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*Research Article*

# Experimental Study of New Insulation Lightweight Concrete Block Floor Based on Perlite Aggregate, Natural Sand, and Sand Obtained from Marble Waste

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The purpose of the present study is to recover marble waste and expanded perlite aggregate (EPA) for use as an additive to cementitious matrix building materials. The main goal is to produce a new insulation block floor from lightweight concrete (LC) by mixing sand from the waste marble crushing process (SWM), natural sand, and EPA. First, optimal mixture of natural sand, SWM, and EPA was determined for a given insulation LC. To this end, plate and cubic specimens were prepared by varying the volume proportion of SWM to natural sand in percentages of 0, 20, 40, 60, 80, and 100. Mechanical and physical properties such as the compressive strength, thermal conductivity, thermal diffusivity, specific heat capacity, and sound reduction index at different frequencies were investigated. Finally, a prototype of a new insulation lightweight block floor was manufactured from the optimal mixture of the studied LC. The results showed that the incorporation of SWM significantly improved the mechanical properties and the thermal insulation of LC compared to those of the natural sand. These results are promising and give the present insulation block floor the opportunity to be used in composite slabs.

## 1. Introduction

Recovery and recycling of waste has recently become an effective way to address economic and ecological constraints [1, 2]. Waste is a real problem, inevitable for all biological life and all industrial activity [3]. Recycling and waste recovery are now considered as a solution for future in order to meet the deficit between production and consumption and to protect the environment [4]. When adding EPA aggregate to the granular matrix, we obtain ordinary concrete, lightweight concrete [5], fire-resistant concrete [6], or insulating concrete. In addition, some research shows that perlite can be used as an aggregate in Portland cement and gypsum plasters for exterior applications [7].

In Saudi Arabia, tile production plants and marble factories emerge in their processes of shaping and manufacturing industrial waste in the form of sludge; the amount of this waste is significant. These wastes pose environmental management and transportation issues as they are dumped into landfills. It is estimated that only 30% of the materials used in construction are currently recycled, while the practice in some European countries shows that 90% are reusable [8].

Several researchers have studied the possibility of incorporating marble waste as a replacement for concrete. For example, Kore and Vyas [9] replaced natural aggregates with marble waste aggregate in ordinary concrete with a water/cement ratio equal to 0.60. The results show that the compressive strength increases approximately to 40% and

18% at 7 and 28 days, respectively, when compared to that of concrete with 100% of natural aggregates. In other research, it is found that the incorporation of marble waste greatly decreases the workability of concrete mixes [9, 10]. The results of the research conducted in Reference [7] show an improvement in the mechanical properties (compressive, tensile and flexural strengths, and Young's modulus of elasticity) of concrete when replacing natural aggregates by marble aggregates. Talah et al. [11] reported that the partial replacement of Portland cement up to 15% in composite cement by marble powder improves the durability of concrete without decreasing its compressive strength. The results presented in Reference [12] show that the durability of concrete or self-compacting concrete was positively affected when adding marble powder to the cementitious matrix as mineral additives. In addition, the results indicate that no significant difference of the carbonation resistance was observed compared to the concrete without marble waste. In addition, Gesoğlu et al. [13] showed that the use of marble powder as filler significantly improves the mechanical and the fresh properties of the SCCs.

The main purpose of this work is to produce a new insulation lightweight concrete block floor based on expanded perlite aggregates, natural sand, and crushed marble waste. These new blocks can be used for the construction of the composite slabs in order to increase the thermal insulation and to decrease the weight of these slabs.

The first part discusses the possibility of using sand from the waste marble crushing (SWM) process as an addition to lightweight concrete with expanded perlite aggregates and characterizes the materials used for the manufacturing of this concrete. In this sense, a series of tests has been conducted, including mixtures with a constant W/C ratio (water/cement). This work also consists of analyzing the mechanical and physical properties of various mixtures in a cured state at a rate varying from 0 to 100% for the addition of SWM and a constant rate of 45% for the addition of EPA in order to determine the optimal mixture. The results of these tests are compared with those of a control LC.

The second part of this experimental work consists of producing a prototype of new insulation lightweight block floor manufactured by using a lightweight concrete based on crushed waste marble, natural sand, and EPA. These bricks have a sufficient mechanical strength and thermal insulation to be used as a new solution for the construction of insulation composite slabs.

## 2. Materials

*2.1. Expanded Perlite Aggregate (EPA).* Perlite rock is imported from Turkey. However, its expansion process is carried out in Tunisia. According to the chemical composition, the two main components of EPA aggregates are silicon dioxide (70–80%) and alumina (12–16%) [6]. Table 1 gives the physical properties of EPA.

Table 1: Properties of expanded perlite aggregate.

| | |
|---|---|
| Color | White |
| pH | 7 |
| Melting point | 1200°C |
| Specific heat | 0.20 kcal/kg C |
| Rough density | 70 kg/m$^3$ |
| Thermal conductivity | 0.040 W/mK |
| Compression strength in the compacted condition | 0.10–0.40 MPa |
| Water absorption | 30–40 (%, V/V) |
| Porosity | 70–85% |
| Size (mm) | 2–4 |
| Sound insulating (125 Hz) | 18 dB |

*2.2. Natural Sand.* The natural sand used in this study has a grain size of 0/5 and a fineness modulus of 2.69. The particle-size distribution curve of the sand is given in Figure 1. The physical characteristics of this sand are presented in Table 2.

*2.3. Crushed Waste Marble.* In this experimental study, the sand resulting from the crushing process of the waste marble (SWM) was used with a grain size of 0/5. The marble waste was first crushed with a hammer, and then a crusher machine was used on the marble waste until the desired particle size was obtained. Figure 2 shows the steps of the crushing process of the marble waste.

The grain size distribution of the marble waste sand SWM, as shown in Figure 1, was carried according to the NF P 94–056 standard [14]. The physical characteristics of this sand are presented in Table 2.

Table 3 shows the chemical analysis of the crushed waste marble performed with an atomic absorption spectrometry (AAS) according to the requirements of the EN ISO 15586 standard [15]. According to the results, SWM is too rich in calcite ($CaCO_3$ = 93.30%), and it is devoid of all organic matter.

Measurement of the calcium carbonate content was performed using the Dietrich-Fruhling calcimeter to calculate the percentage of $CaCO_3$ according to the NF P 94–048 standard [16]. The test results show that the SWM sample contains 94% $CaCO_3$, which confirms that it is too rich in calcite.

