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The Impact of Brick Powder Specific Surface Area on Cement Replacement in Mortar Mixes: A Sustainable and Cost-effective Solution for the Construction Industry

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Abstract

This study examined the use of clay brick powder (CBP) as a partial substitute for cement in mortar mixes. Five mixes were tested, each differing by the fineness of the CBP, obtained by grinding brick waste for different durations (30, 60, 90, 120 minutes). Several parameters were evaluated; apparent density, porosity, spread, ultrasonic pulse velocity (UPV), flexural and compressive strength, and the pozzolanic activity index. The results indicate that, when the brick powder is ground for 60 minutes, the spread of the mortar exceeds 95% compared to the reference mortar. The addition of CBP appears to increase the water absorption and porosity of the mortars, without significantly influencing their apparent density. Most samples have a UPV close to 4000 m/s, attesting to satisfactory mechanical properties. The use of 20% CBP in replacement of cement leads to a decrease in flexural strength. However, this drop is less when the specific surface area of the CBP is close to that of cement. As for compressive strength, a decrease is also noted with the introduction of CBP, but this decrease can be mitigated by using CBP with a specific surface area similar to that of cement. These factors can significantly influence the pozzolanic activity of the mortar mix. Furthermore, our investigations into environmental and economic analyses show that the use of cement mixes including CBP results in a significant decrease in energy consumption and CO_2 emissions. More specifically, the replacement of 20% of cement with CBP of different granulometries has led to promising results.

Keywords

clay brick powder, grinding time, ecological mortar, pozzolanic activity, specific surface, environmental impact, economic impact

1 Introduction

Cement is an essential construction material used worldwide for making mortars and concrete. In 2021, about 4.5 billion tons of cement were produced [1, 2]. However, cement production is one of the most energy-intensive industries, consuming nearly 5% of the world's industrial energy [3]. This results in about 8% of global CO_2 emissions, which is a major contributor to the Earth's rising temperature and environmental changes [4].

Despite the research and development efforts made by cement manufacturing plants to reduce greenhouse gas emissions [5] the expected goals remain far from being achieved. According to Zhao et al [6] each ton of cement produced generates around 0.93 ton of CO_2, a figure that varies from country to country. Opon [7] provides a clear illustration using Japan as an example: the carbon footprint of ordinary Portland cement there is 766.6 kg-CO_2 equivalent per ton of cement derived from clinker. In Thailand, this figure rises to 862 kg-CO_2 equivalent per ton of identical cement. In Morocco, annual cement production averages 12.5 million tons.

In addition to cement production, the rapid urbanization that Morocco has experienced in recent decades has resulted in large quantities of construction waste that is a major environmental nuisance. According to the statistics of building authorizations available to the High Commission for Planning (HCP), about 20,000,000 m^2 of new constructions are erected each year in the country [8]. The quantities of construction waste, excluding excavated earth, are obtained by multiplying the gross surface area in m^2 by the ratio of 85 kg/m^2 [9], 45% of which are clay bricks [8]. This represents a mass of 765,000 tons of brick waste, to which must be added 200,750 tons of waste from the manufacture of bricks (it is estimated that 5% of the annual production of 4,000,000 tons of bricks

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is transformed into waste) [8]. In total, this represents 966,000 tons of waste, or 7.8% of the annual cement production in Morocco.

During the manufacturing process, the clay brick is exposed to temperatures ranging from 600 to 1000°C, which can lead to the transformation of the crystalline silicate structure into amorphous compounds [10]. These amorphous compounds can react with alkali from cement hydration or alkali activator to form bonding products that have a beneficial effect on the development of mortar and concrete properties [6].

Therefore, it is imperative to find solutions to reduce CO_2 emissions associated with cement production in order to limit negative environmental impacts. Initiatives such as the use of alternative materials to partially replace cement in the manufacture of concrete or the use of more sustainable production processes can help achieve this goal. In addition, public awareness of the importance of reducing CO_2 emissions from cement production can also play a key role in this transition to a greener cement industry.

In recent years, researchers have tested the use of recycled materials from waste bricks as supplementary cementing materials (SCMs) in the manufacture of mortars and concretes [11]. Metakaolin, a calcined clay, has been extensively studied and proven to contribute to improved long-term compressive strength and durability of mortar and concrete in aggressive environments [12, 13].

Large amounts of brick waste are produced during manufacturing or at construction and demolition sites. Brick waste can be used as a partial substitute for natural aggregates in concrete if the level of substitution is limited to about 20% [14]. A study showed that the pore size of mortar with clay brick powder (CBP) could be refined over time due to a possible pozzolanic reaction, resulting in higher strength at older ages [6].

Studies have concluded that the proportion of CBP replacing cement in concrete should not exceed 15% [15], while another study found that the 400-day compressive strength of mortar containing 20% CBP was even higher than that of control mortar [16]. One study also found that due to the pozzolanic nature of CBP, there is more C-S-H gel production, which increases the compressive strength of the concrete with increasing CBP content (with substitution of cement with CBP with similar grain size of 5–10%) at both 3 and 28 days of curing [17].

One study showed promising results using 10 and 40 wt% CBP in mortars, resulting in 28% and 82% (at 90 days) increase in strength compared to mortar without CBP, respectively. This study also demonstrated the existence of an inversely proportional relationship between compressive strength and apparent porosity, as shown by Arif et al. [18]. However, Sinkhonde [19] recommends moderation in the use of CBP, as it may result in reduced workability of the concrete. In addition, research by Ma et al. [20] showed that the mechanical properties and water absorption of mortar can be affected by the particle size of CBP. They also suggested that the particle size of the CBP should be carefully selected to optimize the performance of the mortar. Finally, the use of CBP in concrete and mortar manufacturing also helps to reduce the carbon footprint of the cement industry by reducing the amount of waste sent to landfill and by reducing the amount of cement needed in the manufacture of cement composites [19]. As a result, brick waste can be a valuable source of recycled building materials, including CBP, which can be used to improve the properties of cement composites.

Although the effects of CBP replacements on the properties of cement composites have been studied previously, the influence of CBP fineness on the properties of cement composites has received less attention in previous studies [21]. Therefore, this research aims to offer critical insights into the use of clay brick powder (CBP) in construction materials by exploring the influence of CBP's fineness levels and replacement ratios on the properties of mortar. By evaluating a 20% substitution of cement with CBP and delving into the impact of particle dimensions - particularly CBP's specific surface area - on mortar attributes, we extend the breadth of understanding in this field. Moreover, an all-inclusive cost analysis of the various mortars, grounded in prior research, will furnish pragmatic data for decision-making in construction endeavors.

2 Materials and methods

2.1 Raw materials

2.1.1 The brick powders

The broken bricks were collected in a brick manufacturing plant (SOMABRIC) located in Meknes, then crushed for two minutes and sifted to obtain coarse particles. The latter are then crushed using a BB-10 (are designed for samplesup to 1 kg) type crusher (Fig. 1)

Several grinding times were adopted, 30 min, 60 min, 90 min and 120 min, to obtain different levels of fineness of CBP. The obtained powders were named CBP_30, CBP_60, CBP_90, CBP_120, respectively.

Grinding times (30, 60, 90 and 120 minutes) were chosen to produce a variety of samples and examine their influence

Fig. 1 Grinding of brick waste

on the mortar. The aim of these times was to obtain characteristics similar to those of cement. An initial attempt to grind at 15 minutes produced particles that were too coarse, hence the choice of 30 minutes as the minimum duration.

2.1.2 Cement

The cement used in this research is Portland limestone cement CEM II/A-V 42,5 V in accordance with NF EN 197-1 standard [22], which is a type of cement commonly used in the concrete industry because of its physical (its specific surface area is much greater than that of ordinary cement) and chemical properties. The selection of such a type of Portland CEM II / A-V 42,5 V in this research was motivated by the need to produce high strength concrete, which requires a cement that can provide a minimum 7-day mortar cube strength of approximately 30 MPa.

