick as coarse and fine aggregates, respectively, can exhibit similar characteristics to natural aggregate concrete. Arulrajah et al. [10] conducted extensive laboratory testing on recycled crushed brick as a pavement sub-base material, finding that it may need to be blended with other recycled aggregates to improve its durability.

Furthermore, Arulrajah et al. [11] investigated the mechanical properties of recycled concrete and crushed rock aggregate mixtures that incorporated crushed brick. They found that crushed brick had a marginal effect on the mixtures' mechanical properties, but had a significant effect on dry density and moisture content. Cameron et al. [12] presented the technical characteristics of mixtures of recycled crushed clay masonry and recycled concrete aggregate in unbound pavements, finding that a high substitution of aggregates with recycled clay masonry reduced the maximum dry density and increased the optimum moisture content compared to using only recycled concrete aggregate. One challenge with using crushed brick aggregates is their low particle density compared to natural aggregates.

In addition, Diagne et al. [13] found that RAB has low particle density and high porosity, resulting in an increase in Micro-Deval (MDE) and Los Angeles (LA) coefficients when mixed with recycled crushed aggregate. However, the resilient modulus and constrained modulus decrease with an increase in the percentage of RAB and the number of freeze-thaw cycles. The study also showed that water drainage is faster with an increase in RAB percentage due to larger pores. Zhao et al. [14] tested the properties of lightweight aggregate concrete made from used clay bricks and found that it meets the standard requirements for lightweight aggregate concrete. The compressive strength and static modulus of elasticity of the concrete were also found to be suitable for structural requirements of Chinese standard (JGJ 51). Zhang et al. [15] investigated the performance of cement-stabilized recycled mix containing RAB as of the sub-base of expressways. They found that the mechanical properties of the mixes change linearly with a ratio of RAB. Atyia et al. [16] investigated the use of RAB as a substitute for cement and aggregates in concrete production. The study found that RAB can be used to obtain lightweight structural concrete with suitable properties and that ground RAB can be used as a supplementary cementitious material to reduce cement content without significant deterioration of the concrete properties. Overall, these studies demonstrate the potential for using recycled clay bricks and concrete aggregates in road construction and concrete production with careful consideration of their effects on mechanical and physical properties.

When it comes to Life Cycle Assessment (LCA), this method is widely used to quantify the environmental impacts associated with the production of sustainable infrastructure systems over their life cycle [17]. Although LCA has been employed for environmental assessment of various products and processes since the 1980, its application in infrastructure systems is still in its early stages [18]. To estimate the environmental impacts of pavements, several studies have been conducted using LCA. Sudarno et al. [19] evaluated the energy consumption and greenhouse gas emissions resulting from the implementation of the former asphalt pavement aggregate blended with cement, while Kua and Kamath [20] studied the environmental impacts of replacing concrete with brick. Serres et al. [21] proposed to quantify the environmental impacts of three concretes, and Yuan et al. [22] conducted a comparative study of the environmental and economic impacts of concrete and permeable pavement brick using LCA. Khelifa et al. [23] used LCA to study the environmental and mechanical properties of Alfa fibres and polypropylene fibres in fibrous concrete, while Bressi et al. [24] presented a comparative evaluation of the environmental performance of sixteen CTB mixes with and without reclaimed asphalt pavement, with different percentages of cement. The analysis suggests that higher cement percentages in the CTB mix offset the increased environmental burdens associated with cement production and transportation. Including RAB in the mix leads to greater dispersion of LCA results. Overall, LCA is a valuable tool for quantifying and addressing the environmental components of producing sustainable infrastructure systems, but its application in this field is still in its early stages, and more research is needed to fully understand it's potential.

Therefore, the objective of this research is to analyze the effect of varying granular fractions of (0/3) mm and (3/8) mm, as well as 100% RAB aggregates, on the mechanical and environmental properties of cement-stabilized recycled mix used as a base course in road construction. The aim is to determine the optimal fraction of RAB that can be used in such mixes while maintaining satisfactory mechanical and environmental performance.

2. Experimental procedure

2.1. Materials

In this study, Portland cement (CEMII/B 42,5 N) was used to prepare all mixes, as it complies with the (EN 197-1) [25] standard and has a density of 3100 kg/m^3. Tab. 1 shows the chemical and mineralogical composition of the cement used. Two types of aggregates were used in this study, NA and RAB. The NA were sourced from the Tamolgha region in the North of Algeria and consisted of crushed sand (0/3) and crushed gravels (3/8, 8/15, and 15/20 mm) with a measured density of about 2700 kg/m^3. The RAB were obtained from the waste of fired brick from the brick factory of Medea in the North of Algeria and included recycled brick sand with a granular class of 0/3 mm and recycled brick gravel with a granular class of (3/8, 8/15, and 15/20 mm). Tabs 2-3, and Figs 1-2 present the physical and chemical properties of all aggregates. Fig. 3 shows the sizing curves of used aggregates. Drinking water was used in this study, and while no analysis was conducted, it was assumed clean and suitable for consumption.

