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The Effect of Phase Change Materials on the Physical and Mechanical Properties of Concrete Made with Recycled Aggregate

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Abstract: With the world's population increasing, the issue of energy consumption has become increasingly prominent, particularly during the building operation phase, where substantial energy is required for heating and cooling. Presently, the energy necessary for buildings is sourced mainly from the combustion of fossil fuels, leading to not only energy scarcity but also severe environmental pollution and ecological damage. Furthermore, rapid urbanization has generated a lot of construction and demolition waste. To address these challenges, one promising approach is the incorporation of phase-change materials in recycled aggregate from construction and demolition waste to replace the raw materials of concrete. In this study, the phase-change material suitable for the thermal comfort requirements of buildings was selected and combined with recycled aggregate to replace the natural aggregate in concrete. All the materials used were characterized and three compositions were prepared. From the results, the workability of concrete increased with the phase-change materials added. Regarding water absorption performance, the incorporation of functionalized recycled aggregate presented a small water absorption performance. However, the mechanical performance decreased with the phase-change materials used. This work provides data for the application of phase-change materials in green concrete.

Keywords: green concrete; phase-change materials; recycled aggregate; physical properties; mechanical properties

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1. Introduction

Concrete has become one of the most common building materials in current construction. It is widely used in roads, bridges, residential buildings, and other construction fields. According to the Global Cement and Concrete Association's statistics, about 40% of the world's concrete is used in residential buildings [1]. The natural aggregate required for traditional concrete production accounts for about 75% of the total volume. However, the acquisition of natural aggregate has led to serious ecological and environmental problems. On the other hand, a large amount of solid waste is produced during the construction and demolition phases of buildings; this is called construction and demolition waste (CDW). CDW, normally, is composed of concrete, mortar, brick, ceramic, glass, plastic, wood, etc. After processing, a good-quality recycled aggregate (RA) can be obtained. Numerous investigators have studied RAs instead of natural aggregates in concrete [2–5] to realize the resource utilization of CDW, reduce the over-exploitation of natural aggregates, and maximize the ecological, environmental qualities and economic benefits in the construction sector [6]. However, the huge production of CDW and its low reuse rate pose a contradiction, especially in developing countries: for example, in China, the annual production of CDW is about 2.3 billion tons [7] and its utilization rate is less than 5% [8]; and, in India, the annual output of CDW is about 5 million tons and its utilization rate is only 1% [9]. Therefore, the combination of RAs and phase-change materials (PCMs) in concrete can not only optimize the thermal performance of concrete, but also improve the reuse rate of Ras.

Actually, about 40% of total energy consumption is consumed during the operation of buildings [10], and the main consumption form is the heating and cooling of indoor spaces, accounting 50–63% [11]. A large amount of energy is obtained through the use of fossil energy, which not only leads to energy depletion but also produces large amounts of greenhouse gases. In accordance with the Sustainable Development Goal 7 mentioned in the United Nations' 2023 Agenda—'Ensure access to affordable, reliable, sustainable and modern energy for all' [12]—solar energy is gaining attention as a sustainable and clean energy source. PCMs are able to absorb, store, and release latent heat at a defined temperature range when the material changes state (e.g., solid–liquid). A material containing a PCM can act as a transient thermal barrier that regulates the heat flux, thus achieving the effect of regulating the temperature of the space [13–15]. It is a form of utilizing solar energy that has the following characteristics: it is sustainable, safe, pollution-free, cheap, and protects the environment [14,15]. There are numerous studies about PCMs being used in mortar [13,14,16,17], concrete [18,19], brick [20], gypsum/plastic board [21], etc., through encapsulation [17,21], immersion [19,22], direct incorporation [16,18], and form-stable PCM [13,14,20,23] methods. Different methods have their advantages and disadvantages.

