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Recycling of Brick and Road Demolition Waste in the Production of Concrete

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Abstract

Construction and public works sites generate a significant amount of waste that is often costly to dispose of. To reduce the environmental impact and promote sustainability, recycling and recovering this waste is increasingly being recognized as a viable solution. This paper presents the findings of an experimental program investigating the feasibility of using brick and road demolition waste as concrete components. By substituting a portion of sand and cement with recycled materials, this study compares the properties of the reference concrete with concrete containing varying amounts of brick waste and road demolition debris. The obtained results demonstrate that the produced concrete with up to 40 % recycled content achieved a compressive strength exceeding 20 MPa after 28 days. This study suggests that recycled brick and road demolition waste could be a sustainable and economical substitute for conventional aggregates. Incorporating these materials into concrete reduces the cement content while maintaining or even improving the fresh and hardened properties of the concrete. However, it is crucial to limit the use of road demolition sand to 10 %, crushed brick fines to 20%, and brick sand (CBS) to 30% to ensure optimal performance.

Keywords: *waste, recycling, brick, road demolition, fresh and hardened states of concrete.*

1. Introduction

Managing construction and public works waste is crucial for protecting the planet and promoting sustainable development. It is essential for public authorities and professionals to prioritize improvements in waste management. Construction and public works result generate large quantities of various types of waste, some of which may be hazardous. The eradication of illegal dumping and reduction of waste placement in storage facilities can only be achieved through a voluntary approach, particularly by contractors.

Furthermore, owing to the limited space in landfills and their increasing cost, waste management is a major environmental concern worldwide. Waste has become an appealing alternative to disposal [1], [2]. Research has focused on various waste materials, such as waste concrete, discarded tires, plastic, glass, steel, coal, combustion by-products, bricks, and marble waste. Studies have indicated that each type of waste has a specific effect on the properties of fresh and hardened concrete [3], [4], [5], [6].

Indeed, using waste from concrete products offers economic advantages and helps to solve disposal challenges. Reusing bulky waste is a better environmental alternative for addressing the disposal issues and reducing the volume of waste discarded in illegal dumps [7], [8], [9], [10]. Recycled aggregates have high porosity because they have old mortar attached to them. When used in concrete, these aggregates absorb some of the water

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required for cement hydration, which reduces the workability of the concrete and increases its porosity. Consequently, this compromises the strength and durability of the concrete [7], [8]. The use of recycled aggregates, with some pre-treatment requirements (e.g., cleaning, crushing, and grading), can achieve a characteristic compressive strength of more than 20 MPa at 28 days [8]. This exceeds the strength requirements for many concrete applications, making it comparable or even better. Consequently, demolition waste recycling has moved from experimental research to widespread implementation globally, with some developing countries reaching recycling ratios of construction/demolition debris as high as 80% [11], [12]. Previous studies have focused on the use of crushed brick aggregates in concrete. Naceri and Hamina [13] found that the water absorption increased as the content of demolished brick aggregates increased. Several studies [14], [15], [16], [17] [18] have shown that brick waste can be used to make mortars and concretes, resulting in positive effects. Afshinnia, K., & Poursaee, A. [14] reported that replacing 25% of cement by weight with ground clay brick significantly reduced the Alkali-Silica Reaction (ASR) expansion by 67% at 14 days. Mohammed, T. U., & al. [15] found that recycled brick aggregates exhibit a lower absorption capacity compared to standard brick aggregates. The average strength of concrete incorporating recycled brick aggregate was measured to be 29 MPa for a water-cement ratio of 0.45, and 23.5 MPa for a ratio of 0.5. According to the test results from [16], the compressive strength of cement pastes decreases with an increase in the sintered clay brick powder content but improves with an increase in the fineness of sintered clay brick powder and curing temperature.

The amount of $Ca(OH)_2$ in the cement pastes decreased with an increase in the sintered clay brick powder content and curing age, while its microstructure was relatively dense with an abundance of calcium silicate hydrate gel (C–S–H) existing. Oti, J. E., & Kinuthia, J. M. [17] demonstrate that the pozzolanic properties of brick dust waste (BDW) contributes to strength and durability, while also offering environmental and economic benefits. Nežerka, V& al. [18] report that metakaolin exhibits significantly stronger pozzolanic activity than brick dust and that the mechanical properties of pastes are not necessarily enhanced by the addition of pozzolans. Nevertheless, a reduction in shrinkage should lead to the elimination of cracking around the aggregates in the mortar.

