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HYDROTHERMAL AND MECHANICAL PERFORMANCE OF MORTARS CONTAINING WASTE BRICK POWDER

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Abstract. It is widely recognised that green building, environmental sustainability, and technical performance have recently become requirements in the field of civil engineering. For this reason, the new trend in research is to focus on the recycling and recovery of materials, even if some of them such as industrial waste are still underexplored. In this perspective, the main objective of this work is to study the influence of brick powder on the thermophysical and mechanical properties of mortars containing this type of waste, in different environments, and within the temperature range between ambient temperature and 50 °C. To this end, a number of mortar mixtures, in which cement was replaced by brick powder in different proportions, were studied and characterised according to technical standards in order to define the optimal substitution percentage. Three batches of samples were examined at different ages, i.e., 3, 7, 28, and 90 days. The samples of the first batch were kept in water at a temperature of 20 ± 2 °C with a relative humidity RH = 100 %, while those of the second batch were immersed and stored in water at 50 °C in order to simulate a hot and humid climate. As for the samples of the third batch, they were kept in a dry oven at 50 °C in order to investigate the effect of the hot and dry climate. The results obtained revealed that the partial replacement of cement by brick powder makes it possible to improve the thermal insulation characteristics but reduce the mechanical strength of the mortar. In addition, it was shown that in a hot and dry environment, the mechanical characteristics of the different mortars decrease as the rate of weight substitution of cement by brick powder rises. However, in a hot and humid environment, a reverse trend is observed. The findings also suggested that the optimal recommended rate of substitution of cement by brick powder is 20 %.

Keywords: Cement mortar, brick powder, mechanical strength, conductivity, temperature.

1. Introduction

It is widely known that mortar is a workable paste that hardens in order to bind and join building blocks such as stones, bricks, and concrete masonry units and to fill and seal the irregular interstices between them. Mortar generally includes cement, sand, water, and some admixtures. It should also be noted that the manufacture of cement, which is the main component of mortars, requires considerable amounts of energy and engenders the emission of significant quantities of greenhouse gases into the atmosphere. These gases have been shown to be primarily responsible for global warming [1]. It has been revealed that a quantity of CO_2, varying between 0.9 and 1 tonnes is produced for 1 tonne of clinker, which corresponds to approximately 900 g of CO_2 that is released into the environment per day, and per inhabitant. In addition, the current high demand for cement contributes to the progressive and rapid depletion of natural resources, and therefore leads to the production of different types of waste products, not to mention the accompanying costs. Therefore, it is crucial to integrate the approach of sustainable development in the manufacturing process of essential building materials since this will certainly help to ensure a balance between the constraints of environmental protection and economic and social considerations [2]. It is worth indicating that the production of cements containing pozzolanic additives is increasingly growing throughout the world. Moreover, in order to meet the rising demands for construction materials, researchers have recently become increasingly interested in recycling and recovering various types of waste materials that are widely abundant in nature or even those resulting from the demolition of old buildings.

It was found that incorporating industrial waste in the form of additions of very fine crumbs during the manufacture of cement could constitute a complementary and effective solution that can help to significantly reduce the amount of CO_2 released to the atmosphere. Today, this alternative caught only limited attention from professionals, who are faced with regulatory restrictions, and with the absence of in-depth studies on this subject [3]. It is worth indicating that since the 1970s, a large number of research studies have been conducted on the possibility of using cementitious additives as a partial replacement of Portland cement. These additives can come either from natural sources or may be a by-product from various industries [4]. It is interesting to mention that additives have a binding activity that depends on the fineness and mineralogical composition as well as the quantity used [5–7].

Hence, over the past few years, several researchers [8–16] have become increasingly interested in recycling and recovering various industrial waste materials, such as marble, brick, glass, plastic, ash, slag from blast furnaces, and others, in order to use them in the manufacturing process of building materials and to respond to ecological concerns as well. One of the solutions proposed consists of recovering waste in order to use it in the field of public construction (infrastructure, backfilling materials, subgrade, and surfacing), or to develop new eco-construction materials and use them as aggregates in concrete or as additives, such as fillers, binders, or stabilisers, in cementitious matrix of mortars. Unfortunately, it turned out that some of these applications present some limitations that are mainly attributed to the lack of clear regulations and sufficient technical data on their rheological, thermal, mechanical performance, durability, etc.

It has been revealed that the development of new mortars based on brick powder could present an interesting alternative. Several research works have recently been carried out in order to evaluate the potential use of crushed bricks as coarse and fine aggregates in the production of building materials [17–20]. Thus, a number of feasibility studies [8, 21–24] have focused on the manufacture of composite cement based on finely ground brick waste. The above-mentioned research [8, 21–24] comprehensively examines the behaviour of brick crumb mortars under normal conditions, but does not address the effect of crucial variables, such as temperature and environment, particularly in hot and dry or hot and humid climates. Although these studies provide valuable insights into the properties and performance of mortars, the lack of consideration of these environmental factors may limit the applicability of their findings. Understanding how these mortars react in different climatic conditions is essential to assess their durability and adaptability in regions subject to extreme temperatures or high humidity. Therefore, future research that integrates these aspects could provide a more holistic view of the behaviour of brick crumb mortars and their suitability in different environmental contexts. It should be noted that most researchers [25–27] have focused on the recycling and valorisation of crushed bricks in the form of coarse aggregates to be used in concrete. The major problem of not using waste brick powder (WBP) from finely crushed bricks is probably since the preparation of mortar requires large amounts of water. In this regard, several authors asserted that the compressive strength of cement-brick powder mortars at 28 days [28, 29] decreases due to the absorption of a large amount of water by the brick aggregates, which is not the case for natural aggregates. Therefore, in order to overcome this compressive strength reduction, some researchers found out that the incorporation of micro-silica into mortar as a replacement for cement should significantly improve the mechanical properties of the material, because micro-silica acts as a filler material, and therefore reduces porosity and helps to make the cementitious mixture denser [30–33]. Other studies have focused on the water retention capacity of hydrated lime mortars modified by brick dust and the effect of the latter on the pozzolanic behaviour of mortars [34]. Furthermore, it should be noted that the quality of the prepared mortars or concrete depends mainly on their composition, but also on the drying and hardening conditions during the first hours, or even during the first days, of their life [35]. It has indeed been shown that the mechanical performance, physical and thermal properties of mortar during the hardening period, in a hot and dry or hot and humid climate, can be different. However, some researchers found that, under harsh conditions, certain properties can sometimes be improved by incorporating mineral additives [36, 37]. It has also been reported that under similar climatic conditions, concreting without effective curing can lead to significant disadvantageous effects on the rheological properties and long-term durability of the mortar due to the acceleration of the hydration process. It has also been shown that cement hydration on the surface of an exposed element can cease if the relative humidity (RH) of the surrounding air is sufficiently low [38]. For this, Powers et al. [39] suggested that cement hydration practically ceases when the relative water vapour pressure in the capillaries is less than 0.8. Spears [40] asserted that continuous hardening, below 80 % relative humidity, does not contribute to increasing the hydration of the cement that is necessary in order to further improve the quality of the concrete. It is worth emphasising that, in practice, construction site concrete is daily subjected to humidity cycles corresponding to seasonal variations and active hardening may stop before the cement is fully hydrated [38]. Finally, limited studies have been carried out on the effect of temperature in different environments on the mechanical behaviour of mortars based on brick powder as a partial substitute for cement by weight, however, additional research is needed to adequately study the thermophysical and thermomechanical properties of mortars containing a certain percentage of brick powder as a replacement for cement by weight.