Table 1. Chemical and mineralogical composition of Portland cement. *Source*: own study

SiO_2 (%)	CaO (%)	Al_2O_3 (%)	Fe_2O_3 (%)	MgO (%)	SO_3 (%)	L.I (%)	K_2O (%)	CaO_{Free} (%)	Na_2O (%)
23.83	56.35	6.05	4.66	2.44	2.37	2.23	0.83	0.66	0.58

C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	CaO free (%)	Gypsum (%)	Addition phase (%)
45	18	11	8	1	5	12

Table 2. Details of granular fraction of natural and recycled aggregate brick. *Source*: own study

Particle size (mm)	0-3	3-8	8-15	15-20
Natural Aggregates				
Recycled aggregate brick				

Table 3. Physical properties of aggregates. *Source*: own study

Test items	Natural aggregates (mm)				Recycled aggregate brick (mm)				Standards
	0/3	3/8	8/15	15/20	0/3	3/8	8/15	15/20	
Bulk density (kg/m^3)	1570	1390	1380	1430	1073	930	1000	980	EN 1097-3
Absolute density (kg/m^3)	2690	2590	2610	2650	2340	2280	2150	2000	EN 1097-3
Water absorption (%)	3.5	2.0	1	0.5	18.2	16.8	14.1	10.2	EN 1097-6
Los Angeles (%)	/	32.2	26.0	28.4	/	34.2	23.7	30.2	EN 1097-2
Flattening (%)	/	28	19.3	13.3	/	19.4	8.0	13.6	NF P 18-541
Sand equivalent (%)	78	/	/	/	69.1	/	/	/	EN 933-8
Voids (%)	43	48	48	46	54	59	53	51	NF P 18-555
Compactness (%)	57	52	52	54	46	41	47	49	NF P 18-555

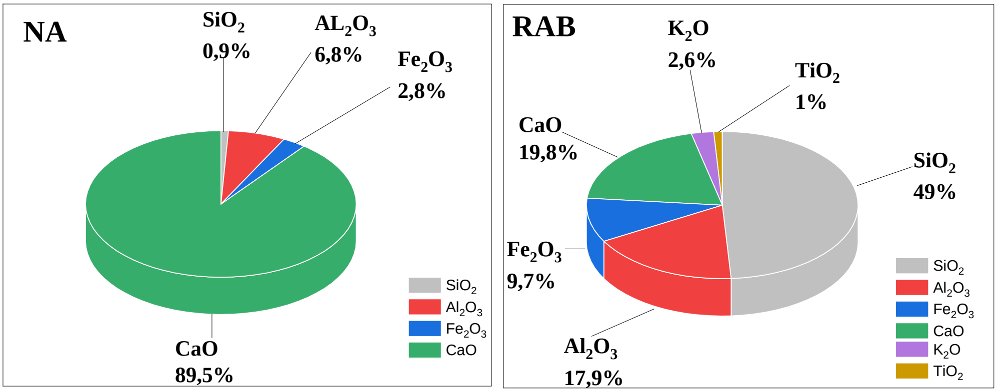


Fig. 1. Chemical composition of aggregates. *Source*: own study

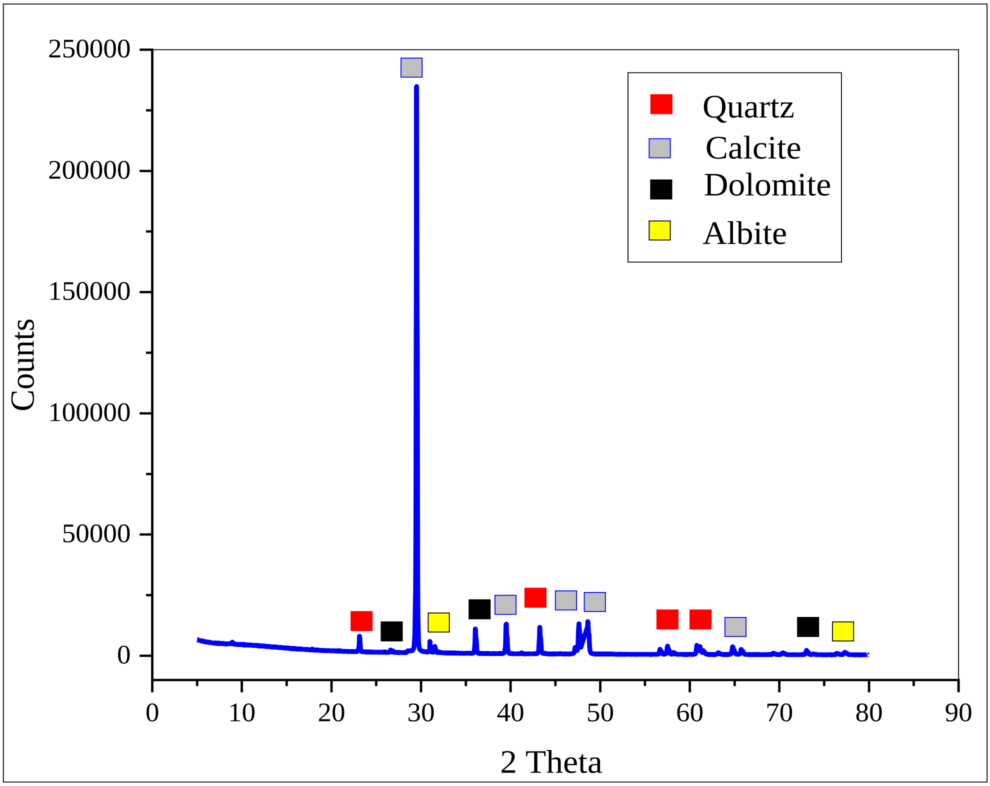
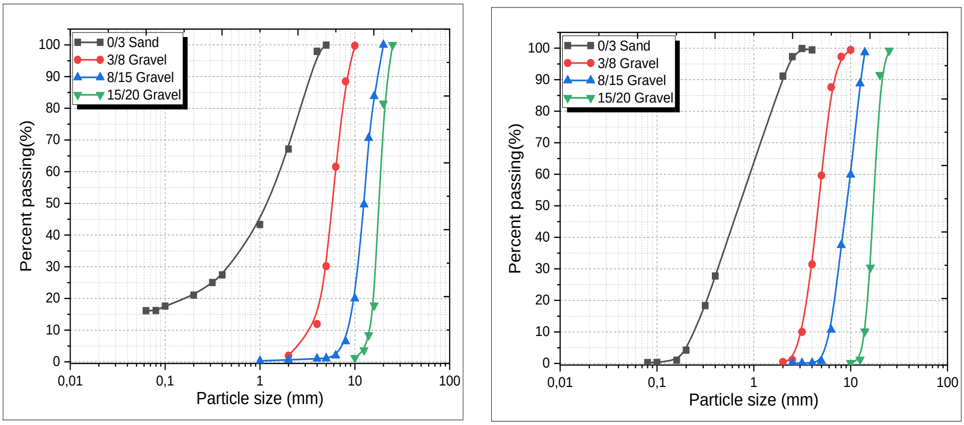