Various studies [19], [20], [21] have demonstrated the benefits of using brick waste in the production of mortar and concrete. These studies suggest that replacing 10% of the cement or aggregates with brick waste is the optimal percentage for achieving the best performance of mortars and concrete.

Researchers and engineers are continuously working to improve the performance of new asphalt mixes by utilizing recycled road-pavement materials. Asphalt concrete, also known as road demolition waste, is one of the materials that generates a significant amount of waste at the end of its useful life [22], [23]. Few studies have been conducted on the use of recycled road materials in regular mortars and concrete. Some research [24], [25], [26], [27] found that replacing natural coarse aggregate with recycled asphalt pavement in self-compacting concrete led to a reduction in workability (by 20-30%), compressive and tensile strengths (by 45-65%), and elastic modulus in conventional concrete (up to 16%).

In addition, studies [25], [26], [27] have demonstrated that substituting natural aggregate with recycled asphalt pavement (RAP) can decrease the energy-absorbing capacity and impede crack propagation. In their study, Ibrahim et al. [28] suggested that the replacement of coarse aggregates with RAP in concrete should not exceed 25%. According to the literature review, there are various ideas for using brick waste and road millings as by-product in cement-based composites. However, there are still research gaps in understanding the behavior of concrete in both its fresh and hardened states when these wastes are used as substitutes for cement or sand. Often, only one dosage of brick waste and road millings is tested, while multiple types and dosages of admixtures are used in cement-based composite mixtures. This can result in the most efficient mixture, with the optimal dosage of these wastes overlooked.

The purpose of this study is to explore the potential of using brick sand (CBS), road demolition sand (CRDS), and crushed brick (CCB) as partial substitutes for cement or sand in the production of regular concrete. This involves varying the dosage from 10% to 40%. The most efficient concrete mix was selected based on laboratory tests for slump, density, porosity, and compressive strength. This selection helps reduce waste through recycling and reuse, thereby protecting the environment and addressing issues related to the shortage of aggregates, especially alluvial aggregates.

2. Materials

2.1. Cement

The cement used was CEM II/A-L 42.5N sourced from the Ain-El Kebira cement plant of S.C.A.E.K in the Sétif region of Algeria. This cement adhered to the current standard NF-EN 197-1 [29]. Its physicochemical properties, as determined using the Bogue empirical formula [30], are presented in Table 1.

Table 1. Physico-chemical characteristics of cement CEM II/ A- L42.5N.

SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	Na_2O
20.4± 0.82	4.05 ±0.21	4.63 ± 0.05	63.48± 1.48	1.71 ±0.03	1.44 ±0.04	0.152±0.01

C_3S = 64.33% ±0.03% C_2S = 10.08%±0.01
C_3A = 2.89% ±0.00% C_4AF = 14.10%±0.01%
Specific Surface Area = 3702 cm^2/g ±22 cm^2/g
Specific density = 3110 Kg/m^3 ±17 cm^2/g

2.2. Water

Tap water from the Sétif University was used in this study. Its quality conformed to the requirements of EN, N. 206+ A2/CN standards [31].

2.3. Aggregates

The crushed aggregates used in this study were sourced from the Ain Roua limestone quarry in Sétif, Algeria. They consist of three granular classes: 0/5 mm sand, 8/15 mm gravel, and 15/25 mm gravel. Their physical properties are presented in Table 2 and were measured using NF P18-560 and NF P18-554 standards [32], [33]. The grading curves of the aggregates are shown in Figure 1.

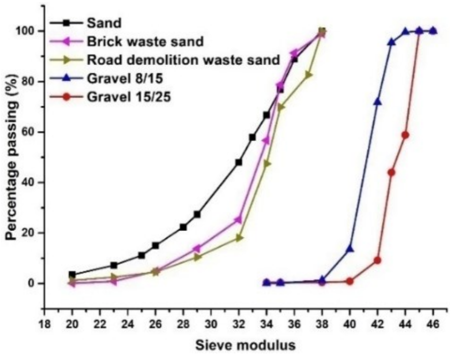

Figure 1. Grading curves of aggregates.