Additionally, brick crumb mortars offer a combination of properties that make them suitable for a range of applications in wet and dry, ambient and elevated temperature environments, whilst providing additional ecological benefits including:

(1.) Resistance to frequent humidity (bathrooms, kitchens or outdoor areas),

(2.) dimensional stability (mortars do not contract or expand excessively in response to variations in humidity or temperature),

(3.) adhesion of mortars based on brick crumb to covering surfaces where humidity is a constant challenge [41],

(4.) resistance to corrosion (coastal areas or industrial installations)

(5.) thermal insulation in a variable high temperature environment,

(6.) increased durability: Due to their resistance to humidity and corrosion, brick crumb mortars tend to be more durable in environments where these factors are predominant, reducing maintenance needs and long-term replacement.

The main objective of this research is to investigate the possibility of valorising brick waste for the manufacture of cementitious eco-composites which, in this case, can be repair and facade mortars, and used to cover and protect, such as when applied as screeds, renders and plasters. On account of the above, a number of mortar formulations in which cement was replaced with powdered bricks at various rates, namely 10 %, 20 %, and 30 %, was prepared. In addition, the effect of mortar curing conditions for hot and humid or hot and dry natural climate was analysed. An experimental study was also carried out on the thermophysical and mechanical properties of the different mortar mixtures in the hardened state under different conditions of temperature and relative humidity. It is useful to remember that one of the major objectives of the study is to assess the satisfactory improvement in the mechanical and thermal behaviour of mortar following the incorporation of brick powder in order to develop a construction material that is, at the same time, economical, efficient, and ecological.

2. Experimental study

2.1. Materials used

2.1.1. Cement

The cement CEM I 52.5N was employed to create the mortars in this study. This cement is from the Lafarge Cement Production Plant at La Malle in France and is compliant with Standard EN 197-1 [42]. It should be noted that this cement contains practically only clinker (95 %), with about 5 % gypsum, which is used to regulate the setting. Its Blaine surface is estimated at 3 480 $cm^2\,g^{-1}$, and its absolute density is 3.15 $g\,cm^{-3}$. The initial and final setting times of this cement are 200 and 260 minutes, respectively. Moreover, the preliminary chemical analysis showed that this clinker complies with Standard NF P 15-301 [43] and contains less than 5 % of the mixture (MgO + CaO (free)). Its potential mineralogical composition can be calculated according to the empirical formula of Bogue [44]. The chemical and mineralogical compositions are shown in Tables 1 and 2, respectively.

Constituents	Cement [%]
SiO_2	19.61
Al_2O_3	4.71
Fe_2O_3	3.15
CaO	63.45
MgO	3.4
SO_3	2.24
K_2O	0.73
Na_2O	0.21
Cl	0.03

Table 1. Chemical composition of cement.

Constituents	Value [%]
Rwp Alite M3	5.632
Alite M1	35.19
Alite Sum	23.17
FractionM1	39.71
Alite CS	175.95 mn
Belite_beta	12.54
Alum_cubic	2.71
Alum_ortho	5.07
Alum_Sum	7.78
Ferrite	8.73
Lime	0.08
Portlandite	1.37
fCaO_XRD	1.11
Periclase	2.49
Quartz	0.18
Arcanite	1.14
Calcite	4.16
SO_3_XRD	2.25
Gypsum	0.14
Hemi-hydrat	2.96
CO_2_XRD	1.83
Aphthitalite	0.07

Table 2. Mineralogical composition of cement.

2.1.2. Sand

The sand used in the mortar mixtures is a quartz quarry sand with a maximum grain size range of 0–2 mm. This sand is characterised by a fineness modulus of 2.40 with a specific and apparent density of 2.72 $g\,cm^{-3}$ and 1.71 $g\,cm^{-3}$, respectively. It is dried and sifted in a laboratory providing absolute consistency.

2.1.3. Brick powder

Brick Waste (BW) for this study was obtained from a brick manufacturing plant located in Henaya municipality (department of Tlemcen, Ouesthern Algeria).

(a). Raw materials. (b). Grinding at the factory. (c). Materials after 1st grinding.

(d). Grinder in the laboratory. (e). Materials after 2nd grinding. (f). Blaine's surface control.

Figure 1. Preparation process of waste brick powder.

Brick powder is obtained by crushing and grinding waste clay bricks. The grinding is usually carried out using a conventional ball mill. In this study, the composition and quantity of the crushed materials as well as the grinding times are kept constant. Afterwards, after a given settling time, the resulting material is sifted through sieves with diameters less than 63 µm, as illustrated in Figure 1. It was found that the absolute density of the material obtained was between 2.60 and 2.70 $\mathrm{g\,cm^{-3}}$, with a specific surface equal to 2 700 $\mathrm{cm^2\,g^{-1}}$. As for the chemical composition of the brick powder used in this study, it is shown in Table 3. Environmental pollution can be reduced by using recycled powder as a cementing material.

Constituents	**Brick powder** [%]
SiO_2	43.84
Al_2O_3	13.06
Fe_2O_3	5.09
CaO	10.99
MgO	3.45
SO_3	0.43
K_2O	0.96
Na_2O	0.45
Cl	0.02
P_2O_5	0.19
TiO_2	0.69
AM	2.57
SM	2.42
LSF	7.77

Table 3. Chemical composition of brick powder.