*2.4. Cement.* The cement used in this study was a CEM I 32.5 with properties in conformity with European Standard EN 197–1 [17].

*2.5. Superplasticizer.* To improve the workability of the lightweight concrete, a superplasticizer (SP) was used. The SP/cement ratio was established with a Marsh cone test in accordance with the standard NF P18-507 [18]. The result shows that this ratio is equal to 1%.

## 3. Specimen Preparation

Plate and cubic specimens were prepared by varying the SWM proportion with percentages ranging from 0% to 100% by substitution of the volume of sand. The values 15, 30, 45, 60, and 100 indicate the SWM proportion. Table 4 shows the shape, dimension, and number of test specimens as well as the adopted standard test methods.

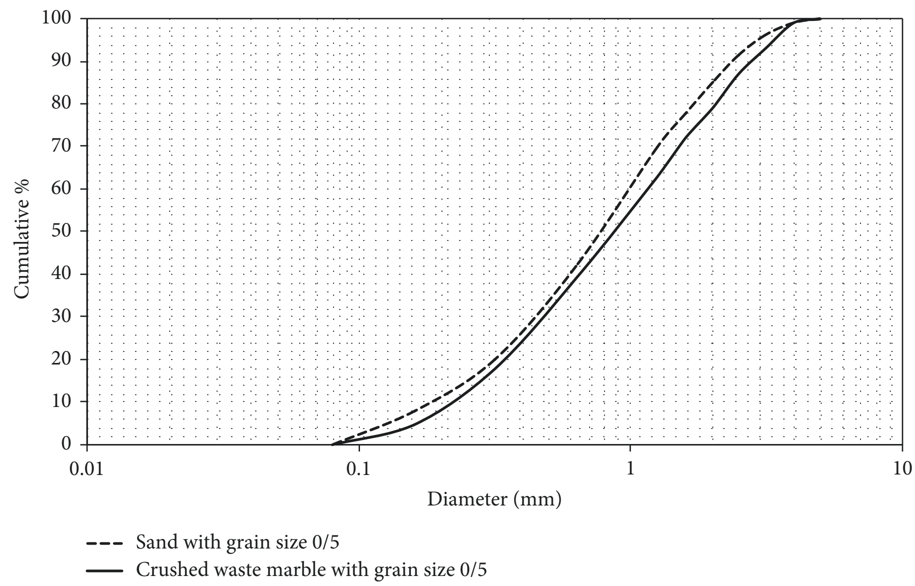



Figure 1: Particle-size distribution curve of SWM and natural sand.

Table 2: Physical properties of natural sand and crushed waste marble.

| Properties | Natural sand | Crushed waste marble |
|---|---|---|
| Absolute density ($g/cm^3$) | 2.51 | 2.69 |
| Bulk density ($g/cm^3$) | 1.42 | 1.45 |
| Equivalent of sand (%) | 91 | 0.81 |
| Los Angeles (LA) (%) | 27 | 22 |
| Water absorption | 3 | 7 |

According to Table 4, 72 cubic specimens were used to determine the compressive strength of the mixtures at 3, 7, and 28 days. 36 plate specimens were used to determine the thermal conductivity and thermal diffusivity of the different mixtures at 28 days by using the boxes method. Finally, 12 special devices were used to determine the sound reduction index of the plate specimens at 28 days.

Lightweight concrete with EPA and lightweight concrete with SWM were, respectively, designated LC and LCM. The effective water/cement ratio (W/C) was equal to 0.70 and was kept constant in all mixtures. The percentage of EPA was chosen to be constant (45%) in order to guarantee a suffusing resistance of specimens [5]. Table 5 gives the composition of all prepared mixtures.

Since EPA is very brittle, the following mixing method was adopted to avoid the crash and change in aggregate size:

(1) Mix Sand and SWM until homogenization (Figure 3(a))

(2) Add cement and mix until homogenization (Figure 3(b))

(3) Add water mixed with SP and mix until complete homogenization of the mixture (Figure 3(c))

(4) Add the EPA at once and mix in a minimum of time until complete homogenization of the mixture (Figures 3(d) and 3(e))

(5) Oil the inside of the mold to prevent the concrete from sticking (Figure 3(f))

(6) Pour the mixture in the mold (Figure 3(g))

(7) Remove the specimen from the mold after 24 h (Figure 3(h))

## 4. Properties of Lightweight Concrete with EPA, Natural Sand, and Sand Marble

*4.1. Effect of SWM Dosage on the Unit Weight of LC.* Figure 4 gives the values of unit weight for different samples at 28 days curing. According to the results, it is clear that the unit weight of specimens was increased with an increase in the SWM dosage. The values of unit weight range from 1065 $kg/m^3$ for specimens that contain 0% SWM waste to 1164 $kg/m^3$ for specimens that contain a percentage of 100% SWM.

Since the six manufactured concretes have the same dosage in cement, water, perlite, and superplasticizer, the high absolute density of marble (2.69 $g/cm^3$) can explain the increase in unit weight, which is larger than that of natural sand (2.51 $g/cm^3$). In addition, this increase in density is due to the decrease in porosity.

The results illustrated in Figure 4 show that the incorporation of SWM in the different mixtures did not change the type of concrete. Indeed, it is always a lightweight concrete since the values of unit weight varies between 560 $kg/m^3$ and 1500 $kg/m^3$ [5]. This is due to EPA, which represents 45% of the concrete volume with a density of the order of 70 $kg/m^3$.

*4.2. Effect of SWM Dosage on the Porosity of LC.* The porosity of the different lightweight concrete was measured according to the NF ISO 5017 standard [19]. For each type of concrete, the test was carried out on 3 cubic samples ($100 \times 100 \times 100$ cm).

(a) (b) (c) (d)

Figure 2: Steps of the crushing process of the marble waste.

Table 3: Chemical composition of crushed waste marble.