2.4. Brick waste and Road demolition waste

In this study, brick and road demolition wastes were used. Crushing and grinding were performed at the Ain-El Kebira cement company region in Sétif-Algeria. Their physical properties are presented in Table 2. The analyses (Fluorescence X), SSA, and density of brick waste are presented in Table 2, Table 3 and, Figure 2 presents brick waste and road demolition waste. All the properties were measured using standards [34], [35], [36], [37].

Table 2. Physical properties of aggregates, brick waste, and road demolition waste.

Aggregates	Apparent density (kg/m^3)	Specific density (kg/m^3)	Sand equivalent Es (%)	Fineness modulus	Flattening factor (%)
Quarry sand (S)	1650 ±12	2660 ±16	69.52 ±0.2	3.2 ±0.01	-
Brick sand (BS)	1680 ±18	2500 ±15	71.8 ±0.4	3.8 ±0.01	-
Road demolition sand (CRDS)	1410 ±22	2410 ±11	70.66 ±0.4	3.9 ±0.01	-
Gravel 8/15	1470 ±10	2660 ±22	-	-	12±0.1
Gravel 15/25	1440 ±09	2660 ±22	-	-	14±0.1

Table 3. Chemical and physical characteristics of the crushed brick.

SiO_2	Al_2O_3	Fe_2O_3	CaO	SO_3	MgO	K_2O	Na_2O
54.46 ±1.46	17.22 ±0.98	7.47 ±0.66	7.08 ±0.41	0.10 ±0.02	5.37 ±0.03	2.71 ±0.01	0.152 ±0.01

Specific Surface Area = 4636 cm^2/g ±12 cm^2/g
Specific density = 3140 Kg/m^3 ±25 cm^2/g

Figure 2. Brick waste and Road demolition wastes.

2.5. Superplasticizer

The superplasticizer used in this study was a MEDAFLOW 30 high water reducer, supplied in liquid form in accordance with the EN 934-2 and NA 774 standards [38], [39].

3. Mix Proportions and Experimental Methods

The granular composition of 13 different concrete mixtures was determined using the Dreux-Gorisse method [40]. A reference mixture was prepared using unsubstituted quarry sand. The other concretes were prepared by replacing quarry sand with brick sand (CBS) or road demolition sand (CRDS) or by replacing cement with crushed brick (CCB). Each substitution was performed in four different ratios: 10%, 20%, 30%, and 40%. The amounts of gravel, water, and adjuvant were kept constant for all mixtures. Cylindrical specimens (16× 32cm^2) were used for the resistance tests (Figure 3). The details of the concrete mixtures for 1 m³ are listed in Tables 4, 5, and 6. In this study, a concrete slump test was performed according to the NFP18-451 standard [41]. Water immersion porosimetry, fresh density, hardened density, and compressive strength tests were carried out according to standards [42],[43],[44],[45]. All tests were performed in triplicate.

Figure 3. Cylindrical concrete Specimens.

Table 4. Compositions of concretes in 1m^3 according to sand proportions BS/S.

Designation	W/C	Water (l/m^3)	Gravel 8/15 (kg/m^3)	Gravel 15/25 (kg/m^3)	Superplasticizer 1%	Cement (kg/m^3)	Sand 0/5(kg/m^3)	Brick sand (kg/m^3)
Ref	0.56	197.74	455.53	583.07	3.5	350	783.35	0
CBS10							705.02	78.33
CBS20							626.69	156.66
CBS30							548.36	234.99
CBS40							470.03	313.32

Table 5. Compositions of concretes in 1m^3 according to sand proportions CRDS/S.

Table 6. Compositions of concretes in 1m^3 according to cement proportions CB/C.

Designation	W/C	Water (l/m^3)	Gravel 8/15 (kg/m^3)	Gravel 15/25 (kg/m^3)	Superplasticizer 1%	Sand 0/5 (kg/m^3)	Cement (kg/m^3)	Crushed Brick (kg/m^3)
Ref	0.56	197.74	455.53	583.07	3.5	783.35	350	0
CCB10							315	78.33
CCB20							280	156.66
CCB30							245	234.99
CCB40							210	313.32

4. Results and Discussion

4.1. Concrete slump

The experimental concrete slump was evaluated by measuring the slump of fresh concrete using an Abrams cone. All the results are shown in Figure 4.