2.2. Preparation of mortar specimens

The experimental study was designed to investigate the influence of incorporating the brick powder into the mixture on the thermophysical and mechanical properties of different mortar mixtures, in the fresh and hardened state, and under different temperature and relative humidity conditions. It should equally be noted that the seasonal climatic conditions can be considered as simulating the Saharan and coastal regions. Regarding the composition of the mortar mixtures, they were all prepared with a ratio $\frac{\text{Water}}{\text{Cement+Addition}}$ constant and equal to 0.58. This was done for the purpose of highlighting the effect of the nature of the additions used on the properties of the prepared mortars and also to obtain better mechanical strength with constant workability, according to the standard EN 196-1 [45]. It should also be noted that three brick powder contents, i.e. 10 %, 20 % and 30 %, were selected to replace the dry cement in the mixes. In addition, before the preparation of the various specimens, the cement (C) and the brick powder (BP) were mixed well in order to obtain a completely homogeneous mixture (C-BP).

It is important to note that the base mortar includes CEM I cement only (rated Mi-0 %). It contains three parts of sand (1 350 g), one part of cement (450 g), and a half-part of water (225 g), in accordance with Standard EN 196-1 [45]. Note that all mixes contain the same proportions of sand and water as the base mortar (Mi-0 %). These mixtures are denoted Mi-BPX %, with X % representing the mass percentage of substitution of cement by brick powder. An electronic scale with an accuracy of 0.1 g was used to weigh

N°	Cement [g]	Brick powder (BP) [g]	Quarry sand [g]	Water [g]
M0-0	450	0	1 350	261
M1PB10	405	45	1 350	261
M2PB20	360	90	1 350	261
M3PB30	315	135	1 350	261

TABLE 4. Proportions of mixtures for one batch.

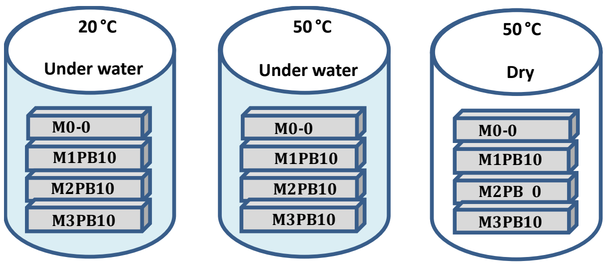


FIGURE 2. Storage of specimens in different media.

the ingredients during the preparation of the different mortar mixtures.

Table 4 shows the proportions of the materials used in the composition of the mortars examined in this study. Several mortar specimens, measuring $(4 \times 4 \times 16)\,\mathrm{cm}^3$, containing different concentrations of brick powder, were prepared. Four cement mortar mixtures were prepared with different BP amounts. The resulting mixutres differed in the amount of BP addition, which was 0 %, 10 %, 20 % and 30 %, replacing the weight of the cement. They were removed from their moulds 24 hours after their manufacture. In addition, three media simulating different hardening states, which in the present case are critical climatic conditions that are typical of Saharan and coastal regions, were tested:

- The first state corresponds to a hot and dry environment. In this case, the samples were introduced into a temperature-controlled oven set at 50 °C, and dry.
- For the second state, the samples were directly immersed in tanks filled with tap water and kept in an oven in a warm environment at a temperature $T = (50 \pm 2)$ °C.
- For the third and last state, the samples were directly immersed in tanks filled with tap water at temperature $T = (20 \pm 2)$ °C, as shown in Figure 2.

It is worth emphasising that all samples were kept as expected until the test deadlines, in accordance with Standard BS EN 12390-2 [46]. In addition, the age of the specimens was calculated from time zero, which corresponds to the first moment from the start of mixing. Note also that, in this study, mortar M0-0% is taken as the reference mixture when different properties were measured.

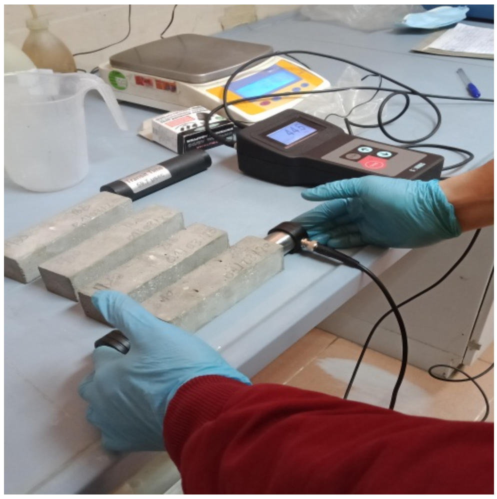


FIGURE 3. Ultrasonic pulse velocity test method for mortar.

Among the wide range of tests that can be carried out on the various mortars prepared, the choice was made according to the most essential characteristics, namely the compressive strength test, bending tensile test, modulus deformation by ultrasonic testing, and tests to measure the thermophysical properties, such as the thermal conductivity λ, the thermal diffusivity α, and the specific heat CP. It is worth specifying that the samples used for the thermophysical measurements are those that were immersed and kept in water tanks at $T = 20$ °C during the hardening period.

2.3. MEASUREMENT OF MECHANICAL PROPERTIES

2.3.1. DEFORMATION MODULUS

This modulus can be determined by means of non-destructive ultrasonic testing which consists of sending ultrasonic waves through the mortar via a transmitting transducer. For this, an ultrasonic pulse is sent across the mortar specimen to be tested, and the time taken by the pulse through the sample is measured in order to calculate the speed of pulse propagation inside the material, at 28 and 90 days as per to ASTM C642 [47] as depicted in Figure 3. Afterwards, the speed thus calculated allows evaluating the elastic modulus given that the Poisson's ratio of the tested material is already known.

The measuring device used in this work is an ultrasound generator that is connected to two wave transducers, i.e. a transmitter and a receiver, which are coupled to each other. They are aligned on two parallel surfaces of the sample to be tested. The acoustic contact between the transducer and the sample is ensured by means of petroleum jelly; the transducer is then pressed against the surface of the mortar specimen. Afterwards, a longitudinal ultrasonic pulse of approximately 20 kHz is emitted by the transmitter and is then received by the receiver that is placed on the opposite surface. This device is intended to measure the transit time of the pulse. For an elastic material, the relationship between the speed of the pulse, the elastic constants, and the density of the mortar tested is used to determine the dynamic modulus of elasticity that is given below:

$$E = \left(\frac{L}{t}\right)^2 \frac{\rho\,(1+\nu)\,(1-2\nu)}{1-\nu}, \tag{1}$$

where

E is the elastic modulus,

L is the distance separating the two transducers,

t is the pulse time,

ρ is the actual density of the eco-mortar used,

ν is the Poisson's ratio.