2.1.3 Sand

The sand used for the project comes from the Adaroche quarry in El Hajeb province. Prior to its use, the sand was adapted to conform to the grain size composition specified by the standard NF EN-196-1 [23]. Table 1 provides details on the particle size composition of the sand used.

2.1.4 Water

Tap water was used for the tests conducted in this study. This water complies with the potability standards in force in Morocco, thus guaranteeing its quality and suitability for laboratory use.

2.2 Physical and chemical properties of the binders

2.2.1 Physical properties of binders

To determine the particle size distribution of CBP and cement, laser particle size analysis was carried out using a specialized device called the "Mastersizer Malvern - size analyzer" (Fig. 2). This technique is based on the use of a laser beam, which measures the amount of light diffracted by particles in suspension, enabling their size to be deduced. Further information on the equipment used and the method can be found at [24]. As our university is not equipped with a similar device, these measurements were carried out in the laboratory of a cement plant in Meknes, under the close supervision of on-site experts. It should be noted that particle size measurement using the laser diffraction method gives a much wider distribution than the Blaine method [25]. In addition, the specific surface area of the particles was also measured using the same laser equipment. The actual density of the CBP particles was measured by the pycnometer method in accordance with NM ISO 17892-3 [26]. The diameters (D_10, D_50, and D_90) of the different brick powders, as well as the specific surface areas and actual densities measured, are shown in Table 2.

Fig. 3 illustrates the particle size distribution of the various binders, including CBP obtained after different grinding times. It can be clearly seen that the fineness of CBP improves in proportion to the grinding time. This manifests itself in a reduction in particle size and an amplification of specific surface area, as presented in Table 2. Analysis results are given in the analysis report [27]

From Fig. 3(a) and Table 2, it can be observed that the fineness of the CBP increases with the grinding time. As the grinding time increases, the particle size decreases.

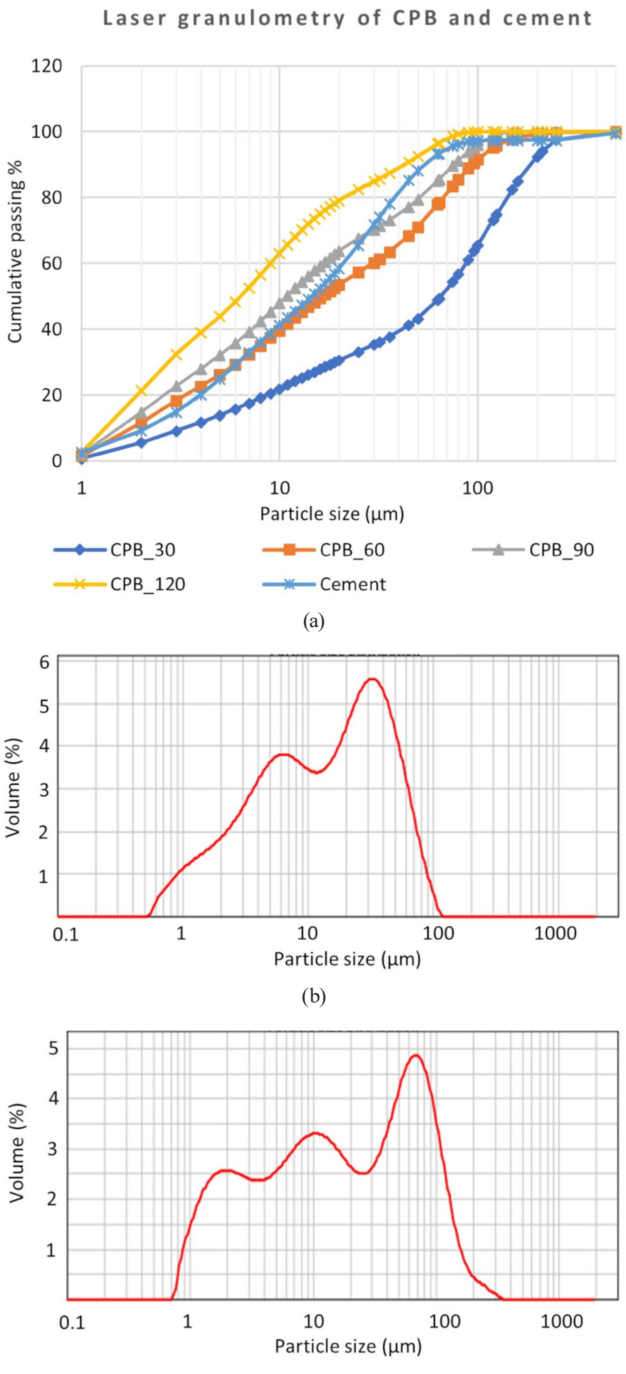
Table 1 Grain size composition of the sand used

Mesh size (mm)	2	1.60	1.25	0.8	0.5	0.16	0.08
Cumulative refusal %	0	7	26	50	70	92	100

Fig. 2 Laser diffraction analyzer

Table 2 Size-physical properties of the particles

Type	Cement	CBP_30	CBP_60	CBP_90	CBP_120
D_10	2.15	3.30	1.81	1.58	1.36
D_50	14.47	65.28	16.44	10.84	6.35
D_90	51.74	184.15	93.69	75.87	42.65
Density	3.00	2.57	2.64	2.66	2.67
Specific surface (m^2/g)	1.05	0.578	1.05	1.27	1.69



(a)

(b)

(c)

Fig. 3 Particle size distribution of binder materials: (a) Particle size distribution of binders, (b) Cement, (c) CBP-60

However, according to the study by Ma et al. [20], additional grinding time does not have a significant impact on the reduction of the average brick powder size once the median CBP size reaches 6 µm.

It can also be seen that CBP with median diameters of 6.35 µm and 10.84 µm show higher fineness than cement. The median diameter of the cement is 14.56 µm, which is between the median diameters of CBP_60 and CBP_90. Finally, the CBP with a median diameter of 65.28 µm indicates that the fineness of CBP_30 is lower than that of cement. Fig. 3(b) and (c) show that the distribution volume of cement particles is similar to that of CBP with a median diameter of 16.44 µm (CBP_60).

It can be observed that the true bulk density of the brick powder increases slightly with increasing grinding time. This can be justified by a reduction in the size of the brick particles and better compaction of the powder particles as the grinding time increases.

Regarding the specific surface area of the different binders, it increases with the grinding time. In particular, the specific surface area of the CBPs varies from 0.578 m^2/g to 1.69 m^2/g for grinding times ranging from 30 to 120 minutes. It should be noted that the specific surface of CBP_60 is equal to that of cement, i.e., 1.05 m^2/g.

2.2.2 Chemical and mineralogical composition of the binders

Table 3 shows the chemical composition of the cement and clay brick powder used in this study. It can be seen that the CBP is rich in SiO_2, Al_2O_3, and Fe_2O_3 with a total of more than 70%, which meets the requirements of ASTM C618 for the content of the main chemical composition of the pozzolanic material [16, 28]. The diffractogram of the CBP indicates that it consists mainly of quartz (Fig. 4). Other minerals are detected notably hematite and feldspar.

Furthermore, the cement has a different chemical composition, with a high content of CaO and a lower content of SiO_2, Al_2O_3, and Fe_2O_3. This difference in chemical composition can affect the mechanical and microstructural properties of the cement composite material when mixed with CBP. CBP can chemically react with cement, which can lead to the formation of new reaction products and changes in the microstructure of the composite material.