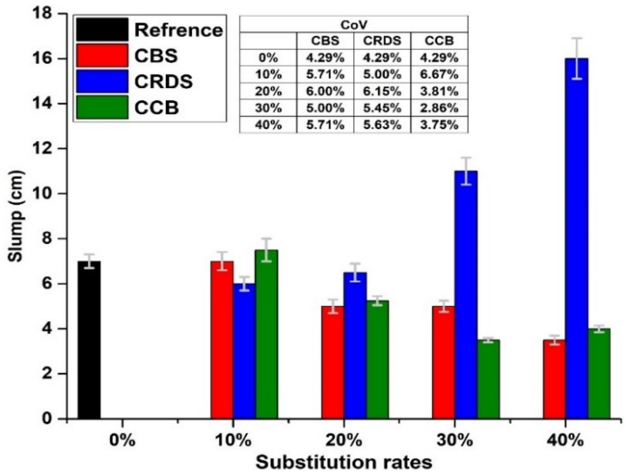

Figure 4. Evolution of concrete slump according to different mixtures and different substitution ratios.

Figure 4 demonstrates that a reference concrete with a water-to-cement ratio (W/C) of 0.56 when combined with a superplasticizer achieves a plastic consistency of A=7 cm.

For concrete based on brick sand (CBS), a plastic consistency was obtained for concrete with 10%, 20%, and 30% waste, while above 30%, the consistency became firm. This was due to the replacement of quarry sand with brick sand, which increased the fine particles present in the mixture (ES < 65%), thus increasing the water adsorption capacity. These finer particles increase the water absorption of the mixture, leading to a reduction in the available water for cement hydration and aggregate lubrication. As a result, the slump decreases.

However, the replacement of quarry sand with road demolition sand (CRDS) resulted in concrete with a plastic consistency at 10% and 20% CRDS, a very plastic consistency of 30% CRDS, and a fluid consistency at 40% CRDS. This transition from plastic to fluid behavior is likely attributed to the presence of aggregates from road demolition sand, which absorb less water for hydration, and their smooth surface reduces friction between particles, thereby enhancing workability.

In addition, for concretes in which cement was replaced with crushed brick (CCB), a plastic consistency was obtained for concretes with proportions of 10 and 20 %. Above 30 %, consistency becomes firm. This result can be explained by the fact that replacing the cement with finely ground brick increases the W/C ratio and reduces the amount of cement paste. As the amount of CCB in the mixtures increases, the amount of water needed to moisten the grains is reduced, resulting in increased friction and reduced workability. Therefore, mixtures based on brick sand have better workability than mixtures based on road demolition sand.

4.2. Fresh density

The evolution of fresh density according to different mixtures and substitution rates is shown in Figure 5.

The experimental results shown in Figure 5 indicate that the fresh density of CBS and CRDS decreases with increasing amounts of waste. This decrease is due to the physical properties of the recycled sand (brick and road demolition sands). Recycled sands have a lower density than natural sand, which leads to a decrease in the density of concrete as their quantities in the mixtures increase.

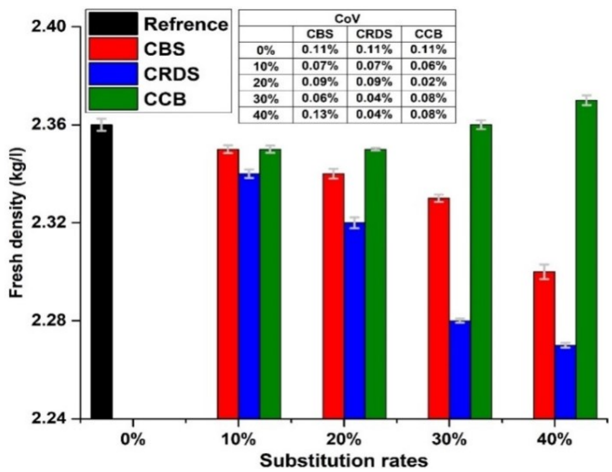

Figure 5. Evolution of fresh density according to different mixtures and different substitution rates.