Fig. 2. Mineralogical composition of natural aggregate. *Source*: own study



a) b)

Fig. 3. Size distribution of: a) natural, and b) recycled aggregates. *Source*: own study

2.2. Microstructure of aggregates

In this study, the microstructure of RAB (sand and gravel) was investigated using Scanning Electron Microscopy (SEM). The SEM micrographs presented in Figs 4-5 revealed that RAB have a smooth and loose structure, with larger and more numerous pores compared to NA. These structural differences in RAB could contribute to its higher water absorption capacity, as reported by Zhao et al. [14], who also observed similar results.

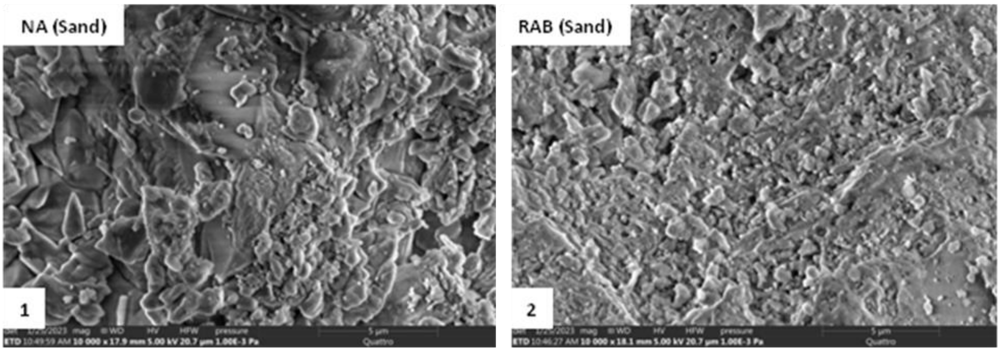


Fig. 4. SEM images of sand : (1) natural sand; (2) recycled brick sand. *Source*: own study

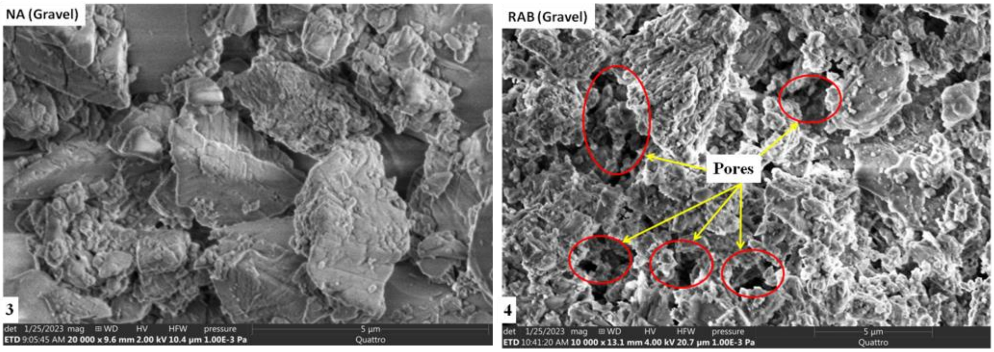


Fig. 5. SEM images of gravel: (3) natural gravel; (4) recycled brick gravel. *Source*: own study

2.3. CTB samples and testing procedure

Samples of CTB were studied and formulated according to the NF EN 14227-1 standard [26]. Four samples were prepared with a cement fixed percentage of 6%, with water amount similar to the optimal water amount determined through Proctor modifier test. Tab. 5 shows the quantities of materials used in each mixture. The samples consisted of natural aggregate treated with cement (CCTB), cement-treated with RAB (CTB 100%B), RAB fraction 0/3 with the remaining fractions natural aggregate (CTB 0/3B), and RAB fraction 3/8 with the remaining fractions NA (CTB 3/8B).

The CTB mixtures were manufactured in a laboratory environment at 20°C and 50% of relative humidity, using a mixer of 150 L capacity. The mixed materials were placed in molds fixed on the vibrating table, and were vibrated for 1 minute after each layer. After 24 hours, the specimens were removed and kept in water at 20°C until the testing age. The composition of a reconstituted granular mix should be carefully selected to ensure that its granularity aligns with the specification range outlined in standard NF EN14227-1. The weights assigned to each fraction to achieve the median curve are presented in Tab. 4.