Encapsulation, including micro-encapsulation and macro-encapsulation, consists in enclosing PCM in microcapsules or macrocapsules, which can prevent the PCM from reacting with the surrounding environment, improving its stability and durability. The encapsulated capsules can be flexibly added to various basic materials, such as mortar, concrete, etc., meaning that the application of PCMs can be more flexible and diverse. Cunha et al. [17] studied the use of PCM microcapsules with dimensions ranging from 5.8 to 339 µm to replace sand in mortar. The results showed that the incorporation of PCM microcapsules caused a decrease in the workability and an increase in the porosity of the mortar. However, the encapsulation process is relatively complex; the preparation of microcapsules requires additional cost investment, and the overall cost is high, limiting the popularity of its application. The immersion method consists in distributing the PCM more evenly across the porous material to achieve better thermal performance. Compared to encapsulation, the immersion process is relatively simple, skipping the steps of preparing the microcapsules and reducing the preparation costs. However, there is a problem of leakage, and this method is only applicable to porous materials, which limits its scope of application [19].

The direct incorporation method does not require additional complicated processes such as encapsulation. Compared to other methods, the cost is lower. Due to its simple preparation process, it is easier to achieve large-scale production. However, Cellat et al. [18] studied the direct incorporation of PCMs into high-strength concrete: the results showed that, with the incorporation of 10% of PCMs in concrete, the compressive strength decreased by 64%. At the same time, the direct incorporation of PCMs can be affected by environmental factors (such as temperature) and its stability may be weak.

The form-stable PCM method consists in absorbing the liquid PCM into the porous support material, compound it through solidification, and then mix it into mortar or concrete, which improves the stability and flexibility of the PCM. This operation process is relatively complex compared to the direct incorporation method, and it is necessary to characterize the physical properties of PCMs and porous support materials, such as a PCM's transition temperature, the volume expansion and water absorption of porous materials, etc., to determine its feasibility and optimal absorption. This method has been investigated by several researchers. For instance, Sarcinella et al. [13] studied the Lecce stone with a size distribution between 1.6 and 2.0 mm as a type of support for the absorption of PCMs and their reuse in mortar. From the microscopic analysis the microstructure of the mortar revealed a good connection between the different components of the mortar, and the thermal results showed a good thermal performance. Shen et al. [20] studied the lightweight clastic light-shale ceramist (CLSC) with a porosity of 58% to absorb the paraffin used in concrete. From the results of the thermal test, the thermal properties of the concrete increased by 41.23% when the paraffin content was 6% (90 kg/m^3) of total concrete mass. Lv et al. [23] reviewed nine types of clay mineral-based form-stable phase-change materials' applications: for example, kaolin, diatomite, sepiolite, montmorillonite, perlite, silica, attapulgite, vermiculite, and fly ash. By analyzing the preparation process and characteristics of each material, the feasibility of using clay mineral-based form-stable PCMs to regulate the indoor temperature in building envelopes was summarized.

In this work, the joint application of PCMs and RAs was realized using the form-stable PCM method, aiming to use these two materials in the preparation of concrete to realize the replacement of natural aggregates. Three groups of specimens were prepared: namely, reference concrete (REF), concrete with 50% of RAs replacing the natural aggregates (50RA), and concrete with 50% of RA-adsorbed PCMs (RA-PCM) instead of the natural aggregates (50RA-PCM). By examining the workability of fresh concrete and evaluating the density, water absorption, water absorption by immersion, compressive strength, and flexural strength of hardened concrete, the impact of PCM-addition on the physical and mechanical properties of the reference concrete and the green concrete were analyzed and discussed.

This work is expected to provide a basis for the application of RAs and PCMs in construction materials, reducing dependence on natural non-renewable energy and environmental pollution and promoting the effective recycling of CDW.

2. Experimental Design

2.1. Materials

The PCM selected for this study is pure paraffin, a commodity PCM from the German company Rubitherm. It is an organic PCM, and its transition temperature is 22 °C, which is suitable for a room-comfortable temperature. The properties of this PCM are presented in Table 1. The RA is a commercial recycled aggregate from a recycling station in Portugal. The original size distribution of the RA was between 0 and 10 mm. After sieving through a four-millimeter-aperture sieve, a particle distribution of the RA between 4 and 10 mm was obtained (this RA part was used in this study). The size distribution curves of the original RA and the prepared RA are presented in Figure 1. Their physical properties will be discussed in Section Density and Absorption of the Aggregates. The natural aggregates used in this study were commercial gravel and river sand from Portugal. Their physical properties will be determined in Section 2.1.1. The binder material was cement 42.5R with a density of 3142 kg/m^3. Tap water was used.