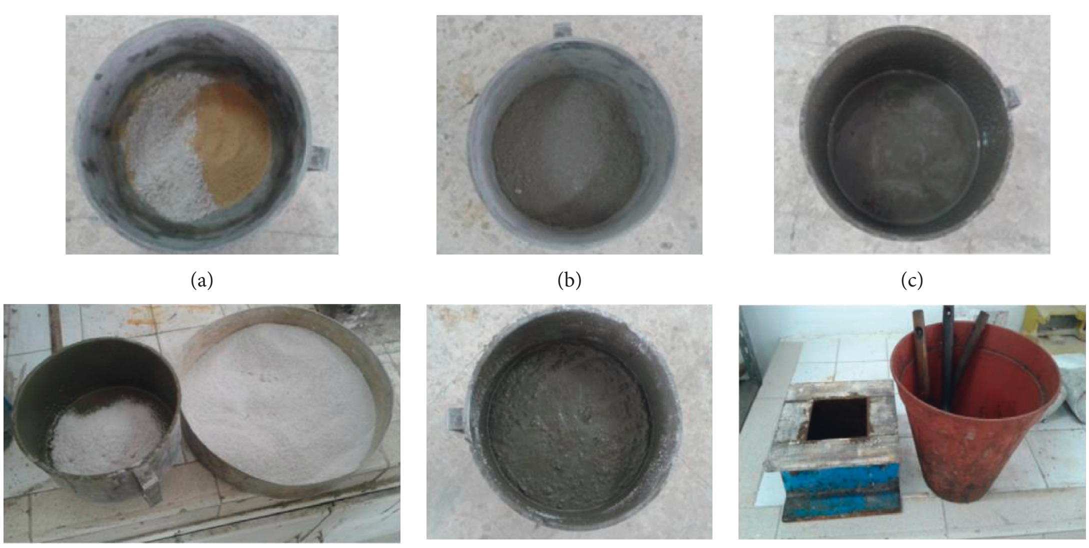
| Component | $CaCO_3$ | PAF | Ca | CaO | MgO | $SiO_2$ | $Fe_2O_3$ | $Al_2O_3$ | $MgCO_3$ | Sulfur (S) | Moisture |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Percentage | 93.30 | 42.60 | 37.36 | 52.28 | 0.50 | 3.00 | 0.39 | 0.14 | 1.04 | 0.03 | 0.20 |

Table 4: Dimensions and shape of the tested specimens.

| Test | Shape of specimens | Dimension of specimens | Standard | Number |
|---|---|---|---|---|
| Compressive strength | Cubic | $100 \times 100 \times 100$ mm | NF EN 12390-3 | 72 |
| Thermal conductivity | Plate | $270 \times 270 \times 40$ mm | NF EN ISO 8990 | 18 |
| Thermal diffusivity | Plate | $270 \times 270 \times 40$ mm | NF EN ISO 8990 | 18 |
| Standardized level difference | Plate | $700 \times 700 \times 50$ mm | EN ISO 717-1 | 12 |

Table 5: Mixture composition.

| Designation of mixture | W/C | EPA | | | Cement (kg) | Water (kg) | Sand | | SWM | | SP |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (%) | ($m^3$) | (kg) | | | (%) | (kg) | (%) | (kg) | (kg) |
| LC | 0.70 | 45 | 0.450 | 31.5 | 300 | 210 | 100 | 781 | 0 | 0 | 3.00 |
| LCM20 | 0.70 | 45 | 0.450 | 31.5 | 300 | 210 | 80 | 625 | 20 | 156 | 3.00 |
| LCM40 | 0.70 | 45 | 0.450 | 31.5 | 300 | 210 | 60 | 469 | 40 | 312 | 3.00 |
| LCM60 | 0.70 | 45 | 0.450 | 31.5 | 300 | 210 | 40 | 312 | 60 | 469 | 3.00 |
| LCM80 | 0.70 | 45 | 0.450 | 31.5 | 300 | 210 | 20 | 156 | 80 | 625 | 3.00 |
| LCM100 | 0.70 | 45 | 0.450 | 31.5 | 300 | 210 | 0 | 0 | 100 | 781 | 3.00 |



(a) (b) (c)

(d) (e) (f)

Figure 3: Continued.

(g)

(h)

Figure 3: Steps of mixing and preparing specimens.

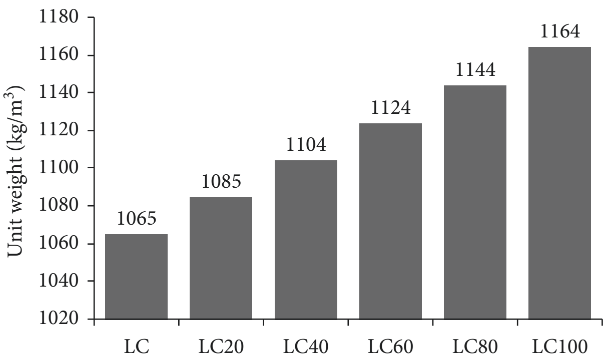



Figure 4: Effect of SWM dosage on the unit weight of LC.

The principle of the porosity measurement is based on three weightings including $m_1$, $m_2$, and $m_3$. First, the sample must be dry until its mass is stabilized and then it is weighed ($m_1$). The sample is then put in a desiccator equipped with a vacuum pump for one hour to eliminate air fully. Immediately, the sample is put in a water tank for 72 hours in a hydrostatic balance until saturation; then, it is weighed again ($m_2$). Finally, the saturated sample is wiped superficially to remove surface water and weighed ($m_3$). The different steps of this test are presented in Figure 5.

The expression of the sample porosity is given as follows:

$$P = \left(\frac{m_3 - m_1}{m_3 - m_2}\right) \times 100. \quad (1)$$

Figure 6 gives the porosity values for the different samples at 28 days of curing as a function of the SWM proportion.

The results show that although the natural sand and crushed waste marble have similar particle size curves (Figure 2), the porosity of lightweight concrete increased from 44% for LC to 56% for LCM100. This difference is essentially due to the grains shape of the two sands: the angular crushed waste marble and spherical natural sand. Indeed, the granular arrangement of crushed waste marble grains gives a void percentage lower than the natural sand.

We also note that, according to Figure 6, the substitution of natural sand by crushed waste marble affects the porosity by decreasing it.

*4.3. Effect of SWM Dosage on the Compressive Strength of LC.* The test of compressive strength was carried out on the specimens of cubic shape of 100 mm side in accordance with the requirements of EN 12390-3 [20]. The testing machine shall be equipped with two steel bearing platens with hardened faces.

The results of the compression strength test on the different specimens at the ages of 3, 7, and 28 days are shown in Table 6. According to the results, all concretes have low compressive strengths (from 8.6 for LC to 12.9 MPa for LCM100). This can be explained by the low compressive strength under the compacted condition of EPA (0.10–0.40 MPa), which represents 45% of the lightweight concrete.

The compressive strength values increase with an increase in SWM content from 0% to 100%. Indeed, the incorporation of SWM significantly improves the mechanical properties of concrete. For example, at 28 days, the compressive strength increased by 18% for a specimen containing 40% SWM and by 33% for a specimen containing 100% SWM. This increase in compression strength is due to the higher strength of marble compared to the sand. In addition, we can explain this increase in compressive strength, both at young and old ages, by the increase in the concrete density, which is due to the increase in the crushed waste marble percentage [21]. Also we can conclude that the concrete compactness positively affects the compressive strength of concrete: the greater the compactness is, the more resistant the lightweight concrete is.