We set ν equal to 0.3, the usual value for mortars.

2.3.2. Compression and tensile strength

The compressive strength test and bending tensile tests of all the mixtures were carried out according to the Standard EN 197-1 [42]. Three specimens were examined in each test. It should be noted that the half-samples resulting from the bending tensile test were crushed by compression (six specimens per formulation and per term) using an automated mortar press, at a speed of 2.4 kN s^{-1}, as shown in Figure 4.

2.3.3. Measuring the thermophysical properties of mortar

The thermophysical properties of the different brick powder-based mortars were determined using the Hot Disk (HD) transient method using the international standard ISO-22007-2 [48]. The HD analyser uses a sensor element in the shape of a double hairspring, as shown in Figure 5. Its working principle is based on the transient plane source (TPS) method. This sensor acts both as a heat source for increasing the temperature of the sample and as a resistance thermometer for recording the time-dependent temperature increase. In addition, the spiral is supported by an unfilled polyimide thermoplastic material (Kapton insulator) for protection and electrical insulation. Figure 5 clearly shows that the sensor is sandwiched between two halves of the sample.

The hot disk (HD) technique is employed for simultaneously evaluating the thermal conductivity λ [W m^{-1} K^{-1}] and the thermal diffusivity α [m^2 s^{-1}] in a rapid, accurate, and non-destructive way [2].

Figure 4. Tensile and compression testing machine.

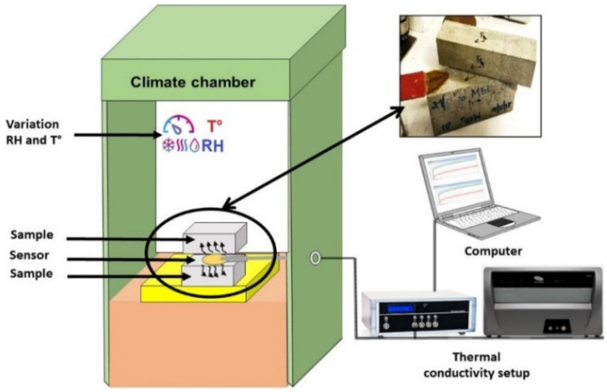


Figure 5. Apparatus for measuring the thermophysical properties of mortar.

Moreover, since the thermophysical properties of porous building materials can depend on several factors other than temperature and moisture content, it is highly recommended to perform the measurements in a well-controlled environment.

It is worth noting that all samples investigated in this study were conditioned to the temperature of 20 °C and 50 % of relative humidity in a climatic chamber, for three weeks, until weight stabilisation. This procedure allows monitoring the humidity of samples because moisture can have a significant effect on the measurement of mortar thermophysical properties. To do this, several measurements were performed at room temperature for each surface of the sample, while changing the probe position and the sample side. In the end, the mean values of the thermal conductivity, diffusivity, specific heat measurements as well as their uncertainties for mortar and brick powder-based mortar composites were calculated.

Furthermore, for the purpose of studying the effect of moisture on the thermophysical properties, the same mortar samples were then kept in an oven at 50 °C for a period of one week in order to achieve dry state before measuring the thermophysical properties. Finally, to perform measurements in the moist state, the samples were placed once again in a climatic room at 100 % relative humidity for a period of one month before performing the measurements.

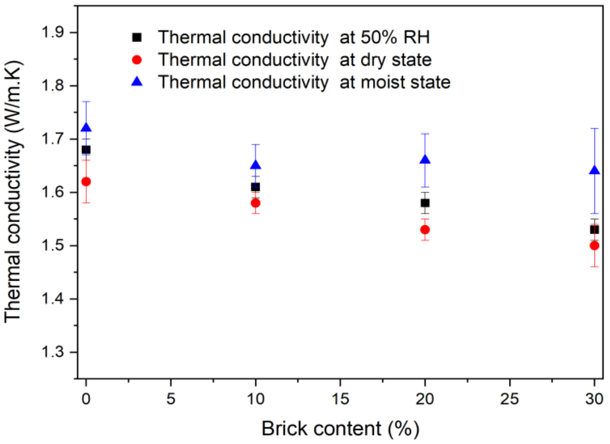


FIGURE 6. Thermal conductivity of brick powder based mortar composites at different moisture contents.

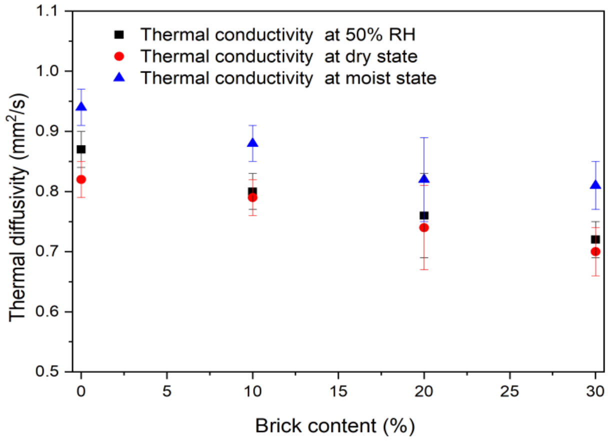


FIGURE 7. Thermal diffusivity of brick powder based mortar composites at different moisture contents.

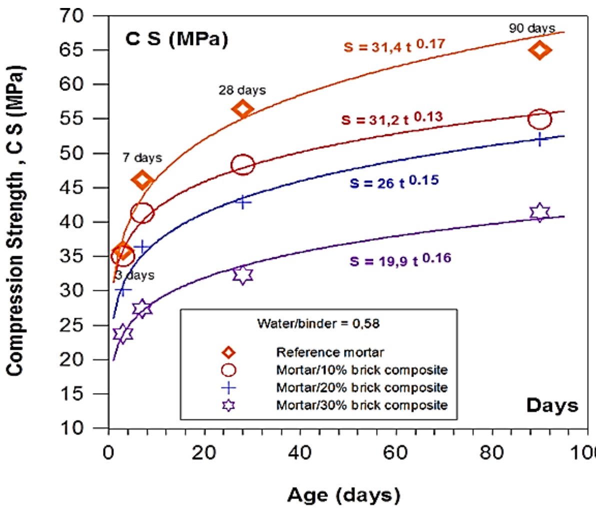


FIGURE 8. Evolution of the compressive strength of the different mortars in an ambient environment.