Table 4. Sample formulations. *Source*: own study

Abbreviation	Grain size (mm)	NA	RAB	Proportion (%)
CCTB	0/3	X		44
	3/8	X		21
	8/15	X		17
	15/20	X		18
CTB 100% B	0/3		X	44
	3/8		X	21
	8/15		X	17
	15/20		X	18
CTB 0/3B	0/3		X	44
	3/8	X		21
	8/15	X		17
	15/20	X		18
CTB 3/8B	0/3	X		44
	3/8		X	21
	8/15	X		17
	15/20	X		18

Tests were performed on the CTB mixes in both fresh and hardened states. Fresh concrete tests included Modified Proctor compaction tests according to ASTM standards [27]. The compaction was carried out with a 4.5 kg hammer dropped from a height of 450 mm into a mold with a diameter of 102 mm and a height of 127 mm.

Hardened CTB experiments included compressive strength, tensile strength, modulus of elasticity, California bearing ratio (CBR), and ultrasonic pulse velocity (UPV) tests. Compressive strength tests were conducted on cubic specimens of 10x10x10 cm^3 at the age of 3, 7, and 28 days according to (EN 196-1: 2002) [28]. Tensile strength tests were performed on prismatic specimens of 7x7x28 cm^3 at the age of 3, 7, and 28 days according to (EN 196-1: 2002) [28]. The modulus of elasticity was tested on cylindrical specimens (D= 16cm, h=32cm) at the age of 28 days according to ISO 1993 [29]. Post-dip CBR tests were performed on samples prepared at optimum points, using the modified Proctor compaction effort and tested after four days of soaking according to EN 2021 [30]. UPV tests were "carried out on cubic specimens of 10x10x10 cm^3 to evaluate the homogeneity and porosity of the specimens, according to ASTM C597-16 [31], and using the following equation: UPV = L/T, where “V” is ultrasound speed (m/s), “L” is sample length in meters, and “T” is the duration of ultrasound time in seconds.

2.4. Environmental assessment

In accordance with ISO 14040-14044 standards, a life cycle assessment (LCA) was conducted to evaluate the environmental performance of the various CTB mixtures. The functional unit (F.U.) for the study was defined as one ton of CTB, and the comparison was carried out using Open LCA software and the Impact 2002+ assessment method. This method allows for the results of both midpoint and endpoint approaches to be obtained and is a compromise between the two. It was obtained by combining the CML and Eco Indicator 99 methods and divides the results into 14 intermediate impact categories, including human toxicity, respiratory effects, ionizing radiation, ozone depletion, and other. These categories are then assigned to four damage categories: Human Health, Ecosystem Quality, Climate Change, and Resources [32]. The purpose of the study was to provide a comprehensive comparison of the environmental performance of various CTB mixtures used in road pavement structures.

3. Results and interpretation

3.1. Microstructure of CTB mixes

The microstructure of the CTB produced with RAB was examined using SEM analysis after 28 days of curing, and the results are presented in Fig. 6.

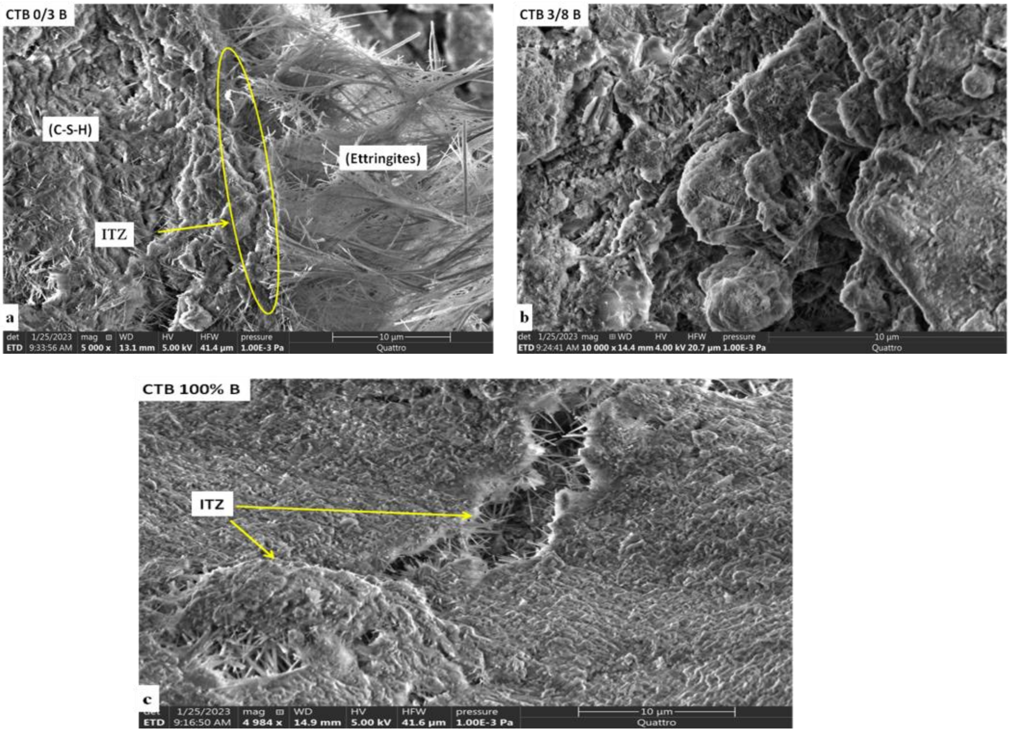


Fig. 6. SEM images of CTB mixtes: (a) CTB0/3 B ;(b) CTB3/8 B ;(c) CTB100% B. *Source*: own study

The chemical composition analysis of RAB showed a higher amount of SiO_2 and Al_2O_3 compared to NA. This increase affects the processes of hydration and the formation of the CTB structure by leading to a more pozzolanic reaction between SiO_2 and Al_2O_3 in RAB and Ca(OH)2 produced by cement hydration, resulting in the formation of a gel (CSH). SEM micrographs in Fig. 6 (a) indicate that the CTB 0/3 B mixture exhibited a stronger interfacial transition zone (ITZ) between the aggregates and cement paste, resulting in more CSH production. On the other hand, SEM micrographs of the CTB 3/8 B and CTB 100% B mixtures revealed a smoother and looser surface and a larger number of pores in the microstructure, which can explain the lower mechanical properties of these mixtures. This finding is consistent with previous studies conducted by Hou et al. [33].