The results also reveal that the compressive strength values increased as the curing period increased from 3 to 28 days. The compressive strength reached 70% of its final value at the age of three days, and then it grew slowly until the age of 28 days. The high compressive strengths at young age were due solely to the superplasticizer, which has the secondary function of accelerating hardening [22].

Finally, according to the results presented in Table 6, the 100% incorporation of SWM gave a compressive strength value equal to 12.9 MPa at 28 days that does not allow for the classification of our mixture as a structural lightweight concrete but rather as insulation lightweight concrete.

*4.4. Effect of SWM Dosage on the Thermal Conductivity of LC.* Thermal conductivity is the amount of heat transferred in one unit of time through a material of one surface unit and one unit of thickness, when the two opposite faces differ by

(a) (b) (c) (d) (e)

Figure 5: Steps of the porosity measurement test.

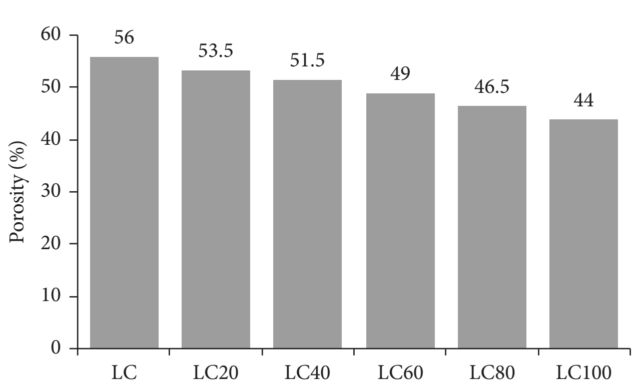



Figure 6: Effect of SWM dosage on the porosity of LC.

Table 6: Effect of SWM dosage on the compressive strength of LC at 3, 7, and 28 days.

| Mixture | LC | LC20 | LC40 | LC60 | LC80 | LC100 |
|---|---|---|---|---|---|---|
| 3 days | 5 | 5.5 | 5.9 | 6.4 | 7.1 | 8 |
| 7 days | 6.2 | 7 | 7.6 | 8.3 | 9 | 10.3 |
| 28 days | 8.6 | 9 | 9.8 | 10.5 | 11.2 | 12.9 |

one unit of temperature. Thermal conduction is the corresponding heat transfer mode.

The thermal conductivity of the specimens was determined using plate samples of dimension 270 × 270 × 40 mm in accordance with the requirements of NF EN ISO 8990 [23] by using the "boxes method" (Figure 7(a)).

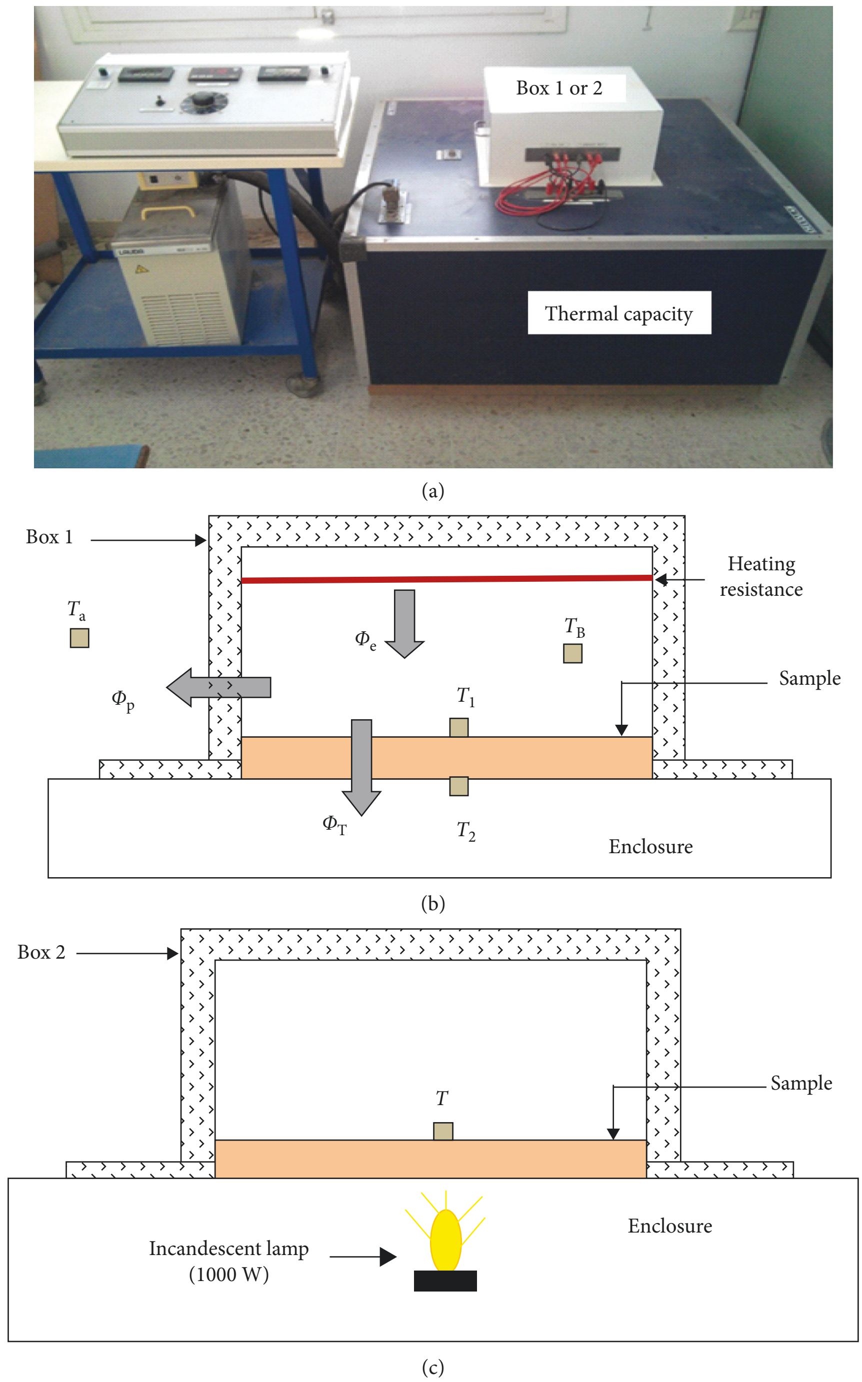



Figure 7: The boxes method test. (a) The boxes method apparatus. (b) Thermal conductivity measurement. (c) Thermal diffusivity measurement.