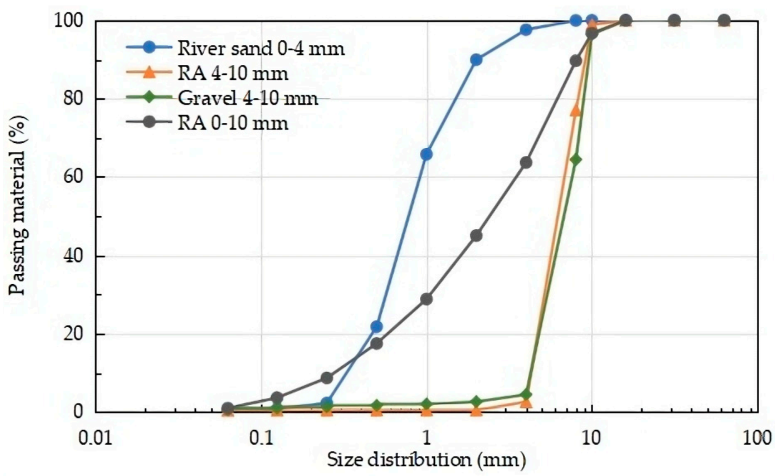

Figure 1. Particle size distributions of the aggregates.

Table 1. The parameters of the PCM used [24].

Characterization	Results
Density solid	0.76 kg/L
Density liquid	0.7 kg/L
Heat storage capacity	190 kJ/kg
Transition temperature	22 °C

2.1.1. Materials' Characterization

Density and Absorption of the Aggregates

According to the standard NP 954 [25], the density and absorption of river sand were determined. First, a sample was selected and dried at 105 °C; after 24 h, it was weighted as $M1$. Then, the pycnometer filled with water was weighted and recorded as $M2$. The sample was immersed in water and, after 24 h, the excess water was drained. A hair-dryer was used to control the moisture content of the river sand to a saturated and surface dryness state, which was recorded as $M3$. Further, the saturated river sand from the previous step was put into a pycnometer, which was filled with water. This weighting was recorded as $M4$. Then, the density and absorption of river sand were calculated using the following equations:

$$\text{Saturated density } (\text{g/cm}^3) = \frac{M3}{M3 + M2 - M4} \tag{1}$$

$$\text{Dry density } (\text{g/cm}^3) = \frac{M1}{M3 + M2 - M4} \tag{2}$$

$$\text{Water absorption } (\%) = \frac{M3 - M1}{M1} \times 100 \tag{3}$$

The coarse aggregate density and water absorption were determined in compliance with NP 581 [26] in controlled laboratory conditions at room temperature. The sample underwent 24 h of desiccation at 105 °C, denoted as $M1$, followed by the complete immersion in water for 24 h ($M2$). Subsequently, the submerged sample's weight was recorded as $M3$. The saturated density and dry density were calculated using Equations (4) and (5), respectively, and the water absorption was quantified using Equation (6). The results of the density and absorption of the aggregates are shown in Table 2.

$$\text{Saturated density } (\text{g/cm}^3) = \frac{M2}{M2 - M3} \tag{4}$$

$$\text{Dry density } (\text{g/cm}^3) = \frac{M1}{M2 - M3} \tag{5}$$

$$\text{Water absorption } (\%) = \frac{M2 - M1}{M1} \times 100 \tag{6}$$

Table 2. The density and water absorption of the aggregates.

Characterization	River Sand 0–4	Gravel 4–10	RA 4–10
Dry density (kg/m^3)	2563	2197	2134
Saturation density (kg/m^3)	2593	2208	2294
Water absorption (%)	1.19	0.51	7.82

Size Distribution of the Aggregates

According to the standard EN 933-1 [27], the particle size distribution of all the aggregates was determined. The results are presented in Figure 1. The size distribution of the original RA (size of 0–4 mm) was characterized, and the results are shown in the gray curve in Figure 1. A sieve with a mesh size of 4 mm was used to separate the aggregates in the 0–4 mm part of the RA; then, the particle size distribution of the aggregates in the 4–10 mm range was determined. It can be observed from Figure 1 that the particle size distribution curve of the RA and gravel basically coincide, which also reduces the influence caused by the difference in aggregate particle distribution during the replacement process.