Table 3 Chemical compositions of CBP (wt%) based on XRF analysis

Oxide	CBP	Cement
SiO_2	65.1	17.98
Al_2O_3	9.84	4.62
Fe_2O_3	5.14	2.83
CaO	9.56	56.37
MgO	1.91	4.27
SO_3	0.8	2.61
K_2O	1.41	0.45
Others	2	4.24
LOI	1.55	9.32

2.3 Design of the mixture proportions

The experimental method set up involved the preparation of five different mixtures named MC_Ref, CCBP_30, CCBP_60, CCBP_90 and CCBP_120. The MC_Ref group corresponds to a reference mixture without CBP, whose proportion was elaborated in accordance with the NF En-196-1-2016 [23]. This standard specifies that the proportions by mass are one part cement product, three parts standardized sand and half a part of water, with a water/cement ratio of 0.50.

The CCBP_30, CCBP_60, CCBP_90 and CCBP_120 mixes were tested with 20% ground clay brick powder for periods of 30, 60, 90 and 120 mn, respectively. For each curing time, five mixes were prepared, including a reference mix. The proportions of each mixture are presented in Table 4. The decision to incorporate 20% clay brick powder into the mortar was taken by balancing the importance of this substitution with maintaining mortar strength. This choice was based on previous studies validating the use of pozzolanic materials to replace up to 30% of cement. This initial stage precedes the development of a high-performance concrete with a ratio adapted to the results obtained. This choice was also guided by a comprehensive analysis of recent research into the impact of CBP as a cement substitute on mortar and concrete performance, as presented in the study by He et al. [15].

All procedures of NF En-196-1-2016 [23] were strictly followed. The specimens were molded in prismatic form with dimensions of 40 mm × 40 mm × 160 mm and were placed in a humid room for 24 hours. Thereafter, the specimens were demolded and immersed in water to the predefined test ages (Fig. 5).

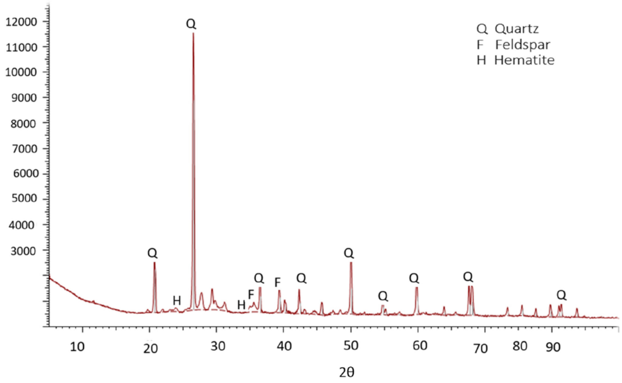


Fig. 4 X-Ray diffraction pattern of CBP

Table 4 Mixing proportions of the mortars

Type	MC_Ref	CCBP_30	CCBP_60	CCBP_90	CCBP_120
Cement (g)	450	360	360	360	360
CBP (g)	0	90	90	90	90
Water (g)	225	225	225	225	225
Sand (g)	1350	1350	1350	1350	1350

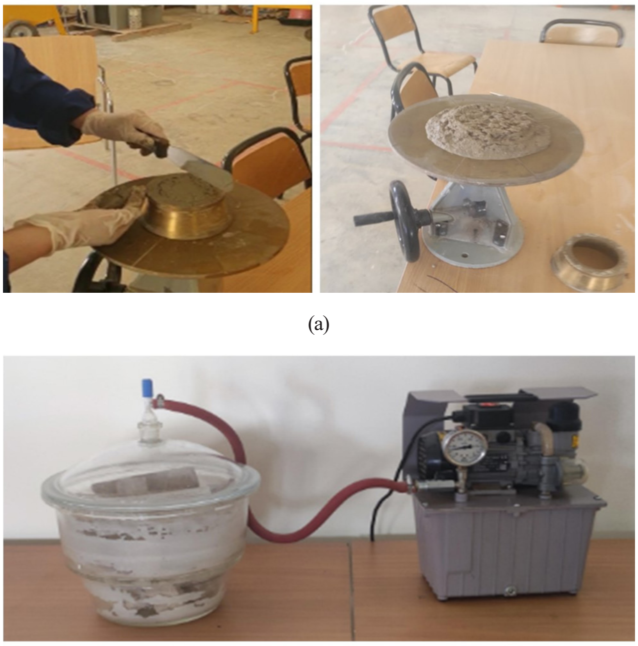
2.4 Test procedures

2.4.1 Consistency test

The consistency test of the mortars was carried out using a shaking table (Fig. 6(a)) shaking the table 15 times. The spread was measured in 3 directions and the average value was calculated.

The result of the flow test is an indicator of the consistency and fluidity of the mortar mixture. A shorter flow indicates a drier, more viscous mixture, while a longer flow indicates a wetter, more fluid mixture. The results of the flow test can be used to adjust the proportions of the mix ingredients and to improve the quality and workability of the mortar.

Fig. 5 Storage of specimens



(a)

(b)

Fig. 6 Test of Spreading Consistency (a) and experiment on air absorption (b)

2.4.2 Densities and porosity

The densities and porosity of the formulated mortars were determined in accordance with NF P 18-459. After 26 days curing, the samples were placed in a desiccator connected to a vacuum pump (Fig. 6(b)) allowing to create a pressure of about 25 mbar maintained during 4 h. After degassing, water was gradually introduced until total immersion while maintaining the vacuum for 44 h. The 3 masses were then determined: the mass in water M_{Hyd} by performing a hydrostatic weighing, the mass in air M_{Sat} after wiping the sample with a wet cloth, and the dry mass after drying at 105 °C.

Once the 3 masses are determined, the formulas below were used:

The bulk density ρ_a is given by:

$$\rho_a = \rho_w \frac{M_s}{M_{Sat} - M_{Hyd}} . \quad (1)$$

The absolute density ρ_s is determined by:

$$\rho_s = \rho_w \frac{M_s}{M_S - M_{Hyd}} . \quad (2)$$

The porosity P is obtained by:

$$P = 100x\left(1 - \frac{\rho_a}{\rho_s}\right), \quad (3)$$

where:

M_s	The dry mass after complete drying in the oven at 105 °C ± 5 °C,
M_{Sat}	The saturated mass,
M_{Hyd}	The hydrostatic mass,
ρ_w	The density of water (1000Kg/m³).

2.4.3 Ultrasonic velocity and dynamic Young's modulus

The sonic auscultation test is performed on the different mortar specimens at different ages (7, 14 and 28 days). The ultrasonic velocity was determined by the direct method using a Controls Ultrasonic Pulse Velocity Tester, this 58-E4800 UPV tester is used for quality control and inspection of mortar. The two transmitter and receiver transducers were placed on opposite sides of each sample (Fig. 7(b)), to determine the travel time (T). In order to ensure proper acoustic contact, soap was used as the coupling product. The travel length corresponding to the length of the sample is measured with a digital caliper (Fig. 7(c)).

The ultrasonic propagation velocity and the dynamic Young's modulus are subsequently calculated according to the formulas:

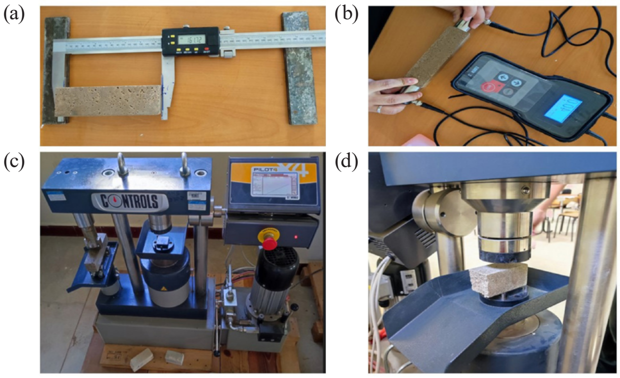


Fig. 7 Measurement of the length and propagation time of waves (a, b). Flexural and compressive strength tests (c, d)

$$E = \rho \frac{(1+\mu)(1-2\mu)}{1-\mu} V_p^2 , \quad (4)$$

where:

V_p	L/T is the propagation speed of ultrasound (longitudinal wave P) in m/s,
L	is the path length, in m,
T	is the travel time, in s,
E_d	is the dynamic Young's modulus in Pa,
μ	is the Poisson's ratio, taken equal to 0.30,
ρ	is the bulk density (g/cm³).