Figure 7(b) shows the measurement principle of the thermal conductivity using box 1. It can be calculated using the following equation:

$$\lambda_{\exp} = \frac{e}{S \cdot (T_1 - T_2)} \left[ \frac{U^2}{R} - C \cdot (T_B - T_a) \right], \quad (2)$$

where $U$ is the electric tension in V; $S$ is the section of the plate sample in m$^2$; $T_1, T_2, T_B$, and $T_a$ are the temperatures determined using platinum temperature sensors in K; $R$ is the heater in Ω; and $C$ is the overall heat transfer coefficient.

Figure 8 gives the thermal conductivity values of the different lightweight concrete, in the dry state, as a function of SWM percentage. The test was carried out by the box method on 3 plate specimens with dimensions $270 \times 270$ mm $\times$ 40 mm for each lightweight concrete sample. All specimens were tested at the age of 28 days under an oven-dry condition [24].

According to the result presented in Figure 8, all tested lightweight concretes have low thermal conductivity values. This is mainly due to the insulating nature of EPA, which has a thermal conductivity equal to 0.040 W/mK and, also, is due to the very low thermal conductivity of the concrete air content (on the order of 0.02 W/mK) [25].

The results also show that the percentage of SWM replacement has a considerable influence on the thermal conductivity of LC. Indeed, the substitution of crushed waste marble in the granular matrix increases the thermal conductivity of lightweight concrete. For a composition of 0% and 100%, it ranges from 0.35 W/mK to 1.1 W/mK. This difference is related to the insulating nature of the air content, which has a thermal conductivity on the order of 0.02 W/mK [26]. Figures 6 and 8 show that the thermal conductivity decreases with porosity. For example, thermal conductivity of LC, with a porosity of 56%, is lower than that of LCM100 concrete, which has a porosity of 44%.

In addition, the thermal conductivity of the tested concretes depends also on the thermal conductivity of aggregates because the dosages in cement, perlite, water, and SP are constant for all lightweight concretes. Indeed, the thermal conductivities of natural sand and crushed waste marble, which are, respectively, equal to 0.4 W/mK [27] and 2.9 W/mK, affect the thermal properties of the studied concretes.

The results show that the thermal conductivities of all lightweight concretes are greater than 0.35 W/mK. This is due to the density values of these concretes, which are considered high compared to other lightweight concretes classified as highly insulating. For example, according to Reference [5], the thermal conductivity of autoclaved aerated concrete is approximately 0.33 W/mK for a density of 770 kg/m$^3$.

Finally, the mixtures can be classified into the following two categories: for a replacement percentage of 0% to 60%, the concrete can be used for the thermal insulation view and its low thermal conductivity $0.35\ \mathrm{W/mK} \leq \lambda \leq 0.87\ \mathrm{W/mK}$. For a replacement greater than 60%, the concrete cannot be used for thermal insulation due to its high thermal conductivity $0.95\ \mathrm{W/mK} \leq \lambda \leq 1.10\ \mathrm{W/mK}$, and it is simply a lightweight concrete filling.

Thermal resistance $R_{th}$ is deduced from the measurement of the thermal conductivity by the following expression:

$$R_{th} = \frac{e}{\lambda_{exp}}, \tag{3}$$

where $R_{th}$ is the thermal resistance in m$^2$K/W; $e$ is the thickness of the sample in m; and $\lambda_{exp}$ is the experimental thermal conductivity in W/m·K.

The thermal resistance of different samples was calculated with equation (3) using the thermal conductivity values of all tested specimens at 28 days. Figure 9 gives the thermal resistance values of all samples with replacement percentages of SWM ranging from 0% to 100% by the volume of sand. The results show a decrease in thermal resistance with a percentage that can reach 68% for a replacement percentage of 100%. This can be explained by the thermal

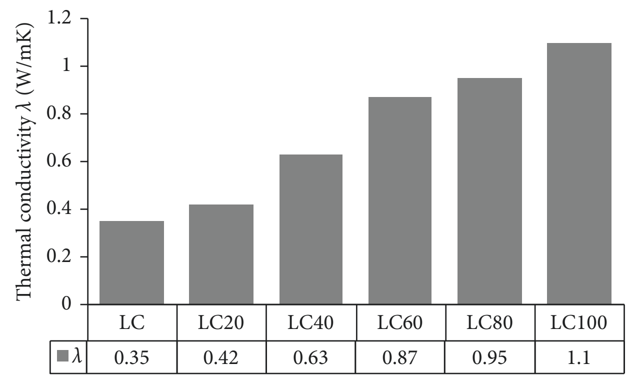



FIGURE 8: Effect of SWM dosage on the thermal conductivity of LC at 28 days.

conductivity of marble (2.90 W/mK), which is higher than that of natural sand (0.40 W/mK). In fact, the thermal resistance of the specimens decreased with increasing thermal conductivity of the aggregates.

The same explanations of the effect of SWM percentage on the thermal conductivity are applicable to explain the difference of thermal resistance values between the six tested samples.

*4.5. Effect of SWM Dosage on the Thermal Diffusivity of LC.* Generally, thermal diffusivity is the speed at which heat is propagated by conduction in a body. It involves the thermal conductivity and thermal capacity of a material. Thermal diffusivity consists of measuring the transient thermal response of a material to a change in temperature. As known, the materials having high thermal diffusivity are considered as a good diffuser of thermal energy, while these with a low thermal diffusivity are much slower at diffusing thermal energy.

The thermal diffusivity was determined on plate specimens with dimensions 270 × 270 mm × 40 mm by replacing box (1) with box (2) of the same apparatus used to measure thermal conductivity (Figure 7(c)).

The principle of the method consists of emitting a heat flux, for a few seconds by means of the lamp, on one face of the sample. Thermal diffusivity was determined from the temperature variation in the nonirradiated face of the sample.