However, the fresh density of CCB increases as the proportion of crushed brick increases because the fineness of the crushed brick is greater than that of the cement.

The grains of the finely crushed brick can intercalate between the cement grains, leading to a reduction in porosity and, consequently, an increase in density.

4.3. Density of concretes at 28 days

The evolution of the density of concrete at 28 days according to different mixtures and substitution rates is presented in Figure 6. The density (ρ_s) of the samples consists of determining the mass (m_1) of the pycnometer filled with water, the mass (m_2) of the dry sample, and the mass (m_3) of the pycnometer containing the sample filled with water, which has a density of 1000 kg/m^3. The mathematical expression in Eq.1 gives the density of the sample.

$$\rho_s = \frac{m_2}{m_1 + m_2 - m_3} \times \rho_w \quad (1)$$

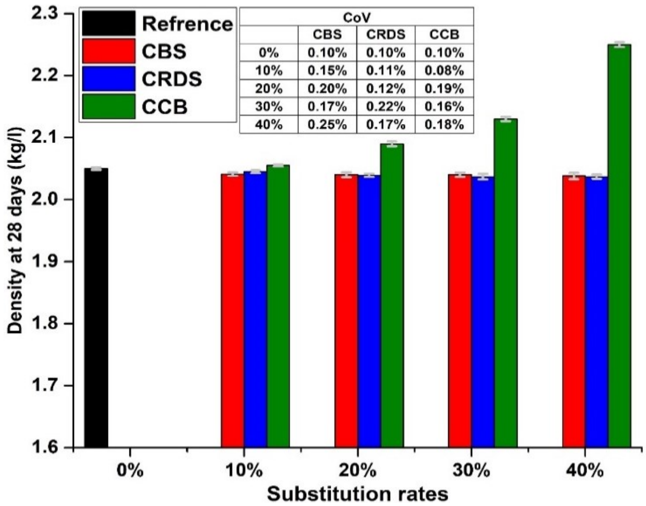

Figure 6. Evolution of hardened density according to different mixtures and different substitution rates.

The results shown in Figure 6 indicate a slight decrease in density (up to 0.634%) as a function of the substitution ratio of CBS and road demolition sand (CRDS). This decrease can be explained by the physical properties of these two sands, which have low densities compared to quarry sand. The CBS and CRDS densities meet the requirements of the standard [44], which requires that the density in the hardened state is greater than 2000 kg/m^3 and less than 2600 kg/m^3 with a tolerance of 100 kg/m^3.

For crushed brick concrete (CCB), an increase in the density was observed as the crushed brick substitution rate increased. For example, a density increase of 9.75 kg/m^3 was observed for concrete with a 40% CCB. This is owing to the filler effect of the crushed brick, which contributes to increasing the compactness of the concrete and consequently the density.

The density of hardened concrete decreases compared to its fresh state primarily due to water evaporation from the concrete matrix upon exposure to open air.

4.4. Water porosity

The evolution of porosity at 28 days according to different mixtures and different substitution rates is presented in Figure 7.

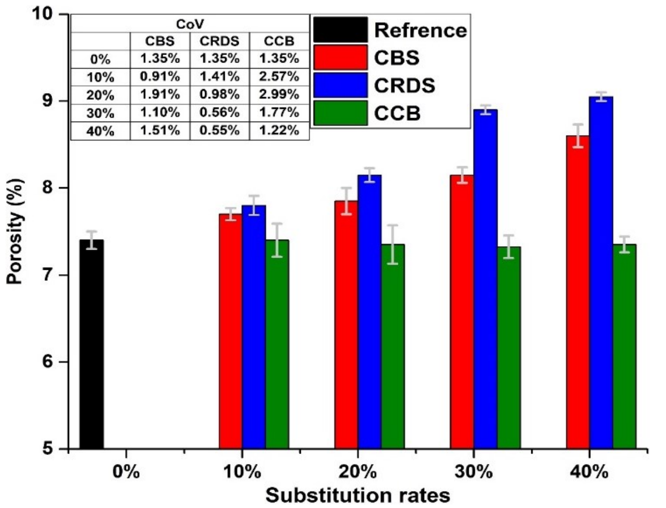

Figure 7. Evolution of porosity according to different mixtures and different substitution ratios.