2.4.4 Flexural and compressive strengths

For the bending strength tests, the mortar prisms were subjected to a vertical load applied to the opposite side face using a CONTROLS 65-L1142 hydraulic press in accordance with [23]. The prism was installed in the apparatus, the load was gradually increased at a constant rate of 50 N/s until the prism failed (Fig. 8(c)). The compressive strength test was then performed on each half of the prism in accordance with the above standard. The load was increased at a constant rate of 2400 N/s until the prism failed.

The tests were conducted over three ages 7, 14 and 28 days, to evaluate the strength of the mortar at different stages of curing. These results are critical in determining the mortar's ability to resist bending and compressive stresses in structural applications.

The flexural strength R_f and compressive strength R_c are determined according to the following formulas:

$$R_f = \frac{1.5xF_f xl}{b^3} , \quad (5)$$

and

$$R_c = \frac{F_c}{b^2} , \quad (6)$$

where:

R_f is the bending strength, in megapascals,
R_c is the compressive strength, in megapascals,
F_c is the maximum load at break, in newtons,
b is the side of the square section of the prism, $b = 40$ mm,
F_f is the load applied to the middle of the prism at failure, in newtons,
l is the distance between the supports, $l = 100$ mm.

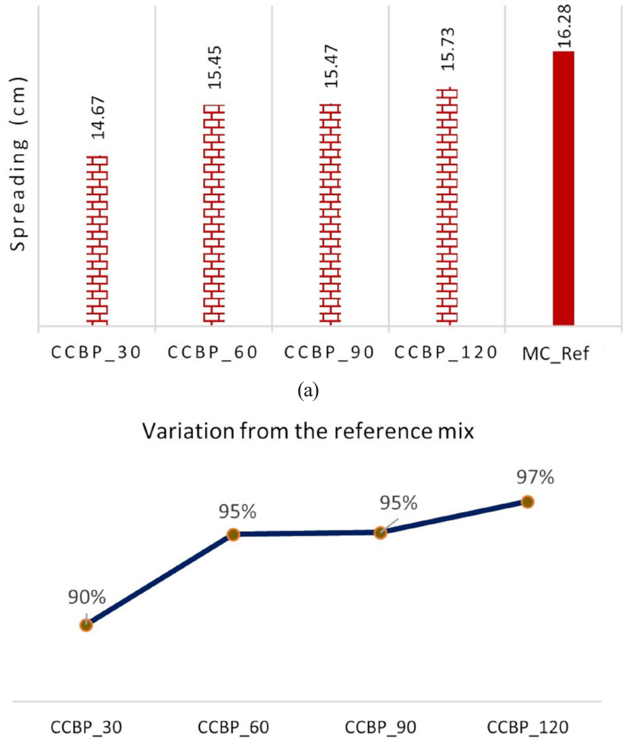
3 Results and discussion

3.1 Mortar spread

Referring to Fig. 8(a), it can be observed that CCBP_30 exhibits the lowest spread, whereas CCBP_120 has the highest spread among the other mortars containing CBP.

However, the spread of CCBP_120 remains very close to that of CCBP_60 and CCBP_90. Thus, it is possible to conclude that the spread approaches that of the MC_Ref mortar (95%) from the mortar containing ground powder for 60 minutes, as shown in Fig. 8(b).

This observation is supported by other studies. For instance, [21] concluded that the spread of a mortar containing 10% brick powder was 8.5% lower than that of a control mortar without brick powder. Similar results were obtained by [20], who worked on brick powder with median diameters ranging from 6 µm to 42 µm and found that an increase in the fineness of the brick powder leads to a reduction in the water demand of the mix. Irki et al. [28] showed that mixes with 20% brick powder have a lower flow rate. He et al. [15] found an average reduction of approximately 3% compared to the control mortar and observed that the flowability increases with the fineness of the CBP. It was explained that this is due to the continuous decrease in particle size of the CBP, causing the destruction of some pores within the CBP, which in turn reduces its water absorption capacity. When the grinding time is prolonged, the brick powder particles undergo progressive refinement and tend to take on a spherical shape. Spherical brick powder particles have less frictional resistance and reduce the viscosity of the mix, which reduces the amount of water needed to achieve the desired consistency [6].



(a)

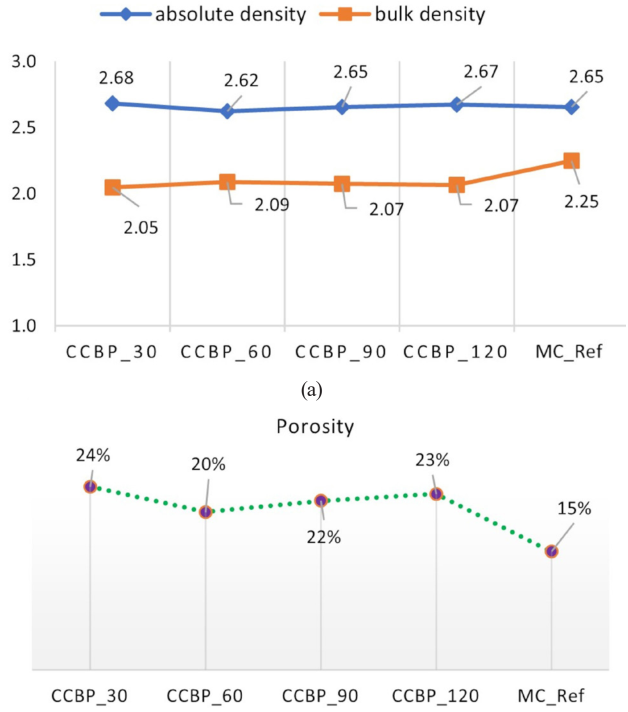
(b)

Fig. 8 Spreading test of mortars (a) and variation of spreading from the reference mix (b)

3.2 Bulk density and porosity

Fig. 9 shows the results of bulk density (*ρa*) and porosity (*P*) of the mortars studied after 28 days.

Fig. 9(a) presents a comparison of the apparent and absolute densities for the different mortars studied. The results reveal that the mortars containing CBP have bulk densities similar to their absolute densities, representing more than 91% of the density of the reference mortar MC_Ref. This observation suggests a slight reduction in the bulk density of the mortars with the addition of CBP.



(a)

(b)

Fig. 9 Densities of mortars (a) and porosity of mortars (b)

Moreover, a correlation between the decrease in porosity and the approximation of density values is observed. This trend is particularly marked for the reference mortar MC_Ref and weakly for CCBP_60. Fig. 9(b) shows the porosity of each type of mortar. The results obtained indicate that mortars containing CBP have higher porosity due to the ceramic absorbing more water. However, the porosity is not impacted by the degree of fineness of the ground particles beyond 30 mn, especially since the actual densities of the three brick powders (CBP_60, CBP_90, CBP_120) are very close (see Table 2), on the contrary, it can be noticed that the mortar CCBP_60 has a relatively lower porosity compared to the other two, which have undergone longer grinding times. This difference can be explained by the fact that CCBP_60 has the same specific surface area as the cement, namely 1.05 m^2/g.

3.3 Ultrasonic pulse velocity UPV

Fig. 10 represents the results of the UPV (in km/s) for the different mortars at different ages. The results show that the ultrasonic velocity (UPV) of the mortar increases with age, regardless of the grinding time. On the other hand, the mortars containing the brick powder show lower ultrasonic velocities than the mortar without cement replacement. This observation suggests that UVI is affected by material density [29], and that partial replacement of cement with CBP may affect the mechanical properties of the mortar.