To calculate the thermal diffusivity, we used the approximate method presented by using the Degiovanni model based on the method of partial time [5, 28, 29]. The thermal diffusivity of the sample is given as follows [29]:

$$\begin{aligned} \alpha_{1/2} &= e^2\left[\frac{0.761t_{5/6} - 0.926t_{1/2}}{(t_{5/6})^2}\right],\\ \alpha_{2/3} &= e^2\left[\frac{1.150t_{5/6} - 1.250t_{2/3}}{(t_{5/6})^2}\right],\\ \alpha_{1/3} &= e^2\left[\frac{0.617t_{5/6} - 0.862t_{1/3}}{(t_{5/6})^2}\right], \end{aligned} \tag{4}$$

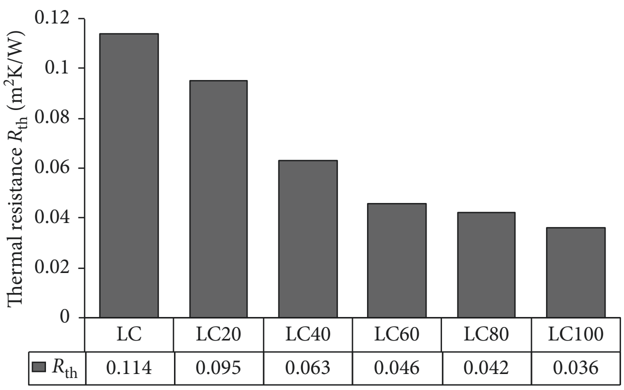



FIGURE 9: Effect of SWM dosage on the thermal resistance of LC at 28 days.

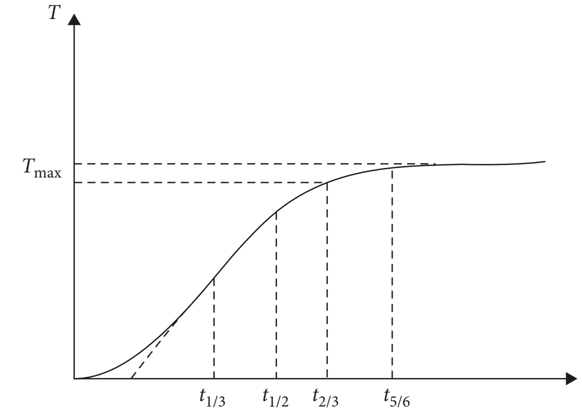



FIGURE 10: Schematic diagram representing partial times [30].

where $e$ is the specimen thickness and $t_{1/3}, t_{1/2}, t_{2/3}$, and $t_{5/6}$ are, respectively, the partial times for 1/3, 1/2, 2/3, and 5/6 of the maximum value of the temperature (Figure 10).

Finally, the thermal diffusivity of the sample is given by an average of the three values [29]:

$$\alpha = \frac{\alpha_{1/2} + \alpha_{2/3} + \alpha_{1/3}}{3}. \quad (5)$$

The results of the thermal diffusivity measurements for the different specimens are presented in Figure 11. It is noted that replacing normal sand by a percentage of SWM ranging from 0% to 100% increased the thermal diffusivity and hence decreased the thermal insulation of the concrete.

The results clearly show that incorporating crushed waste marble in the granular concrete matrix significantly increases its thermal diffusivity. For example, the SWM replacements with 40% and 80% produced an increase of 17.66% and 27.12% in thermal diffusivity compared to LC, respectively. This can be explained by the thermal diffusivity of marble, equal to $1.35 \times 10^{-6}\,m^2/s$, which is higher than that of the natural sand, equal to $0.3 \times 10^{-6}\,m^2/s$ [27]. Indeed, the thermal diffusivity of lightweight concrete depends on the thermal characteristics of the aggregates since the dosages in cement, perlite, water, and SP are constant.

In fact, the lower the thermal diffusivity value, the greater the amount of time it takes the heat to reach the thickness of the material, and the greater the time the heat takes to reach the wall side.

According to Figures 9 and 11, the increase in the thermal conductivity increased the thermal diffusivity; this may be explained by the decrease in air content, which caused the increase in density for different specimens. The lightweight concrete, for example, with 40% SWM and a unit weight of $1104\,kg/m^3$ produced an 18% augmentation in thermal conductivity and a 12% augmentation in thermal diffusivity compared to LC with a unit weight of $1065\,kg/m^3$. Thereafter, the thermal conductivity and diffusivity are proportional and vary in the same direction if the density and specific heat are constant.

Finally, according to the obtained results, the thermal diffusivity of this porous material is an increasing function of both the SWM percentage and the lightweight concrete density.

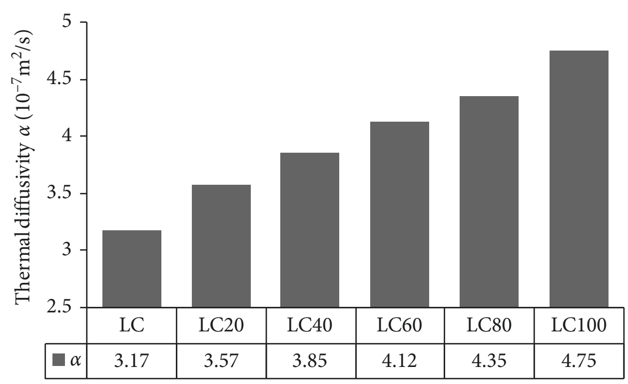



FIGURE 11: Effect of SWM dosage on the thermal diffusivity of LC at 28 days.

*4.6. Effect of SWM Dosage on the Specific Heat Capacity of LC.* The specific heat capacity ($C_p$) of a material was defined as the amount of heat required to raise the temperature by one degree of a mass unity of a material. Indeed, more heat energy is required to increase the substance temperature with high specific heat capacity than when using low specific heat capacity material.

The specific heat capacity was determined from thermal conductivity and diffusivity measurements by using the following equation:

$$C_p = \frac{\lambda_{exp}}{\rho \cdot \alpha_{exp}}, \quad (6)$$

where $\rho$ is the unit weight in $kg/m^3$; $\alpha_{exp}$ is the experimental thermal diffusivity in $m^2/s$; and $\lambda_{exp}$ is the experimental thermal conductivity in W/mK.

Table 7 illustrates the evolution of the specific heat capacity measured on dry samples as a function of the substitution rate of natural sand by SWM.

According to the results shown in Table 7, the specific heat capacity of specimens was increased with increasing SWM dosage and can reach a value of 1989 J/kg·K for 100%

Table 7: Effect of SWM dosage on specific heat capacity of LC.

| Mixture | LC | LC20 | LC40 | LC60 | LC80 | LC100 |
|---|---|---|---|---|---|---|
| Specific heat (J/kg·K) | 1036 | 1085 | 1483 | 1879 | 1909 | 1989 |

SWM. This can be explained by the specific heat capacity of marble (798 J/kg·C), which is higher than that of the natural sand (531 J/kg·C).