3. RESULTS AND DISCUSSION

3.1. HYDROTHERMAL PROPERTIES OF BRICK POWDER-BASED MORTAR COMPOSITES

With the aim of examining the effect of moisture on the thermophysical properties of the mortar specimens, while the brick powder content varied, several measurements were performed in a climatic chamber with 50 % RH. The moist state and dry state are shown in Figure 5.

Figures 6 and 7 show both the thermal conductivity and the thermal diffusivity behaviour and their uncertainties for the three investigated states. One can easily see that when the brick powder content in the mixture increases, both the thermal conductivity and the thermal diffusivity decrease. This may certainly be attributed to the difference between the thermal conductivity of a brick ($0.85\,\mathrm{W\,m^{-1}\,K^{-1}}$) and that of mortar ($1.78\,\mathrm{W\,m^{-1}\,K^{-1}}$). In fact, at 50 % RH, we notice that the thermal conductivity decreased by 12 % and the thermal diffusivity decreased by 17 % for the formulation M3PB30 compared to the neat mortar.

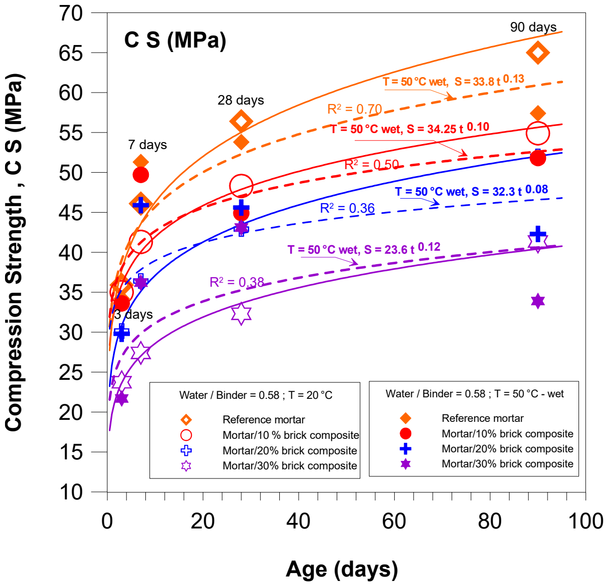
Furthermore, both Figures 6 and 7 explicitly show the difference in thermophysical behaviour when the relative humidity conditions of the samples are changed (dry and moist states). This difference suggests that the impact on the thermophysical properties of materials is higher in the moist state than in the dry state, due to the water content. The increase in the thermal conductivity and diffusivity remains constant as the brick powder content changes. This increase was estimated at 9 % for the thermal conductivity and 11 % for the thermal diffusivity.

3.2. THERMOMECHANICAL BEHAVIOUR OF BRICK POWDER BASED MORTARS

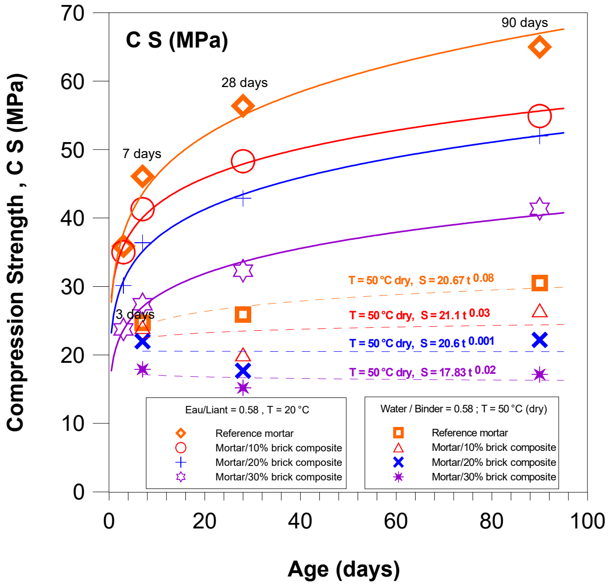
The obtained results of compressive and flexural strength tests for the different mixtures were discussed and compared with those of the reference mortar, according to the different dosages and curing times (3, 7, 28 and 90 days), and under different climatic. With regard to the formulation of the mortars studied in this work, mixtures were prepared with identical consistencies, i.e. spreading on the vibrating table of about (18 ± 2) cm. This was done to produce mortars that are easy to apply.

Figures 8, 9, 10, and 11 show the evolution of the compressive and tensile strength at ambient temperature (20 °C) and at high temperature (50 °C) in hot and humid environments, respectively, for the reference mortar as well as for the different brick powder-based mortars, and for different ages. According to Figure 8, the compressive strength of the reference mortar increased from 36 to 65 MPa for the age in the range of 3 to 90 days. The same observations are made for the other brick powder-based mortars (M, % PB). It was also observed that the compressive strength of the mortar containing 10 % brick powder is higher than that of mortars containing 20 % or 30 % BP, this is true for all ages.

It can clearly be seen that the strength increase as a function of cure time follows a nonlinear trend;



(A). Hot and humid environment.



(B). Hot and dry environment.