The experimental results in Figure 7 show that the addition of crushed brick sand causes an increase in porosity of 16% compared to the reference concrete (0% substitution percentage) at a substitution ratio of 40%. This increase can be attributed to the influence of the granularity of the brick sand (Mf= 3.8) and the influence of the presence of impurities in this sand (ES<65%). These findings are consistent with the results reported in the literature [46], [47], [48].

On the other hand, CRDS exhibited a 22% increase in porosity compared to the reference concrete (0% substitution) at a 40% replacement ratio. In addition, CRDS demonstrated higher porosity than CBS. This can be attributed to the bitumen's effect on CBS, where it coats the aggregate grains, hindering their cohesion and leading to increased concrete porosity.

As regards, the effect of replacing cement with crushed brick, it was found that there was a slight reduction in porosity of 1% compared to the reference concrete (0%

substitution percentage). These results can be explained by the high fineness of the crushed brick (SSB= 4631 cm^2/g) compared to that of the cement, which can interlace between the cement grains, thus reducing the porosity. These findings align with the density measurements of these concretes.

4.5. Compressive strength test

The results shown in Figures 8 and 9 illustrate the development of compressive strength after 7 and 28 days, respectively, for different mixtures and substitution ratios. The compressive strength is calculated using the formula (2) following EN 12390-3[49].

$$C_s\ (f_{ck}) = F_{max}\ /\ A \qquad (2)$$

with:

$C_s(f_{ck})$	Compressive strength (MPa)
F_{max}	Maximum load in newtons (N)
A	Cross-sectional area (mm^2)

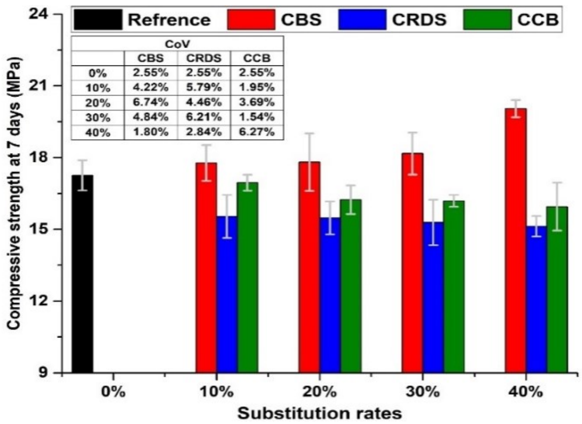

Figure 8. Evolution of compressive strength at 7 days of different mixtures.

According to Figure 8, at the age of 7 days, the CBS strength of concrete increases with the proportion of brick sand in the mixture. For example, concrete containing 40% brick sand showed a 16% increase in CBS strength compared to the reference concrete (0% substitution percentage). This is due to the higher silica content in brick sand compared to natural sand. Silica can accelerate the hydration reaction, leading to increased strength.

However, the CRDS shows a decrease in resistance as the waste ratio increases. These results can be attributed to the size of the sand grains, which increases their porosity, and to the effect of the bitumen coating the grains, which reduces the cohesion between the aggregates and consequently the resistance.

The results of CCB showed a decrease in strength compared to the strength of the reference concrete (0% substitution percentage). This can lead to a reduction in cement dosage, which increases the porosity of the concrete structure and therefore reduces the resistance [48]. On the other hand, Figures 8 and 9 illustrate the evolution of the mechanical strengths of mortars as a function of substitution percentage. In general, mortars cured for 28 days exhibited higher strengths compared to those cured for 7 days. This finding is consistent with previous research on concrete and cement strength, where longer curing periods typically lead to increased strength development.