3.2. Results of modified Proctor's

The study involved the use of Modified Proctor's test to investigate the dry density and water content of different CTB mixtures. The results are shown in Fig. 7.

The results showed that the density decreased by about 7%, 9% and 26% for CTB 3/8 B, CTB 0/3 B and CTB 100% B respectively compared to CCTB. In contrast, the moisture content increased when 100% RAB was used, with an increase of about 59% compared to CCTB. This moisture content also increased by up to 33% and 25% when 100% fine fraction (0/3) of RAB and 100% fraction (3/8mm) of RAB were used, respectively. The use of RAB led to an increase in the optimum moisture content and a decrease in the maximum dry density, likely due to the high water absorption and low density of the RAB particles.

Additionally, the irregular shape of the RAB particles may have increased the amount of voids inside the material and led to a decrease in the maximum dry density. These findings are consistent with previous studies conducted by Poon et al.[8], Hu et al.[34].

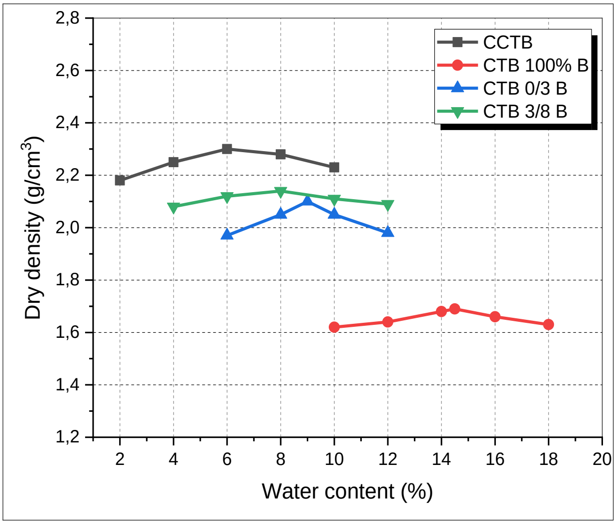


Fig. 7. Modified Proctor's test results of CTB mixes. *Source*: own study

3.3. Results of compressive strength

The results of the compressive strength at different ages (3, 7, 28 days) for the different CTB mixes are shown in Fig. 8.

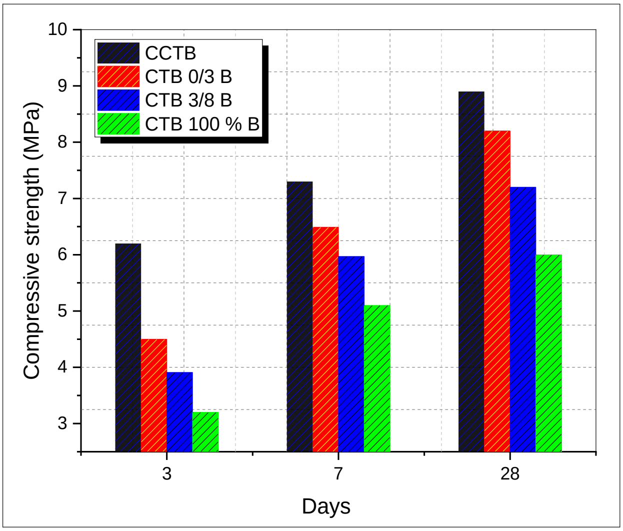


Fig. 8. Compressive strength of CTB mixes. *Source*: own study

It can be seen that the addition of recycled brick sand 0/3 and recycled brick gravel 3/8 decreases the compressive strength by about 9% and 19% respectively, compared to the CCTB. The CTB 100% B mixes give the lowest strength compared to the other mixes. The reason for the reduction in compressive strength of CTB with RAB is due to the lower density of RAB. Meanwhile, its higher porosity could promote the consumption of water during mixing, which increased the water/binder ratio in the design of the mix. resulting in a reduction in compressive strength and flattened shape that causes poor adhesion between the NA, RAB and cement matrix, which thus creates a weak interface zone. This result has been confirmed by other researchers Poon et al.[8], Hu et al.[34], Aliabdo et al.[35], Atyia et al.[16].

3.4. Results of tensile strength

The evolution of tensile strength by flexion of the different CTB manufactured with and without RAB materials at 3, 7 and 28 days is represented in Fig. 9.