It should also be noted that most of the specimens have a UPV value of about 4000 m/s, which indicates that these mortars have very satisfactory mechanical properties (in general, for common mortars used in construction, a UPV of 3500 m/s to 5000 m/s is considered acceptable). For example, a study [30] on a reference mortar (cement without addition or replacement) found a UPV of 4.30 km/s, while for mortars containing substitutes such as granulated blast furnace slag and cement kiln dust, the UPV was 4.17 km/s. Another study [31] on a reference mortar found a UPV of 4 km/s, and for mortars containing substitutes such as calcined clay and limestone, the UPV was less than 4 km/s. It should be noted that these values may vary depending on project specifications or applicable standards.

Furthermore, the UPV values of the three CCBP_60, CCBP_90, and CCBP_120 mortars are very close, which means that one hour of grinding is sufficient. However, it is important to note that UPV is just one indicator among others to assess the quality of a construction material, and other tests are necessary for a complete evaluation. Thus, we can deduce the Young's modulus as presented in Table 5.

Looking at the values in the table, it can be seen that CCBP_60 has the highest value of Young's modulus with 26.40 GPa, this value is 86% of that of MC_Ref. Furthermore, the results of the other specimens (CCBP_30, CCBP_90 and CCBP_120) have similar levels of stiffness, with very minimal differences between the Young's modulus values. This may suggest that increasing the grinding time beyond 60 minutes does not provide a significant gain in stiffness.

3.4 Flexural strength

Fig. 11 shows the evolution of flexural strength as a function of time for four mortars containing different proportions of brick powder (CCBP_30, CCBP_60, CCBP_90 and CCBP_120) and a control mortar (MC_Ref) which does not contain brick powder. The results are given in MPa for ages 7, 14 and 28 days.

Table 5 Young's modulus of the 5 specimens

	MC_Ref	CCBP_30	CCBP_60	CCBP_90	CCBP_120
Young's modulus (GPa)	30.57	25.29	26.40	26.03	25.59

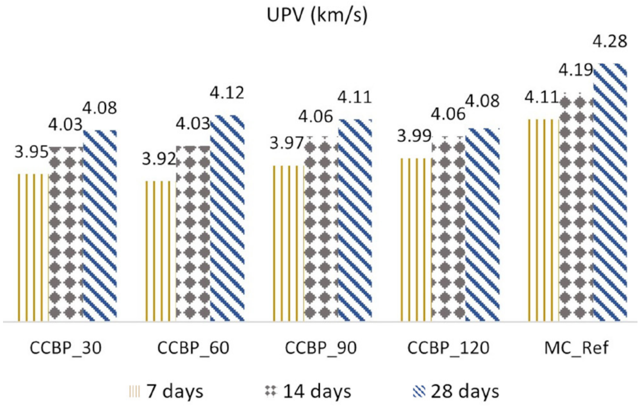


Fig. 10 Ultrasonic pulse velocity

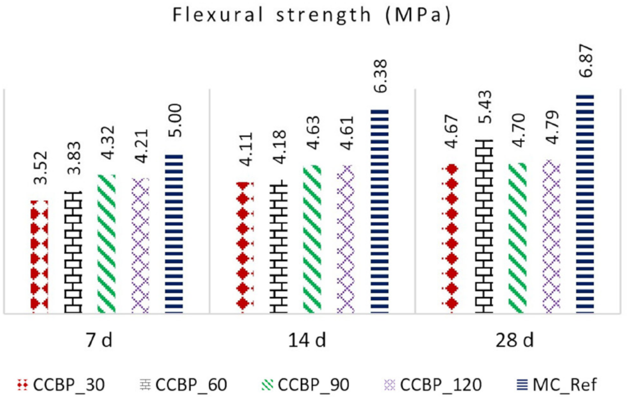


Fig. 11 Flexural strength of mortars

It is found that the flexural strength varies with the age of the mortar for each type of mortar. In general, the flexural strength of the control mortar (MC_Ref) is higher than that of the mortars containing brick powder, indicating that substituting 20% of the cement with brick powder decreases the flexural strength of the mortar. However, it is interesting to note that the flexural strength of CCBP_60 mortar at 28 days is the highest among mortars containing brick powder.

This suggests that the 60-minute grinding time is sufficient to have a proper flexural strength. In other words, this indicates that the closer the specific surface area of the brick powder is to that of the type of the cement in the present research, the higher the flexural strength. Naceri and Hamina [32] also found that the flexural strength of the cured mortar decreases with increasing brick content at 7 and 28 days, but for mortars containing up to 10% brick waste, the flexural strength at 90 days can reach a value comparable to that of a control mortar without brick waste due to the variation in SiO_2 and Al_2O_3 content and CaO/SiO_2 ratio.

3.5 Compressive strength

The results presented in Fig. 12 show the compressive strength of cement and clay brick powder (CBP) mortars at different setting times (7, 14, and 28 days) for 20% replacement of cement with CBP (CCBP_30, CCBP_60, CCBP_90, and CCBP_120) as well as a mortar reference without the addition of CBP (MC_Ref). Compressive strength values are expressed in (MPa).

The analysis of the results shows that, the compressive strength decreases with the replacement of the cement mass by 20% of that of the PBM, for all setting times and for all PBM considered. This is in agreement with the results of other similar studies [33, 34]. However, an interesting observation is made regarding the compressive strength of CCBP_60 at 14 and 28 days. Indeed, despite the fact that the particles of CCBP_90 and CCBP_120 are finer than those of CCBP_60, the compressive strength of the latter is slightly higher. This observation can be explained by the fact that the specific surface area of CCBP_60 is equal to that of the cement, which allows for better interaction between the cement and CBP particles. The study conducted by [6] came to a similar conclusion. Indeed, the author studied four types of mortars containing brick powder, which were ground at different times. The results showed that mortar M2, ground at 30 minutes, had a higher strength than mortars M3 and M4, which were ground successively at 60 and 120 minutes. This observation can be explained by the specific surface area of the different cementitious materials. In particular, the specific surface area of the cement used in the study (384.1 m^2/kg) was closest to that of the brick powder used in the M2 mix (367.2 m^2/kg).

The graph presented in Fig. 13 illustrates the evolution of the mechanical strength of the ecological mortar containing 20% crushed brick powder at 60 minutes. Over time, the flexural and compressive strengths are measured at different stages of mortar maturity and are plotted on the y-axes.

The main observation that emerges from this graph is that the flexural and compressive strengths gradually increase as the mortar reaches a more advanced stage of maturity. At 28 days this strength exceeds 50MPa, a strength.