The thermal resistance and specific heat capacity varied in the opposite direction. For example, the lightweight concrete with 60% SWM produced a 60% reduction in thermal resistance and produced a 45% increase in specific heat capacity compared to LC.

The porosity was provided by natural sand, so the thermal conductivity of lightweight concrete decreased with the increase in the mass fraction of natural sand. On the contrary, when SWM fraction increases, the specific heat of light concretes increases. In fact, the thermal conduction in a porous material results from the thermal properties of the solid phase and the interconnected pores, knowing that the granular skeleton conductivity is greater than that of the air.

We also note that the lightweight concrete based on 100% natural sand has a maximum porosity (56%) compared to other concretes. Normally, in a more porous material, the conduction surface of the solid decreases and that of the air increases. However, the heat flux is proportional to the conduction surface. It requires more energy and higher specific heat to increase the temperature of a more porous concrete. In this case, the tested concretes have different SWM fractions and porosity. Indeed, despite the decrease in porosity, we notice that the specific heat increases (Figure 11 and Table 7) due to the higher marble conductivity.

Finally, the specific heat of lightweight concrete increases with the increase in the SWM substitution rate. This also leads to a greater material capacity to store heat and produce better thermal performance.

*4.7. Effect of SWM Dosage on the Sound Reduction Index of LC.* The sound reduction index $R_W$ characterizes the acoustic protection qualities of a wall for a set of standardized noises. The higher the index, the greater the protection. It is obtained in the laboratory and corresponds for each octave band to the difference between the sound pressure levels prevailing in the transmitting and receiving rooms. The sound reduction index is defined in the series of international standards ISO 16283 [31] and the older ISO 140 [32]. It can be calculated using the following equation:

$$R_W = D + 10\log\frac{S}{T_r}, \tag{7}$$

where $T_r$ is the reverberation time in seconds in the receiving room and $S$ is the section of the plate specimens. Additionally, $D$ is the level difference calculated with the following equation:

$$D = L_1 - L_2, \tag{8}$$

where $L_1$ and $L_2$, in dB, are the average sound pressure levels, respectively, in the source room and in the receiving room.

The reverberation time in the receiving room is calculated in seconds using Sabine's formula with the following equation:

$$T_r = 0.16\frac{V}{A}, \tag{9}$$

where $V$ is the receiving room volume in $m^3$ and $A$ is the equivalent absorption area in $m^2$.

The measuring principle of the sound reduction index is given in Table 8. The reverberation time $T_r$ is frequently stated as a single value, if measured as a wide band signal (20 Hz to 20 kHz); however, being frequency dependent, it can be more precisely described in terms of frequency bands (one octave, 1/3 octave, 1/6 octave, etc.). In this study, a sonometer measures the reverberation time for a signal to drop by 30 dB. The reverberation time for a signal to drop by 60 dB was determined by multiplying the value of the reverberation time by 2 to decrease it by 30 dB.

The variation in the sound reduction index depending on frequency for the different specimens is given in Figure 12. Collected data were elaborated and compared with reference values given by ISO 717–1 [33] within the frequency range of 125 Hz to 5000 Hz to standardize a method whereby the frequency-dependent values of airborne sound insulation can be converted into a single number characterizing the acoustical performance.

According to the results presented in Figure 12, the percentage of SWM replacement has a considerable influence on the sound reduction index of LC. For the frequency of 500 Hz, the sound reduction index can increase by 34% to reach a maximum value of 35 dB for a percentage of 100% SWM. This result is logical since the sound reduction index of a single wall increases with its mass.

The results also show that, for the frequency range 3000–5000 Hz, there is a decrease in the sound reduction index values for the different specimens compared to LC. It is therefore advisable to use the material for low frequencies.

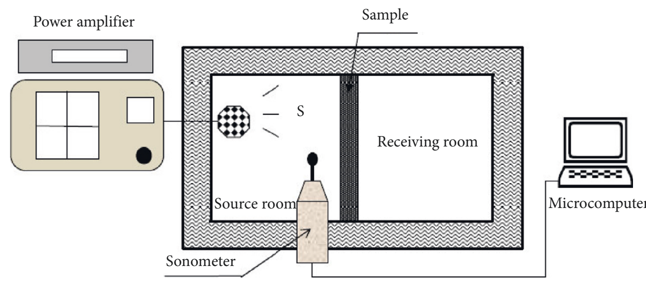
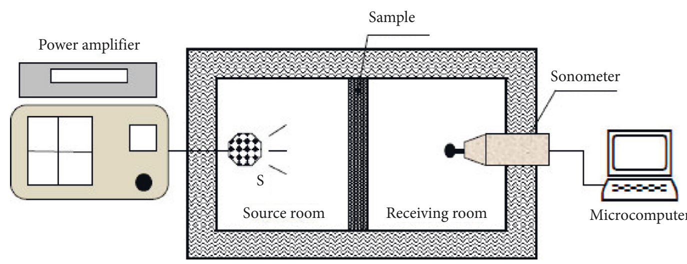
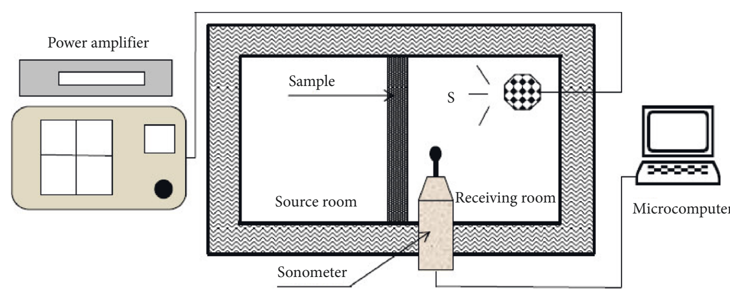
By comparing the sound reduction index of the LC100 specimen with that of other types of lightweight concrete with the same unit weight, LC100 finds its place in the category of insulation lightweight concrete ASTM C 332 [26].

## 5. Design of a New Insulation Lightweight Concrete Block Floor Based on the EPA, Natural Sand, and Crushed Waste Marble

*5.1. Design of the New Block Floor.* According to the pervious results, for a SWM replacement percentage of 0% to 60%, the lightweight concrete can be used for the thermal insulation view and its low thermal conductivity (0.35 W/mK ≤ $\lambda$ ≤ 0.87 W/mK). Indeed, the optimal mixture is composed of EPA, 40% natural sand and 60% SWM.