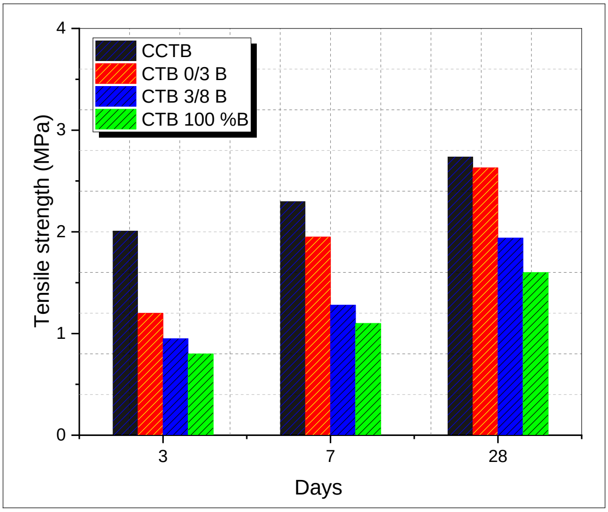


Fig. 9. Tensile strength of CTB mixes. *Source*: own study

The addition of RAB to CTB mixtures decreased the tensile strength of CTB 0/3 B and CTB 3/8 B by 5% and 30%, respectively, at 28 days compared to CCTB. The use of 100% RAB decreased tensile strength by 42%. Tensile strength was found to depend mainly on the cohesion of the mixtures and less on the strength of the aggregated particles [34]. The surface of RAB was less rough than NA, which adversely affected tensile strength. CTB 0/3B with RAB as fine aggregate showed a higher rate of tensile strength development between 3 and 28 days due to its pozzolanic action between its active silica and alumina and the cement hydration products.

3.5. Results of modulus of elasticity

The modulus of elasticity of the CTB varies in the same way as the compressive strength and the results are presented in Fig. 10.

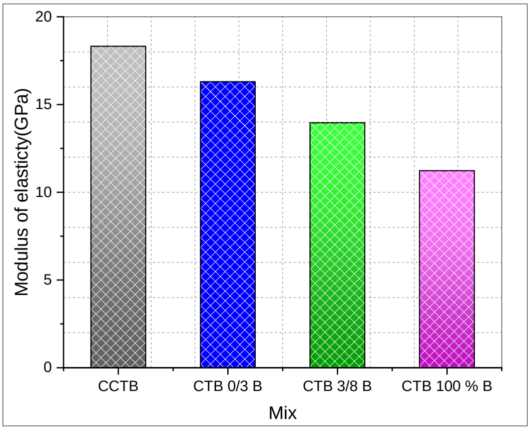


Fig. 10. Modulus of elasticity of CTB mixes. *Source*: own study

It can be seen that the modulus of elasticity at 28 days decreased with the replacement of fine aggregate (0/3 mm) and coarse aggregate (3/8 mm) and total replacement (100% RAB) respectively, and the maximum value of 28 days was 18.32 GPa, the minimum value of 28 days was 11.23 GPa. The decrease in 28-day modulus of elasticity in the fine (0/3mm) and coarse (3/8) and 100% aggregate replacement levels was 12%, 24%, and 39%, respectively, compared to the mixes using 100% NA. This decrease in modulus of elasticity due to the higher porosity of the RAB compared to the NA. The material with higher porosity always has a greater potential for deformation under load. This finding is consistent with previous studies [9], [34].

Fig. 11 shows a strong correlation ratio (R^2>92 %) between the values of the modulus of elasticity of the cured mixtures and the values of the UPV which indicated that there is a direct relationship between the last two. This figure shows that the UPV is very dependent on the modulus of elasticity. When the modulus of elasticity increases, the UPV value increases as well.

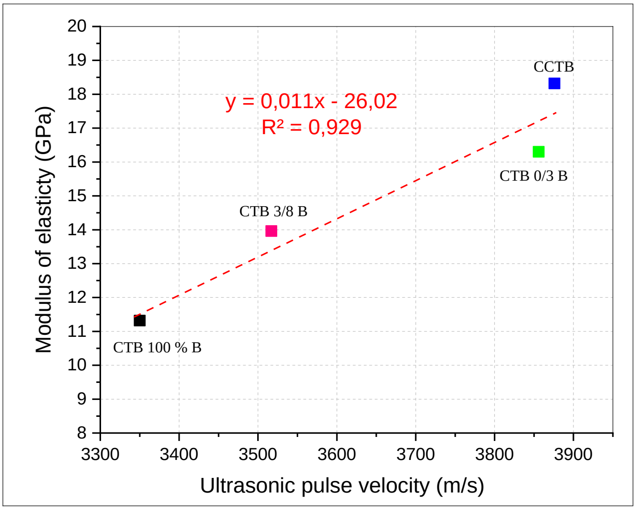


Fig. 11. Correlation between modulus of elasticity and UPV of CTB mixes. *Source*: own study

3.6. Results of California bearing ratio (CBR)

The cement-treated base mixes were subjected to CBR tests after being compacted to their corresponding optimum moisture content. The CBR tests were performed under soaked conditions for 4 days and the results are summarized in Fig. 12.