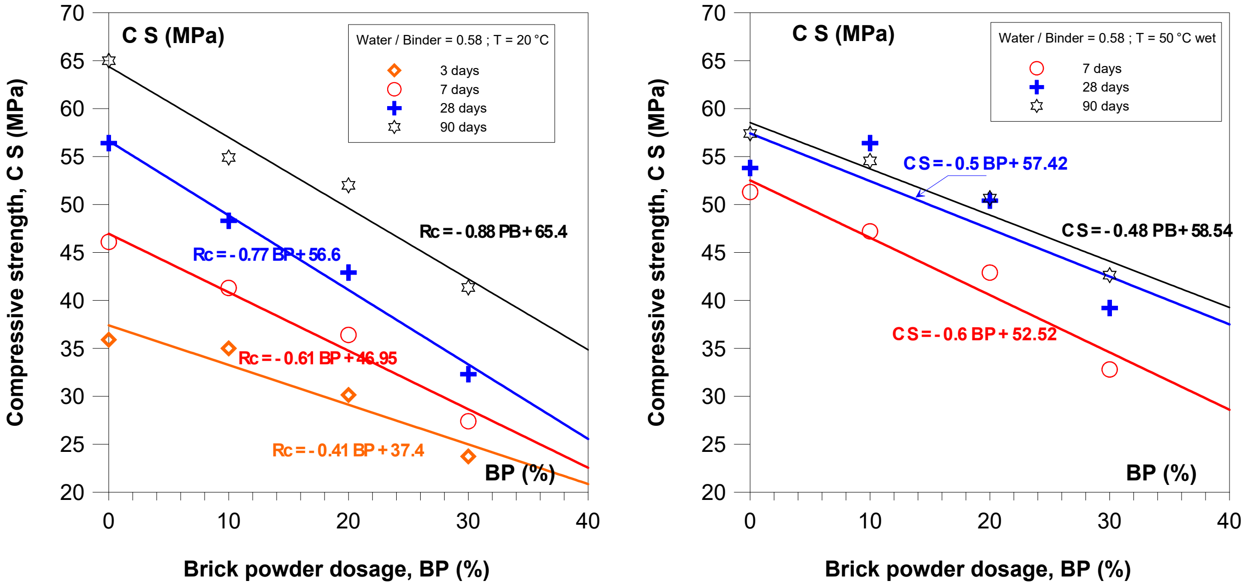
FIGURE 9. Evolution of the compressive strength of different mortars in a hot and humid environment and a hot and dry environment.

it can be expressed using a power function of the form: CS $= At^B$, where S is the strength, t the time (days), and A and B are constants. This is true regardless of the percentage of brick powder (BP) used. The strength values of mortar samples including 10 % of BP vary between 35 and 54.90 MPa, which represents an improvement rate of 85 % compared to the reference mortar, while those of samples containing 20 % and 30 % BP, vary between 30.14 and 52 MPa, and between 23 and 41.35 MPa, respectively. Which translates to an improvement rate of 80 % for the case of 20 % brick powder and 64 % for the case of 30 % brick powder. This can be attributed to the high-water absorption capacity of the brick waste (BW) aggregate (16 %). This high hygric characteristic is caused by the affinity of BW to water as well as its porosity (50 %), as indicated by Boukour et al. [49]. These strength values are considered as acceptable for mortars intended for filling or repair. It should be noted that the brick waste used in the mortars is recovered from bricks fired at 900 °C, this causes a slightly lower resistance than that of the reference mortar. This phenomenon of decrease in resistance was also explained by Dos Reis et al. [50], where they present results showing that CS of a brick depends on the firing temperature. Indeed, in the work of Dos Reis et al. [50], the CS values of brick samples fired at 800 °C reached higher CS values than those of fired at 1 000 °C, hence the reduction in resistance brick-based mortars when the rate of replacement by bricks exceeds 10 % (low pozzolanic effect and the specific surface area of brick crumb is lower than that of cement).

Regarding the case with the temperature set at 50 °C with humid climate (100 % RH), it can be noted that the strength increase at young age is similar to that of the different mixtures prepared and cured in an ambient environment. It should be noted that the compressive strength continued to increase up to 90 days (Figure 9a). This is primarily due to the continued hydration of cement and the presence of sufficient moisture in the cementitious matrix of the various mixtures as well.

However, after 28 days, the compressive strength in a hot and humid environment (Figure 9a) is always lower than that of the mixtures cured in an ambient environment (20 °C). Furthermore, it was noted that after 7 days, the strength of the reference mortar increased from 51.3 to 57.40 MPa, whereas that of mortars containing 10 % of brick powder increased from 47.2 to 54.55 MPa, this means a resistance rate varying from 92 % to 95 % compared to the reference mortar. However, for mortars with 20 % BP, this strength increased from 42.90 to 50.66 MPa, i.e. a rate of 84 % to 88.3 % compared to the reference mortar, while for mortars with 30 % BP, the strength ranged between 32.80 and 42.63 MPa, which represents a rate of 64 % to 74.3 %, compared to the reference mortar. For the mortar with 30 % BWP, we observe a clear improvement in resistance at a very young age, this is due to the acceleration of hydration under the effect of temperature, which leads to the formation of an additional hydrated calcium silicate, CSH [51, 52]. This gain in resistance is also observed in the other mixtures of 10 % and 20 % brick powder at a very young age.

Figure 9b shows the results related to the compressive strengths of cured mortars in a hot and dry environment, i.e. 50 °C and 0 % RH. It can be seen that the strength increase was interrupted due to the lack of water by capillary rise during the hydration process. Consequently, in a hot environment and in the presence of a low humidity rate, very low resistances



(A). Ambient environment. (B). Hot and humid environment.

FIGURE 10. Evolution of the compressive strength as a function of brick powder dosage for different mortars in an ambient environment and a hot and humid environment.

were observed for the various mixtures regardless of the brick powder percentage. That is, in such an environment, the compressive strength practically does not change. These results are in good agreement with those reported by Spears [40].

Similarly, Figures 10a and 10b show the evolution of the compressive strength of mortars as a function of the brick powder (BP) dosage, for standard hardening under different temperatures (20 °C and 50 °C) for humid climate. For example, at an advanced age, as at 90 days (Figure 10a), the compressive strength is estimated at 52 MPa which is lower than that of the reference mortar (around 65 MPa). The same observations were noted for the other mortars containing different BP percentages. As such, the findings are as follows: Rc90 (M1-PB10) = 54.90 MPa > Rc90 (M2-PB20) > Rc90 (M3-PB30) = 41.35 MPa, which shows a slight decrease in performance of around 15 %. It is also observed that the values obtained for the mechanical strength are acceptable without, however, reaching that of the reference mortar.