These interesting results led us to design a new insulation lightweight block floor made by using the optimal mixture. This new insulation lightweight block floor can be used for the construction of composite slabs. They are equipped with a system of cells which improve its thermal and phonic insulation.

Table 8: Measuring principle of the sound reduction index $R_W$.

| Measurement | Figure |
|---|---|
| The Omni Power sound source ($S$) and the sonometer are placed in the source room in order to measure the average sound pressure level $L_1$ |  |
| The sonometer was moved into the receiving room in order to measure the average sound pressure level $L_2$ |  |
| The source is brought back into the receiving room local for the measurement of the reverberation time $T_r$ |  |

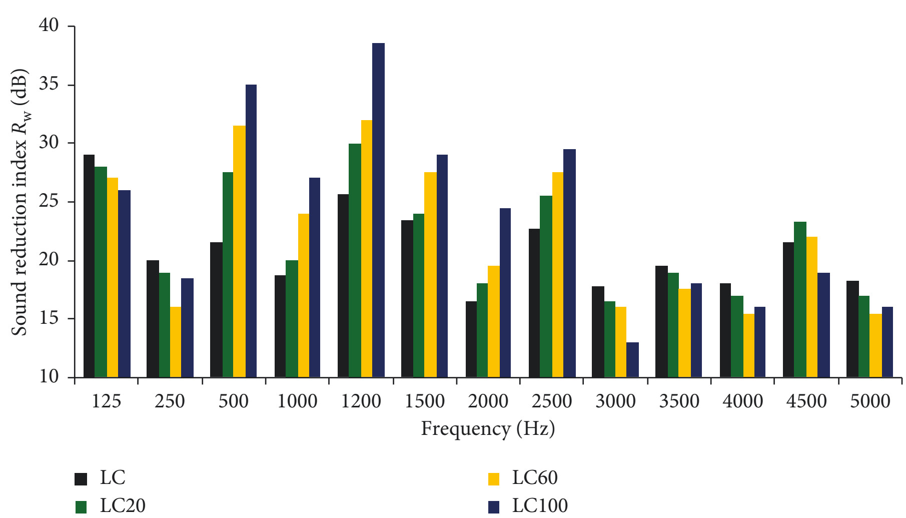



Figure 12: Effect of SWM dosage on the sound reduction index of LC.

*5.2. Preparation of the Prototype.* The prepared three prototypes have the dimensions of $20 \times 25 \times 50$ cm (Figure 13).

The procedure for preparing the block floor prototype is as follows:

(i) Preparation of the mold

(ii) Pouring of the mixture in the mold

(iii) Remove the specimens from the molds after 24 h

*5.3. Results and Discussion.* The different tests were made on the new block floor according to the requirements of NF EN 15037–2+A1 standard [34]. The results are presented in the Table 9. This table shows also a comparison between the new

(a) (b)

Figure 13: Photo of the block floor prototype.

Table 9: Properties of lightweight concrete block floor.

| | Concrete block floor | Lightweight concrete block floor |
|---|---|---|
| Weight (kg) | 22 | 10.50 |
| Punching-flexural strength (kN) | 3.95 | 2.12 |
| Thermal conductivity (W/mK) | 0.96 | 0.44 |
| Thermal resistance ($m^2K/W$) | 0.26 | 0.56 |

insulation lightweight concrete block floor and the concrete block floor.

According to the results presented in Table 9, we remarked an increase of about 50% on the weight of the new block, 22 kg for the concrete block, and 10.50 kg for the new block. Thereafter, this block can be considerate as a lightweight block floor. This makes the construction of the composite floors very easy using this kind of blocks.

The second test consists of measuring the punching-flexural strength of the two blocks (Figure 14). The results show that the punching-flexural strengths of the concrete block floor and the lightweight concrete block are, respectively, equal to 3.95 kN and 2.12 kN. According to the NF EN 15037–2+A1 standard [34], the class of the concrete block is resistant class (designated RR) and that of the lightweight concrete is the semiresistant class (designated SR).

For the SR class, the blocks were involved in the transfer of loads to the beams. The top wall alone cannot act as a compression slab in the finished floor system. On the other side, for the RR class, the blocks provide the same functions as semiresistant blocks but whose upper wall can serve as a slab compression in the finished floor system.

We also remarked, according to the results presented in Table 9, that the thermal properties of the new block were significantly improved compared to those of the concrete block. Indeed, the thermal conductivity of the new block increases about 54% (from 0.96 W/mK for the concrete block and 0.44 W/mK for the lightweight concrete block). In addition, the thermal resistance was improved about 53% (from 0.26 $m^2K/W$ for the concrete block and 0.56 $m^2K/W$ for the lightweight concrete block).


Figure 14: Punching-flexural test on the lightweight concrete block floor.

Finally, we can conclude that the new lightweight concrete block can be considered as an insulation block floor.

## 6. Conclusion

This study presented experimental investigation results of the design of new insulation lightweight concrete blocks based on EPA, natural sand, and crushed waste marble.

According to the experimental results, the following conclusions have been drawn:

(1) Since EPA is very brittle, a mixing procedure was performed to avoid aggregate crushing and size maintaining.

(2) The unit weight of specimens was increased with an increase in the SWM dosage and range from 1065 kg/$m^3$ for specimens containing 0% SWM waste to 1164 kg/$m^3$ for a specimens that contain a percentage of 100% SWM.

(3) The incorporation of SWM significantly improves the mechanical properties of concrete. In fact, the incorporation of 100% SWM exhibited a compressive strength value equal to 12.9 MPa at the age of 28 days.

(4) The incorporation of SWM was classified with specimens into the following two categories: for a replacement percentage of 0% to 60%, the concrete can be used for the thermal insulation view with its low thermal conductivity. For a replacement greater than 60%, the concrete cannot be used for thermal insulation due to its high thermal conductivity, and it is simply a lightweight concrete filling.

(5) The incorporation of SWM by percentage ranging from 0% to 100% increased the thermal diffusivity and decreased the thermal insulation of the concrete.

(6) The specific heat of specimens increased with increasing percentage of SWM from 0% to 100%.

(7) For the frequency of 500 Hz, the sound reduction index increased by 34% to reach a maximum value of 35 dB for a percentage of 100% SWM.

(8) The results on the prototype of the insulation lightweight concrete blocks, prepared with EPA, 40% natural sand, and 60% crushed waste marble, show a remarkable improvement in the thermal properties and a decrease of about 50% in the weight of these blocks compared to those of the concrete blocks. However, these blocks can be used easily for the construction of an insulation lightweight composite floor.

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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