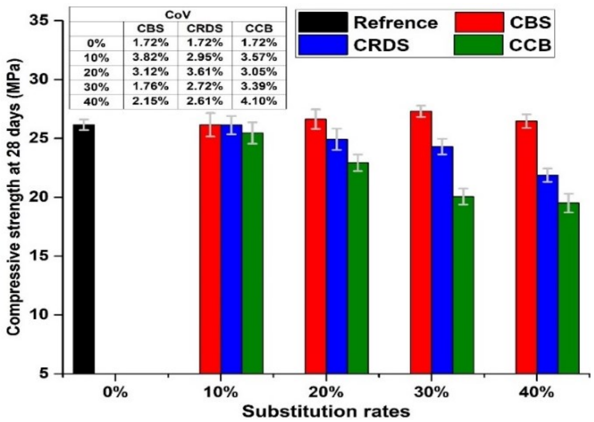

Figure 9. Evolution of compressive strength at 28 days of different mixtures.

Concerning the compressive strength at 28 days, the CBS has a higher strength than the reference concrete (0% substitution percentage). Replacing 10 to 30% of the quarry sand with brick sand increases the strength in a relatively linear way. This is due to the clay nature of the brick sand, which reduces the amount of mixing water (W/C) due to its absorption capacity. Beyond 30% of CBS, the strength decreases but remains higher than the reference concrete (0% substitution percentage), due to the presence of impurities in the brick sand that prevent cohesion between the aggregates and the grain size that makes the sand porous.

On the other hand, increasing the amount of CRDS leads to a decrease in the compressive strength of concretes compared to the reference concrete (from 0.1% for 10% of CRDS to 16.38% for 40% CRDS). This is due to the size of the CRDS grains, which increased the porosity of the concrete.

The increase in the cement replacement ratio by the crushed brick (CCB)resulted in a decrease in the strength compared to the strength of the reference concrete (0% substitution percentage). This can be attributed to the quantity of cement available for hydration which decreases as a function of the increase of the amount of crushed brick (CCB). Reducing the amount of cement in the mix leads to the formation of fewer hydrates (especially portlandite and hydrated calcium silicate C-S-H) compared to the reference concrete (0% substitution percentage) because these hydrates confer better resistance to the materials.

5. Conclusion

This paper presents experimental research aimed at investigating the recycling of brick and road demolition wastes in the production of concrete. Based on the experimental results, the following conclusions can be drawn.

- The use of concrete with brick sand (CBS) enables the production of concrete with a plastic consistency, lower fresh and hardened density, and high strength at 7 and 28 days (up to 4.39% in strength gain), provided that the percentage of CBS does not exceed 30%. Beyond this percentage, water adsorption and the fine content increase, leading to an increase in porosity of the order of 16%.
- Concrete with road demolition sand (CRDS) provides concrete with plastic or very plastic consistency, lower fresh and hardened density, and good strength at 7 and 28 days, as long as the percentage does not exceed 10%. Exceeding this limit may result in increased porosity (22.29%), leading to a 12.34 % reduction in compressive strength at 7 days and a 16.40% reduction at 28 days.
- Replacing cement with crushed brick (CCB) allows for obtaining concrete with plastic consistency, high fresh and hardened density (up to 9.75%), and low porosity (1.1 % decrease in porosity) compared to the reference concrete, if the crushed brick fines (CCB) do not exceed 20%, despite the reduction in strength due to the reduction in the amount of cement available for hydration.

In conclusion, the findings demonstrate the potential for recycling brick and road demolition waste as a viable and cost-effective alternative to traditional aggregates and for reducing the cement content in concrete, provided that the suggested limits are respected. This approach not only addresses waste management issues and reduces environmental pollution but also preserves attractive visual qualities, minimizes landfill waste, conserves natural resources, and reduces the necessity for extracting materials such as natural aggregates and cement. This is achieved despite the difficult and expensive processes (crushing, screening, and washing) required to obtain waste suitable for use in mortar and concrete.

Conflicts Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

All data generated or analyzed during this study are included in this article.

Author Contribution Roles

Conceptualization: C.B. M.L.K.K and O.T.; methodology: C.B. and M.L.K.K.; software: All authors; validation: All authors; formal analysis: All authors; investigation: All authors; resources: C.B., M.L.K.K, O.T., and S.H.; data curation: All authors; writing—original draft preparation: C.B., M.L.K.K, O.T and S.H; writing—review and editing: All authors; visualization: All authors; supervision: All authors.; project administration: All authors; funding acquisition: All authors. All authors have read and agreed to the published version of the manuscript.

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