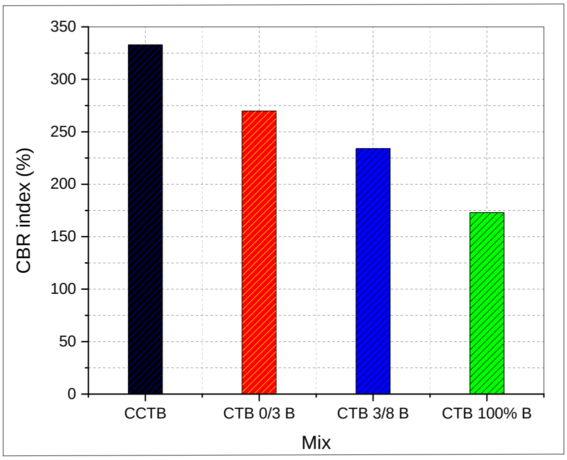


Fig. 12. CBR values of CTB mixes. *Source*: own study

The use of RAB in CTB mixtures decreased the CBR index. The CBR index of CTB 100% B was 46% lower than that of CCTB. The replacement of NA with RAB in fine (0/3) mm and coarse (3/8) aggregates levels decreased the CBR index by 30% and 50%, respectively, compared to the mix using 100% NA. This decrease was due to the lower mechanical properties of RAB and the lower density of cement treated bases RAB compared to CCTB. This finding is consistent with previous research by Poon and Chan [8]. In term of CTB classes, Caltrans [37] manual provides specifications based on the California load-bearing capacity index (CBR). The CTB classes range from Class 1 to Class 4, with each class having specific requirements for CBR values and other performance characteristics. These specifications help ensure the appropriate design and construction of CTB layers in transportation projects, considering the soil conditions and load-bearing capacity needed for safe and durable infrastructure. The CTB classes are categorized as follows: 1. Class 1 CTB, designed for heavy-duty traffic, typically with CBR values above 100%; 2. Class 2 CTB is suitable for moderate to heavy traffic loads, with CBR values ranging from 80% to 100%; 3. Class 3 CTB is Intended for moderate traffic loads, with CBR values between 50% and 80%; and 4. Class 4 CTB designed for light to moderate traffic, with CBR values ranging from 30% to 50%. It appears clearly that the use of RAB materials in CTB can provide materials suitable for heavy-duty traffic and high-stress conditions. The incorporation of RAB can enhance the strength and performance of CTB, making it suitable for applications with significant traffic loads and demanding conditions.

3.7. Results of ultrasonic pulse velocity (UPV)

Fig. 13 represents the different values of the UPV of sound for the different CTB made at 28 days of age.

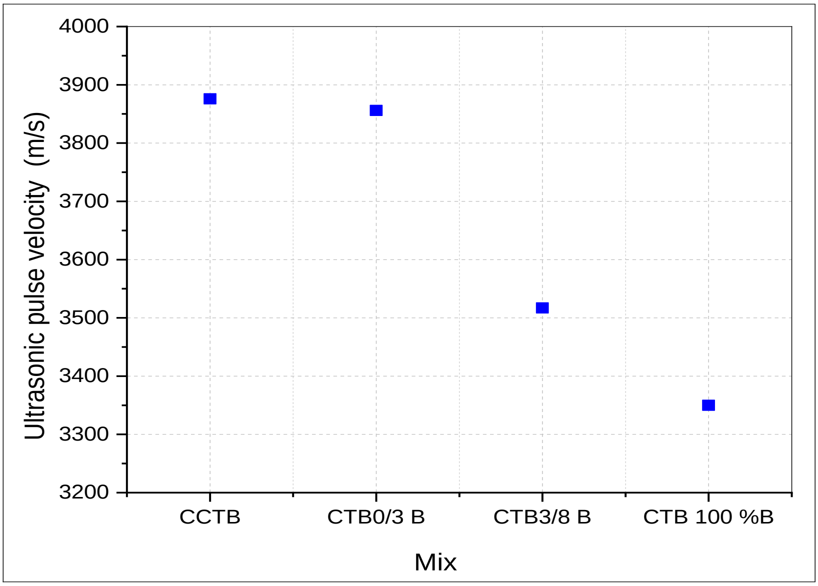


Fig. 13. Ultrasonic pulse velocity of CTB mixes. *Source*: own study

The use of RAB as sand (0/3mm), gravel (3/8) or as a total replacement of NA in CTB mixtures resulted in a decrease in UPV values. The UPV values of CTB mixtures decreased due to the higher porosity of RAB compared to NA. This finding is consistent with previous research by Atyia et al. [16].

3.8. Environmental comparisons of CTB mixes

Based on the Impact 2002+ method, the environmental impact distribution results for the four CTB blends studied were compared in Fig. 14 and Tab. 5. The findings suggest that all the environmental impact indicators are lower for CTB 100% B, CTB 0/3 B, and CTB 3/8 B compared to CCTB, respectively. This indicates that the incorporation of RAB (sand and gravel) in the CTB formulation is highly beneficial for its environmental performance. As the percentage of RAB increases compared to NA in the mix design, the environmental impact decreases. The CTB 100% B, CTB 0/3 B, and CTB 3/8 B mixtures respectively exhibit lower environmental impacts compared to CCTB, as these samples are formulated fully or partially with RAB aggregates. This eliminates the need to extract and transport raw materials from a quarry, thereby reducing organic emissions and dust emissions into the air. These findings are consistent with the studies of other researchers, such as Kua et al. [20], Serres et al. [21], Yuan et al. [22] which confirmed that the use of recycled aggregates is effective in reducing environmental impacts.

However, some few indicators, specifically non-renewable energy, ozone layer depletion, respiratory inorganics, respiratory organics, and terrestrial acid/nutri, exhibit an increased negative impact on the natural environment for the CTB 3/8 B mixture, either equal to or greater than CCTB. This could be attributed to the production process or the handling of recycled aggregates, which may result in additional emissions. It is important to acknowledge that these values are based on the provided figures and may vary depending on regional specificities, industry practices, and other local factors.