3.6 Pozzolanic activity index

The pozzolanic activity index (PAI) is an important parameter that measures the rate of reaction between a pozzolanic material and the $Ca(OH)_2$ present in the mortar. More specifically, it describes the degree of reaction over time. It is given by the ratio between the compressive strength of the mortar containing CBP, R_c (CCBPi) and the compressive strength of the reference mortar with 100% cement:

$$PAI(Mi) = 100 \times \frac{R_C(CCBPi)}{R_C(MC_{Ref})} . \quad (7)$$

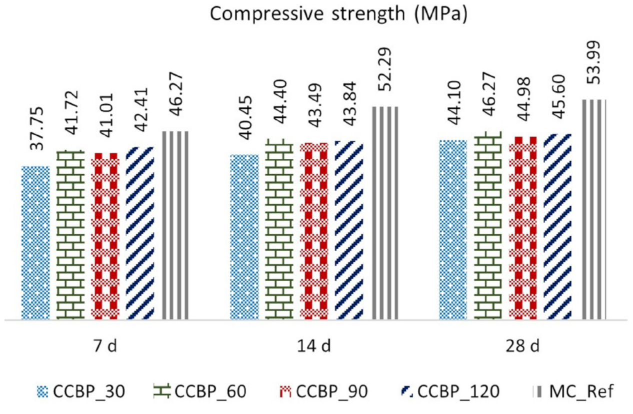


Fig. 12 Compressive strength of mortars

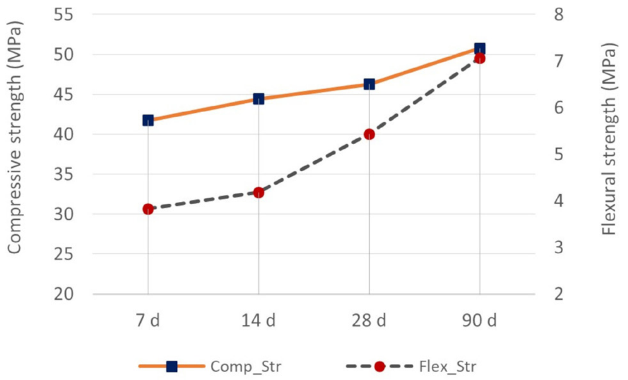


Fig. 13 Evolution of mechanical strengths

In this study, the Pozzolanic Activity Index (PAI) was used to assess the impact of the addition of Crushed Brick Powder (CBP) on the compressive strength of mortars. The data show a variation in PAI between 82% and 86%, indicating that CBP can be recognized as an effective pozzolanic material. Fig. 14 shows a higher PAI for the mortar incorporating powder ground for 60 min, compared with that containing powder ground for 120 min.

This phenomenon can be explained by the factors of particle size and specific surface area. CBP_60, which has a particle size similar to that of cement and an equivalent specific surface area, facilitates interaction with cement particles. This helps to increase the PAI and compressive strength of the mortar.

The evolution of the Pozzolanic Activity Index (PAI) is influenced by several factors such as particle size, specific surface and grinding time. Increasing grinding time initially reduces CBP particle size and increases specific surface area, promoting better interaction with cement and thus increasing pozzolanic activity and PAI. However, excessively long grinding can lead to a particle size that is too small and to particle agglomeration, thereby reducing the effective specific surface area and thus pozzolanic activity and PAI. The subsequent increase in PAI may be due to changes in the crystalline structure of the brick powder caused by long grinding times, or to renewed dispersion of the agglomerated particles. These interpretations are based on specific laboratory experiments carried out at ENSAM and may require further study for confirmation.

Fig. 15 provides a comparison of pozzolanic activity index (PAI) values derived from different research, with particular emphasis on the work of Zhao et al. [6] and Ma et al. [20]. These researchers opted for the use of brick powders as cement substitutes, with a replacement rate of 30%.

In his work, Zhao et al. [6] studied four variants of brick powders, three of which were ground for times similar to those applied in our own research (30, 60, and 120 minutes). A notable finding was that mortar M2, which contained brick powder ground for 30 minutes, recorded the highest PAI. This result indicates a higher pozzolanic activity for this specific mix. It is interesting to note that the specific surface area of the cement used in Zhao et al.'s [6] M2 mix closely matches that of the brick powder. This correspondence in specific surface area seems to favor optimal interactions between the various constituents of the mix, leading to improved performance.

For its part, Ma et al. [20] did not provide precise indications on the grinding time but presented particle size distributions with three particle sizes coinciding with those observed in our study, which also correspond to the same grinding times (30, 60 and 120 minutes). Although Ma et al. [20] did not provide information on specific surface areas, his conclusion indicates that the pozzolanic activity index increases with the fineness of the brick particles. This again emphasizes the importance of particle fineness in optimizing the pozzolanic activity of mixes.

Overall, this study provides valuable information on the potential use of brick powder as a partial substitute for cement in mortar mixtures. Comparison with the studies of Zhao et al. [6] and Ma et al. [20] highlights the importance of controlling the specific surface area of cement and brick powder, as well as the particle size distribution of the latter. These factors can have a significant impact on the pozzolanic activity of the mortar mix and should be considered in future studies.

4 Environmental impact and cost analysis

Given the massive use of concrete worldwide, with annual production equivalent to around 2 tons per person [34], this results in considerable consumption of energy and natural resources. As previously mentioned, cement manufacturing is responsible for around 8% of the world's man-made

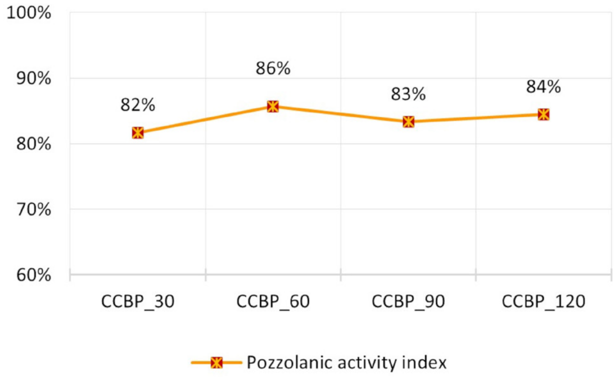


Fig. 14 Pozzolanic activity index at 28 days

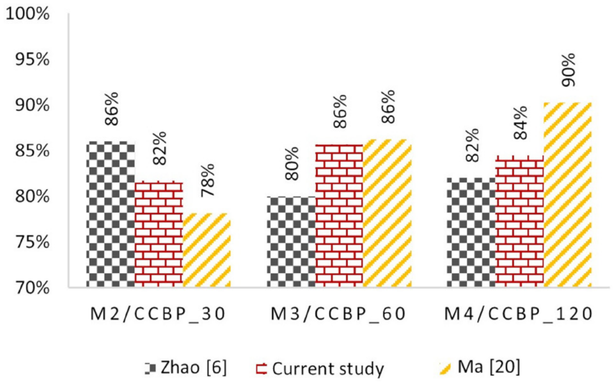


Fig. 15 Pozzolanic index comparison

greenhouse gas emissions, expressed in CO_2 equivalents. Nearly a third of these CO_2 emissions derive from fuel combustion, while the remainder come from process-related CO_2 emissions resulting from the decarbonation of limestone during calcination [35]. A typical calcination reaction is as follows Eq. (8):

$$CaCO_3 + heat \rightarrow CaO + CO_2 \uparrow . \tag{8}$$

This reality has led to the search for cement substitutes to reduce the environmental impact and costs of building materials. Several research studies have been conducted to reduce and/or offset the greenhouse gas emissions associated with cement production by seeking alternatives. The use of natural pozzolans can save contractors up to 25% per bag of cement [36]. Cementitious and pozzolanic materials are known to add value to mortar/concrete, not only in terms of mechanical properties and durability, but also in terms of energy efficiency and improved socioeconomic and industrial indicators [37].

These cement substitutes can therefore reduce the environmental impact and costs of construction materials. Indeed, several research studies have shown that the use of these materials can improve the environmental footprint of construction projects while providing equivalent or superior mechanical performance [38]. In addition, these materials can contribute to the reduction of construction waste and the reclamation of salvaged materials [39].

Table 6 presents the results of the environmental impact analysis of the materials studied, in terms of energy intensity, CO_2 emissions and cost. Cement has a relatively high energy intensity of 1,528 kWh/kg, and a significant CO_2 emission of 0,930 kg/kg. In addition, its cost is higher than that of CBP (1,635 DH/ton vs. 89 to 357 DH/ton for CBP). In comparison, CBP has lower energy intensities, ranging from 0.083 to 0.333 kWh/kg, and lower CO_2 emissions, ranging from 0.084 to 0.333 kg/kg. In terms of cost, they are also more advantageous than cement.