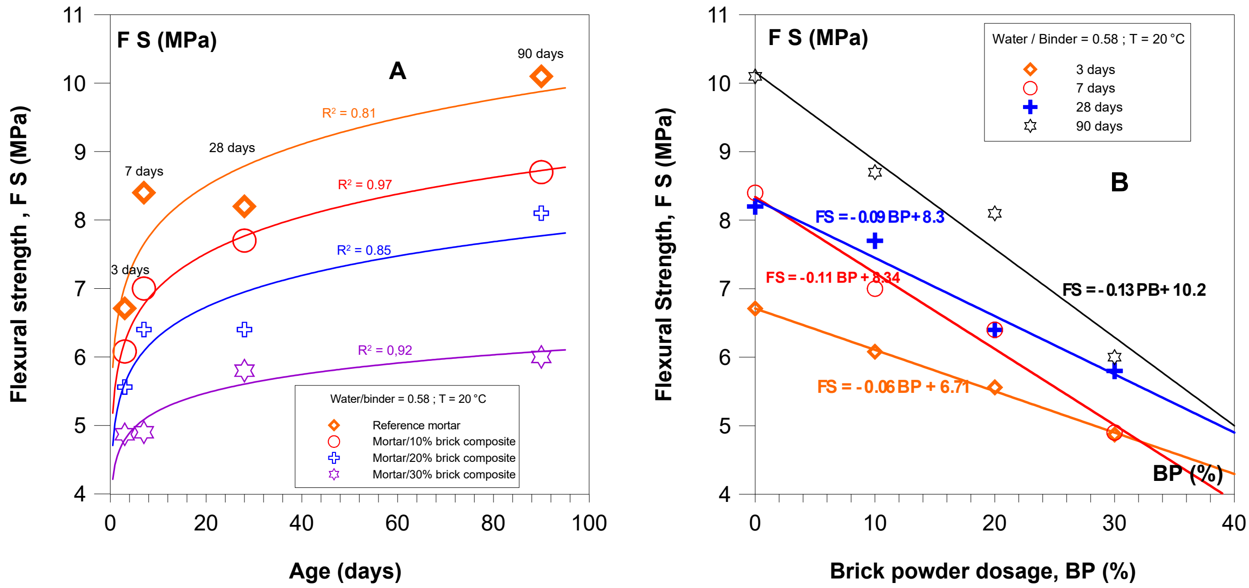
It is noted that the compressive strength decreases as the brick powder content increases (Figure 10b). In other words, the substitution of cement by brick powder is accompanied by a drop in performance, especially at young ages. This compressive strength drop is quite significant, for brick powder dosages greater than or equal to 20 %, in comparison with the values recommended by the French Association of Civil Engineering (FACE).

Furthermore, one may say that the decrease in strength is attributed, to the specific surface of the brick powder, which is smaller than that of pure cement ($2\,690\,cm^2\,g^{-1} < 3\,480\,cm^2\,g^{-1}$), and to the increase in porosity due to the larger quantity of water absorbed by the brick powder. The porosity increase engenders a slower hydration of cement. This strength is due to the hydration of several hydraulic compounds that form hydrated calcium silicates (commonly CSH phases) as the main compounds [53].

Figure 11a indicates that the flexural tensile strength values of the different mortars made by partially replacing cement by the brick powder represent increasing functions, of the form $Fs = CtD$, similar to those found for the compressive strengths. Here C and D are constants that depend on the curing times (3, 7, 28, and 90 days) and the ambient environment (20 °C, 90 % RH), regardless of the addition rate. Moreover, the flexural tensile strengths are close to each other for a given age. Nevertheless, the bending tensile strengths values of the reference mortars remain higher than those of the other mortars. The results show a rapid evolution between day 1 and day 28, with a significant increase in resistance. After 28 days, the rate of change in tensile strength decreased, regardless of the formulation of the mortars produced. Note as well that the tensile strength decreases as the percentage of substituted cement increases.

As clearly shown in Figure 11b, the curves corresponding to each addition percentage are positioned in a tight spindle at advanced ages, under ambient (20 °C) which explains the fact that the effect of mineral additions is mainly observed at young ages. These findings and those reported by Husson [54] are contradictory. The replacement of brick powder led to a reduction in the flexural strength of the mortar specimens (M10 %, M20 % and M30 %) by 13 %, 22 %, and 40 %, respectively. The reduction in resistance is significant above 30 % replacement of brick powder.

Figure 12 presents the results of the flexural resistance tests of the different mortars stored underwater (humid environment) in a hot environment (at 50 °C).



(a). Flexural strength as a function of age.

(b). Flexural strength as a function of brick powder dosage.

Figure 11. Evolution of the flexural tensile strength of mixtures in an ambient environment.

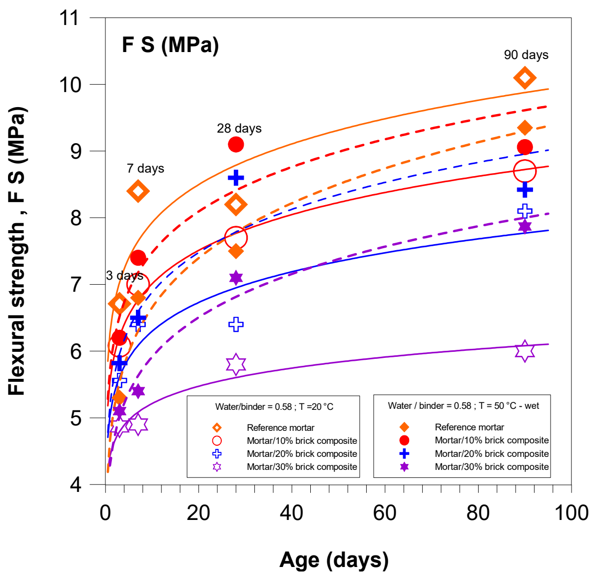


Figure 12. Evolution of the compressive strength of different mortars in a hot and humid environment.

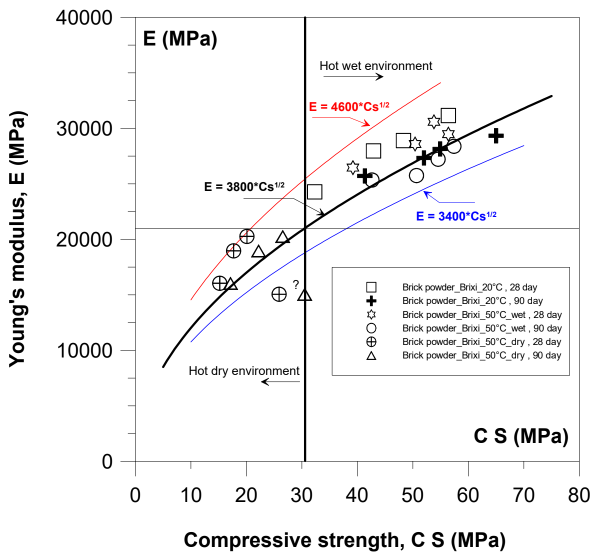


Figure 13. Correlation between the compressive strength and modulus of elasticity in a hot and humid environment.