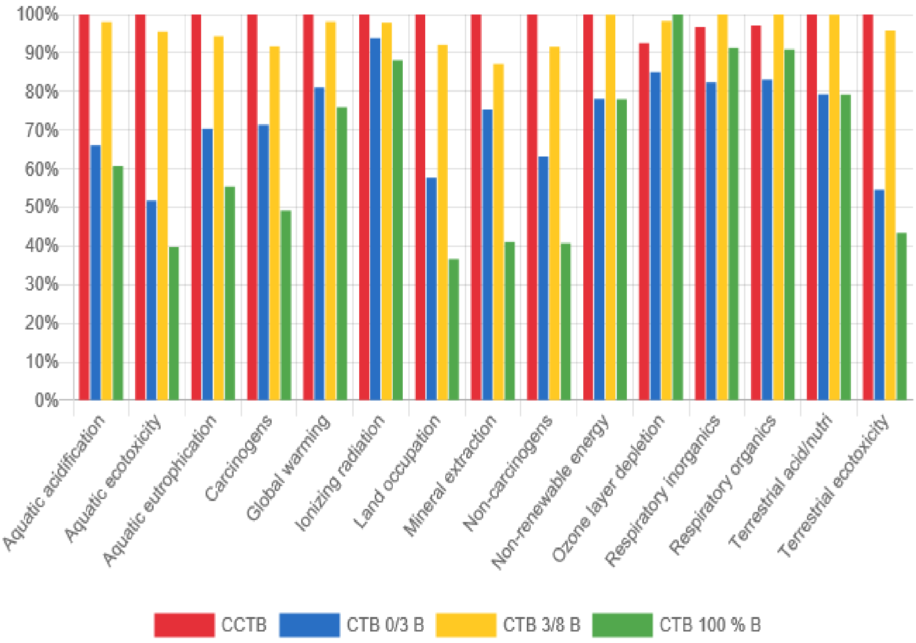


Fig. 14. LCA results of the CTB mixes. *Source*: own study

Table 5. LCA results of the CTB mixes. *Source*: own study

Impact category	Reference unit	CCTB	CTB 3/8 B	CTB 0/3 B	CTB 100 B
Aquatic acidification	kg SO2 eq	0.28	0.27	0.18	0.17
Aquatic ecotoxicity	kg TEG water	5028.93	4802.01	2602.47	1997.30
Aquatic eutrophication	kg PO4 P-lim	0.0072	0.0068	0.0051	0.0040
Carcinogens	kg C2H3Cl eq	0.32	0.29	0.23	0.16
Global warming	kg CO2 eq	72.46	71.07	58.73	55.03
Ionizing radiation	Bq C-14 eq	519.90	508.73	487.74	457.96
Land occupation	m2org.arable	0.98	0.90	0.56	0.36
Mineral extraction	MJ surplus	1.03	0.89	0.77	0.42
Non-carcinogens	kg C2H3Cl eq	0.54	0.50	0.34	0.22
Non-renewable energy	MJ primary	525.65	525.48	410.58	410.12
Ozone layer depletion	kg CFC-11 eq	3.34E-06	3.54E-06	3.07E-06	3.61E-06
Respiratory inorganics	kg PM2.5 eq	0.056	0.058	0.048	0.053
Respiratory organics	kg SO2 eq	0.015	0.015	0.012	0.014
Terrestrial acid/nutri	kg SO2 eq	1.263	1.262	1.001	0.999
Terrestrial ecotoxicity	kg TEG soil	1639.56	1570.74	895.08	711.56

3.9. Conditions of use of CTB in road techniques

The conditions for using CTB in road construction may be put into two categories. The mechanical class of the mix design indicates the usage of CTB in treated sub-base, derivative from the European standard NF EN 14227-1[26]. The compressive strength at 28 days determines the mechanical class. To assess the acceptability of the CTB mixture, the obtained compressive strength values should be compared to the classes listed in Tab. 6. Second, Halsted et al. [36] Guide to Cement-Treated Base gives the usual parameters of CTB material, demonstrating the appropriateness for road technology usage for all mixes with a 6% cement content.

Table 6. Results of the CTB mixes. Source: own study.

CTB mixes	Compressive strength at 28 days MPa	Strength class
CCTB	8.8	$C_{8/10}$
CTB 0/3 B	8.2	$C_{8/10}$
CTB 3/8 B	7.2	$C_{8/10}$
CTB 100 % B	6	$C_{5/6}$

4. Conclusions

The purpose of this study was to investigate into the mechanical and ecological implications of adding RAB, such as sand and gravel, into CTB for sustainable solid waste management, natural resource conservation, and environmental protection. The following inferences can be made in light of the results:

1. In comparison to NA, our findings indicate that RAB have lower density, increased water absorption, and porosity.
2. The chemical composition analysis of RAB showed a higher amount of SiO_2 and Al_2O_3 compared to NA. This increase leads to a more pozzolanic reaction between SiO_2 and Al_2O_3 in RAB and Ca(OH)2 produced by cement hydration, resulting in the formation of a gel (CSH).
3. As a result of the low density and high RAB absorption, including RAB in the form of gravel (3/8 mm) and sand (0/3 mm) in the CTB causes a drop in maximum dry density and an increase in optimal moisture content, respectively.
4. Furthermore, substituting fine RAB (0/3 mm), coarse RAB (3/8 mm), and complete NA with RAB resulted in compressive strength reductions of 9%, 19%, and 33%, respectively, due to RAB lower density and increased porosity.
5. A slight decrease in tensile strength of about 2% at 28 days was observed when replacing natural sand (0/3 mm) with fine RAB (0/3 mm) due to the amount of fines existing in RAB from its pozzolanic action.
6. The modulus of elasticity decreased compared to mixes containing NA.
7. Microstructural studies using SEM revealed that RAB have good pozzolanic reaction because of more CSH.

Overall, the previous experimental results indicate that although the use of RAB shows less performance than NA, it still has appreciable performance and may be encouraged for use in the road field, especially considering its lower environmental impacts compared to NA.

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