- Specific energy consumption (KWh/kg): the energy consumption (MJ) during the grinding of 1 kg of CBP.
- CO_2 emissions (kg/kg): the mass of CO_2 emissions (kg) during the grinding of 1 kg of CBP.
- Cost (DH/ton): the cost (DH) of shredding 1 ton of CBP.

It should be pointed out that the environmental impact analysis method used to obtain these results was borrowed from the study by Zhao et al. [6], which is based on input parameters similar to those used in our research. In this study, CBP of different particle sizes were ground in a ball mill in the laboratory, enabling their specific energy consumption and CO_2 emissions to be assessed. Brick waste, obtained free of charge from a factory based in Meknes, accounts for 40% of Moroccan brickworks production [40]. As for the cost of CBP, it was estimated taking into account industrial electricity consumption in Morocco, without taking into account waste collection and transport costs, in accordance with tariffs [41]. Table 7 presents the results of the sustainability analysis of cement mixtures, including a reference cement (MC_Ref) containing 80% cement and 20% CBP, as well as different mixtures containing various types of CBP.

The results obtained show that CCBP blends are more environmentally friendly than MC_Ref, thanks to their lower energy consumption and CO_2 emissions. In particular, CCBP_30 and CCBP_60 mixes reduce energy consumption and costs by 19% and 18%, respectively, while CO_2 emissions are reduced by about 18% and 16% compared to MC_Ref. Taking into account the quantities of cement and brick waste mentioned in the introduction of this paper, the use of brick powders ground for 30 and 60 minutes could result in annual savings of between 1.4 and 1.5 billion Dirhams.

It is essential to stress that our results are based on laboratory grinding of CBP and do not include the entire CBP life cycle. An exhaustive environmental assessment remains to be carried out to fully grasp the impacts of using CBP in cement mixes. Although the values of the sustainability indicators and the cost of CBP were derived from a laboratory context, we assume that these values

Table 6 Energy intensity, carbon emissions and cost of materials

Material	Specific energy consumption (KWh/kg)	CO_2 emissions (kg/kg)	Cost (DH/ton)
Cement	1.528	0.930	1,635
CBP_30	0.083	0.084	89
CBP_60	0.167	0.167	178
CBP_90	0.250	0.25	268
CBP_120	0.333	0.333	357

Table 7 Material sustainability indicators

Material	Specific energy consumption (KWh/kg)	CO_2 emissions (kg/kg)	Cost (DH/ton)
MC_Ref	1.528	0.930	1 635
CCBP_30	1.239	0.817	1 326
CCBP_60	1.256	0.833	1 344
CCBP_90	1.272	0.850	1 362
CCBP_120	1.289	0.867	1 379

would decrease significantly in industrial production, thanks to economies of scale. These promising results call for further studies to explore the environmental and economic efficiency of large-scale CBP use, offering an exciting avenue for a more sustainable cement industry.

5 Conclusions

This research evaluated the suitability of brick powder, obtained from crushed brick waste, to replace 20% of cement in mortar mixes. The main conclusions are as follows:

1. An increase in the fineness of brick waste, resulting from different grinding times, has a positive effect on the bulk density and spreadability of the mix.
2. CBP-based mortars have a higher water absorption, due to the ceramic present in the brick powder, but maintain a bulk density comparable to the reference mortar. Porosity is also higher, with no significant impact from the degree of fineness of the particles.
3. Regarding mechanical properties, an ultrasonic pulse velocity of 4000 m/s indicates good performance, while compressive strength can be improved by aligning the specific surface area of CBP with that of cement.
4. The pozzolanic activity index, ranging from 82% to 86%, suggests that CBP can be considered an effective pozzolanic material.
5. The use of CBP as a partial substitute for cement in mixes can contribute significantly to reducing the environmental impact of the construction industry.

This study demonstrates that the integration of brick waste crushed for 60 minutes represents a viable method for replacing part of the cement CEM II/A-V 42,5 V in the production of eco-responsible mortars. These conclusions encourage further research, particularly into the adjustment of the cement substitution rate for high-performance concrete.

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References

[1] Lim, C., Jung, E., Lee, S., Jang, C., Oh, C., Shin, K. N. "Global Trend of Cement Production and Utilization of Circular Resources", Journal of Energy Engineering, 29(3), pp. 57–63, 2020. https://doi.org/10.5855/energy.2020.29.3.057

[2] Wang, F., Long, G., Bai, M., Wang, J., Shi, Y., Zhou, X., Zhou, J. L. "A new perspective on Belite-ye'elimite-ferrite cement manufactured from electrolytic manganese residue: Production, properties, and environmental analysis", Cement and Concrete Research, 163, 107019, 2023. https://doi.org/10.1016/j.cemconres.2022.107019

[3] Ma, X., Shao, W., Cui, Z. "Energy and thermodynamic analysis of a typical cement production system based on experimental and simulated investigations", Case Studies in Thermal Engineering, 38, 102357, 2022. https://doi.org/10.1016/j.csite.2022.102357

[4] Peys, A., Isteri, V., Yliniemi, J., Yorkshire, A. S., Lemougna, P. N., Utton, C., Provis, J. L., Snellings, R., Hanein, T. "Sustainable iron-rich cements: Raw material sources and binder types", Cement and Concrete Research, 157, 106834, 2022. https://doi.org/10.1016/j.cemconres.2022.106834

[5] International Energy Agency (IEA) "Technology Roadmap - Low-Carbon Transition in the Cement Industry", IEA, Paris, 2018. [online] Available at: https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry

[6] Zhao, Y., Gao, J., Liu, C., Chen, X., Xu, Z. "The particle-size effect of waste clay brick powder on its pozzolanic activity and properties of blended cement", Journal of Cleaner Production, 242, 118521, 2020. https://doi.org/10.1016/j.jclepro.2019.118521

[7] Opon, J., Henry, M. "An indicator framework for quantifying the sustainability of concrete materials from the perspectives of global sustainable development", Journal of Cleaner Production, 218, pp. 718–737, 2019. https://doi.org/10.1016/j.jclepro.2019.01.220

[8] Département de l'environnement – Maroc, Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), "Etude d'état des lieux sur les déchets de construction et démolition au Maroc" (Inventory study on construction and demolition waste in Morocco), 2019. [unpublished]

[9] Enviro Consulting InterNational (ECI), MEVAC "Stratégie Nationale de Réduction et de Valorisation des Déchets"(National Waste Reduction and Recovery Strategy), 2019. [pdf] Available at: https://www.logipro.ma/images/Traitement_des_deee/Rapport_de_synthese_SNRVD_FR.pdf

[10] Zhao, Y., Gao, J., Xu, Z., Li, S., Luo, X., Chen, G. "Long-term hydration and microstructure evolution of blended cement containing ground granulated blast furnace slag and waste clay brick", Cement and Concrete Composites, 118, 103982, 2021. https://doi.org/10.1016/j.cemconcomp.2021.103982

[11] Aalil, I., Badreddine, D., Beck, K., Brunetaud, X., Cherkaoui, K., Chaaba, A., Al-Mukhtar, M. "Valorization of crushed bricks in lime-based mortars", Construction and Building Materials, 226, pp. 555–563, 2019. https://doi.org/10.1016/j.conbuildmat.2019.07.265

[12] Said-Mansour, M., Kadri, E.-H., Kenai, S., Ghrici, M., Bennaceur, R. "Influence of calcined kaolin on mortar properties", Construction and Building Materials, 25(5), pp. 2275–2282, 2011. https://doi.org/10.1016/j.conbuildmat.2010.11.017

[13] Si-Ahmed, M., Belakrouf, A., Kenai, S. "Influence of Metakaolin on the Performance of mortars and concretes", International Journal of Civil and Environmental Engineering, 5.0(11), pp. 1010–1013, 2012.
https://doi.org/10.5281/zenodo.1331725