It can be seen that the flexural strengths increase with curing time for the different mixtures and are positioned in a narrow pin. We note a rapid evolution between 3 and 28 days, this evolution is more pronounced in the case of mortars based on brick powder. This observation is the opposite of that made on flexural tensile strengths in an ambient hardening environment. After 28 days, the increase in bending resistance tends to stabilise.

It appears that the flexural strength of the specimens stored at 50 °C has increased, and even more significantly when the dosage of brick powder increases, an optimum was found to be 10 % replacement by brick powder, without however, achieving the bending strength of the specimens stored at room temperature. These results can be explained by the fact that the hydration process of the binders is accelerated faster and more strongly as the temperature rises from 20 to 50 °C. It can therefore be concluded that the brick powder in the samples immersed in water at a temperature of 50 °C reacts in the long term.

Figure 13 illustrates the results of the ultrasonic pulse velocity (UPV) tests translated into deformation modulus of the different mortars stored at 28 and 90 days under different environments (ambient, hot/humid and hot/dry). The results indicate that the moduli of mortars containing the different percentages of brick powder waste at 28 days of curing

Samples	Curing conditions	α	β	R^{2*}
$E_d = \alpha CS^{\beta}$	50 °C Hot and immersed in water 20 °C Immersed in water 50 °C Hot and dry	3 400 to 4 600	0.5	0.83 to 0.98

* Coefficient of determination.

Table 5. Power function parameters: $E_d = \alpha CS^{\beta}$.

increase in a hot and humid environment compared to the control mortar. However, these mortars show a slight increase in moduli when stored for 90 days in the same environment. The trend is similar for mortars containing the same dosages of brick powder but in a hot and dry environment. The results revealed a slight to moderate decrease for different percentages of these additives which require sufficient quantity of water, hence the interruption of hydration, resulting in an increase in porosity and the void ratio in hardened mortar compared to mortars stored in a hot and humid environment.

Figure 13 shows the results relating to the modulus of elasticity of the different brick powder based mortars for different compressive strength values, under different curing conditions, and for different relative humidity levels. One can easily see that the modulus of elasticity increases as a power function with compressive strength, regardless of the curing time and under a conditioned environment. This power function has a lower limit and an upper limit. It is in the form: $E_d = \alpha CS^{\beta}$, where α and β are constants, E_d is the dynamic modulus of elasticity, and CS is the compressive strength, as shown in Table 5. For a hot and dry environment, the values of Young's modulus for this brick powder-based mortar are less than 21 GPa with strength values not exceeding 30 MPa. In a hot and humid environment, the modulus of elasticity values are greater than 21 GPa with strength exceeding 32 MPa.

4. Conclusion

This main aim of this research was to study the characteristics of cement-brick powder mortars. For this, several tests, such as the compressive strength test, the flexural tensile strength test, the ultrasonic test, the thermal conductivity test, and the thermal diffusivity test, were conducted on mortar samples in the hardened state, at different curing ages, and under different environmental conditions. The mortar samples under study were made by partially replacing the mass of cement with finely ground brick waste at different percentages (0, 10 %, 20 % and 30 %). The results obtained for the different mixtures were discussed and compared with those of the reference mortar at different curing ages (3, 7, 28 and 90 days).

The experimental study led to the following conclusions:

- It should be noted that the amount of energy required for heating and cooling buildings strongly depends on the thermal properties of the building material (thermal conductivity, specific heat capacity, and thermal diffusivity of the building envelope). Therefore, it was found that using brick powder at different percentages (0 %, 10 %, 20 % and 30 %) in the formulation of mortar improves the thermal insulation characteristics of this material. It can be said that the thermal conductivity and thermal diffusivity coefficients are strongly influenced by the brick powder content. Thermal properties as a function of brick powder dosage give a linear relationship.
- The partial substitution of cement by powdered bricks decreased the compressive strength of mortars, especially at a young age. This was due, on the one hand, to the fact that the specific surface of waste bricks is lower than that of the cement used and, on the other hand, to the increase in porosity due to the decrease in hydrates. This compressive strength decrease was more significant for a brick powder percentages greater than 20 %. The replacement ratio of 10 % shows the best performance of mortar compared with another replacement ratio at ambient temperature. Furthermore, the specimens cured for 28 days in a hot and humid environment presented resistances almost equal to the control mortar. However, at higher curing times, these resistances decrease slightly compared to the control mortar. In the case of mortars stored in a hot and dry environment, there is a remarkable reduction in compressive strength with higher curing times.
- The compressive strength was lower for samples stored in a dry environment at a temperature of 50 °C compared to those obtained for samples stored in water at 50 °C. This was certainly due to the different hydration rates in the different curing environments.
- Concerning the flexural resistance of different mortars stored in different climates, we note a decrease in this resistance for higher percentages of brick powder at room temperatures. On the other hand, an increase in bending strength is observed when the specimens are stored in a hot and humid climate. The increase is more significant as the percentage of brick powder increases and we find that the optimum percentage is 10 % of brick powder, without however reaching the bending resistance of the specimens stored at room temperature. These results can be explained by the fact that the hydra-

tion process of the binders is accelerated faster and more strongly as the temperature increases from 20 to 50 °C.

- The desert and Mediterranean climates of North Africa are characterised by hot-dry and hot-humid climates, respectively, where the temperature can reach up to 50 °C and the relative humidity can drop to 8 % [4]. Mortars tested under similar climatic conditions showed a reduction in compressive strength and an increase in flexural strength for ages up to 28 days. The use of powdered brick waste by substitution of cement under similar conditions can lead to rapid loss of fresh properties of ready-made mortars due to the evaporation of fresh mixing water, which causes an increase in shrinkage and leads to the formation of cracks, and therefore the performance of mortars at a later age is negatively affected.
- The elastic modulus of the mortars under study decreased slightly when the brick powder dosage was smaller or equal to 20 %, regardless of the different hardening conditions at 28 and 90 days. A correlative relationship between the compressive strength and the deformation modulus is proposed in this study: $E_d = \alpha \mathrm{CS}^{\beta}$, where α and β are constants, E_d is the dynamic modulus of elasticity, and CS is the compressive strength.

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