[14] Kirgiz, M. S. "Effects of blended-cement paste chemical composition changes on some strength gains of blended-mortars", The Scientific World Journal, 2014, 625350, 2014.
https://doi.org/10.1155/2014/625350

[15] He, Z., Shen, A., Wu, H., Wang, W., Wang, L., Yao, C., Wu, J. "Research progress on recycled clay brick waste as an alternative to cement for sustainable construction materials", Construction and Building Materials, 274, 122113, 2021.
https://doi.org/10.1016/j.conbuildmat.2020.122113

[16] Letelier, V., Ortega, J. M., Muñoz, P., Tarela, E., Moriconi, G. "Influence of Waste brick powder in the mechanical properties of recycled aggregate concrete", Sustainability, 10(4), 1037, 2018.
https://doi.org/10.3390/su10041037

[17] Ortega, J. M., Letelier, V., Solas, C., Moriconi, G., Climent, M. Á., Sánchez, I. "Long-term effects of waste brick powder addition in the microstructure and service properties of mortars", Construction and Building Materials, 182, pp. 691–702, 2018.
https://doi.org/10.1016/j.conbuildmat.2018.06.161

[18] Arif, R., Khitab, A., Kırgız, M. S., Khan, R. B. N., Tayyab, S., Khan, R. A., Anwar, W., Arshad, M. T. "Experimental analysis on partial replacement of cement with brick powder in concrete", Case Studies in Construction Materials, 15, e00749, 2021.
https://doi.org/10.1016/j.cscm.2021.e00749

[19] Sinkhonde, D. "Modeling and experimental studies on energy consumption and properties of concrete containing waste brick powder and waste tire rubber for sustainable construction", Cleaner Engineering and Technology, 13, 100631, 2023.
https://doi.org/10.1016/j.clet.2023.100631

[20] Ma, Z., Tang, Q., Wu, H., Xu, J., Liang, C. "Mechanical properties and water absorption of cement composites with various fineness and contents of waste brick powder from C&D waste", Cement and Concrete Composites, 114, 103758, 2020.
https://doi.org/10.1016/j.cemconcomp.2020.103758

[21] Schackow, A., Stringari, D., Senff, L., Correia, S. L., Segadães, A. M. "Influence of fired clay brick waste additions on the durability of mortars", Cement and Concrete Composites, 62, pp. 82–89, 2015.
https://doi.org/10.1016/j.cemconcomp.2015.04.019

[22] AFNOR "NF EN 197-1: Ciment - Partie 1: composition, spécifications et critères de conformité des ciments courants" (Cement - Part 1: Composition, specifications and conformity criteria for common cements), Paris, France, 2012.

[23] AFNOR "NF EN 196-1: Méthodes d'essais des ciments - Partie 1: Détermination des résistances" (Methods of testing cement — Part 1: Determination of strength), Paris, France, 2016.

[24] Malvern Panalytical Ltd"Understanding and Using the Malvern Particle Analyzer: A Practical Guide to its Features and Functions", 2000. [online] Available at: https://www.malvernpanalytical.com/

[25] Naceri, A., Bouglada, M. S., Grosseau, P. "Mineral Activator and Physical Characteristics of Slag Cement at Anhydrous and Hydrated States", World Academy of Science, Engineering and Technology, 32, pp. 137-139, 2009.
https://doi.org/10.5281/zenodo.1080578

[26] IMANOR "NM ISO 17892-3: Reconnaissance et essais géotechniques - Essais de laboratoire sur les sols - Partie 3: détermination de la masse volumique des particules solides " (Geotechnical investigation and testing - Laboratory testing of soil- Part 3: determination of particle density), Rabat, Morocco, 2019.

[27] Holcim "Result Analysis Report", 2023. [online] Available at: https://www.holcim.com/investors/publications/results-and-presentations

[28] Irki, I., Debieb, F., Ouzadid, S., Dilmi, H. L., Settari, C., Boukhelkhel, D. "Effect of Blaine fineness of recycling brick powder replacing cementitious materials in self compacting mortar", Journal of Adhesion Science and Technology, 32(9), pp. 963-975, 2018.
https://doi.org/10.1080/01694243.2017.1393202

[29] Mansoor, S. S., Hama, S. M., Hamdullah, D. N. "Effectiveness of replacing cement partially with waste brick powder in mortar", Journal of King Saud University - Engineering Sciences, 2022.
https://doi.org/10.1016/j.jksues.2022.01.004

[30] Majdi, H. S., Shubbar, A. A., Nasr, M. S., Al-Khafaji, Z. S., Jafer, H., Abdulredha, M., Al Masoodi, Z., Sadique, M., Hashim, K. "Experimental data on compressive strength and ultrasonic pulse velocity properties of sustainable mortar made with high content of GGBFS and CKD combinations", Data in Brief, 31, 105961, 2020.
https://doi.org/10.1016/j.dib.2020.105961

[31] Parsompech, N., Rianyoi, R., Chaipanich, A. "Compressive strength, water absorption and pulse velocity tests of calcined clay-limestone cement mortars", Materials Today: Proceedings, 65, pp. 2394–2398, 2022.
https://doi.org/10.1016/j.matpr.2022.05.526

[32] Naceri, A., Hamina, M. C. "Use of waste brick as a partial replacement of cement in mortar", Waste Management, 29(8), pp. 2378-2384, 2009.
https://doi.org/10.1016/j.wasman.2009.03.026

[33] Savadogo, N., Messan, A., Hannawi, K., Tsobnang, F., Agbodjan, W. P. "Durability of composite cement with Tefereyre (NIGER) coal bottom ash: Capillary absorption, porosity to water and acid attack", Journal of Materials and Engineering Structures, 2, pp. 213-223, 2015. [online] Available at: https://www.asjp.cerist.dz/en/downArticle/246/2/4/117934

[34] Cherkaoui, K. "Characterization of the microstructure and short- and long-term behavior of an Extrudable Reactive Powder Concrete", PhD Thesis, University of Evry-Val d'Essonne, 2010.

[35] Izumi, Y., Iizuka, A., Ho, H.-J. "Calculation of greenhouse gas emissions for a carbon recycling system using mineral carbon capture and utilization technology in the cement industry", Journal of Cleaner Production, 312, 127618, 2021.
https://doi.org/10.1016/j.jclepro.2021.127618

[36] Huntzinger, D. N., Eatmon, T. D. "A life-cycle assessment of Portland cement manufacturing: comparing the traditional process with alternative technologies", Journal of Cleaner Production, 17(7), pp. 668–675, 2009.
https://doi.org/10.1016/j.jclepro.2008.04.007

[37] Meddah, M. S., Benkari, N., Al-Saadi, S. N., Al Maktoumi, Y. "Sarooj mortar: From a traditional building material to an engineered pozzolan -mechanical and thermal properties study", Journal of Building Engineering, 32, 101754, 2020.
https://doi.org/10.1016/j.jobe.2020.101754

[38] Poon, C. S., Kou, S. C., Lam, L. "Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete", Construction and Building Materials, 20(10), pp. 858–865, 2006. https://doi.org/10.1016/j.conbuildmat.2005.07.001

[39] Amran, M., Onaizi, A. M., Qader, D. N., Murali, G. "Innovative use of fly ash-finely powdered glass cullet as a nano additives for a sustainable concrete: Strength and microstructure and cost analysis", Case Studies in Construction Materials, 17, e01688, 2022. https://doi.org/10.1016/j.cscm.2022.e01688

[40] Aalil, I. "Contribution to the study of the built heritage: methods of diagnosis of pathologies of the structures and means of restoration. Case study: the archaeological site of Volubilis in Morocco", PhD Thesis, University of Orleans, 2017.

[41] Global Petrol Prices "Morocco electricity prices" [online] Available at: https://www.globalpetrolprices.com/Morocco/electricity_prices/