2.1.2. Functionalization of RA Using a PCM

The purpose of enhancing the functionalization of an RA is to maximize the absorption of the PCM. On the other hand, the phase transition and ensuing state change of the PCM are closely linked to the variations in its volume. Liquid PCM was introduced into the RA through immersion techniques. Consequently, it was imperative to rigorously assess the volume changes that the PCM might undergo during the phase transition and determine whether these changes could have adverse effects on the RA.

It is a well-established fact that alterations in the volume of water within concrete can result in significant damage, particularly during freeze–thaw cycles, primarily due to water's volumetric expansion, which is approximately 9% [28,29]. Similarly, if the volume changes associated with the PCM's phase transition are excessively high, they could potentially harm the RA. To ascertain the integrity of the RA–PCM during the operational process, it was therefore necessary to conduct volumetric tests on the PCM during its phase transition.

Volumetric Variation of the PCM

In order to better observe the PCM's volumetric variation, a beaker with a total volume of 25 mL and a minimum graduation of 0.1 mL was used. The test was carried out in a temperature-controlled chamber. A total of 15.4 mL of liquid PCM was injected into the beaker at 35 °C. The chamber temperature was varied in steps of 5 °C. As the temperature progressively decreased, the volume of the PP underwent a contraction, until it solidified at 20 °C, resulting in the volume's reduction to 15 mL (at this time the volume was at its smallest). The maximum volumetric variation of the PCM during phase transition was calculated using the following expression:

$$\text{Volumetric variation of PCM } (\%) = \frac{Volume\ at\ 35\ ^\circ\text{C} - Volume\ at\ 20\ ^\circ\text{C}}{Volume\ at\ 20\ ^\circ\text{C}} = \frac{15.4 - 15}{15} \times 100 = 2.67\% \quad (7)$$

Aggregate Impregnation

In this study, the form-stabilization technique was applied to create functionalized aggregates incorporating the PCM. The evaluation of the PCM's absorption by the RA was conducted under atmospheric pressure conditions, with assessments performed at both one- and four-hour intervals. To ensure the optimal PCM's absorption by the RA specimens, which were characterized by dimensions ranging from 4 to 10 mm, a pre-drying step was carried out in an oven set to 105 °C for a duration of 24 h.

To effectively gauge the RA's capacity for absorbing the liquid PCM, it was imperative to maintain the PCM in a liquid state throughout the experimental procedure. To accomplish this, the PCM was subjected to a controlled temperature of 30 °C, intentionally surpassing the PCM's melting temperature of approximately 22 °C. Subsequently, the RA specimens underwent immersion in the liquid PCM for both one- and four-hour durations, with periodic stirring using an iron rod every 15 min to ensure uniform absorption.

Following either a one-hour or four-hour immersion period in the liquid PCM, the RA was extracted using a colander and then allowed to cool, leading to the formation of RA–PCM thermal aggregates. The results detailing the PCM's absorption by the RA during both one-hour and four-hour immersion tests are presented in Table 3. In light of achieving the maximum PCM dosage, a four-hour immersion time was selected as the optimal duration for this investigation.

Table 3. The absorption of the PCM by the RA (%).

Immersion Time	Absorption Rate (%)
1 h	7.47
4 h	8.02

2.2. Concrete Mix Design

In this study, three concrete mixtures were formulated. The reference concrete, denoted as REF, was prepared following the Faury method. The cement consumption was 400 kg/m^3. In order to obtain a better workability in the fresh concrete, the slump of fresh concrete was controlled within the range of 13–14 cm (within the Class S3 [30]) by adjusting the water/cement ratio. Subsequently, two additional concrete mixtures, namely 50RA and 50RA-PCM, were developed by replacing 50% of the gravel component with 50% of RA and 50% of RA–PCM, respectively, through a weight substitution process. Since the river sand, RA, and gravel were used after drying at 105 °C for 24 h, the water saturation was accounted as part of the absorption process for the dry aggregates (for example, river sand, gravel, and RA). All the compositions of the concretes are presented in Table 4.

Table 4. The compositions of the concretes (kg/m^3).

Mixtures	Cement	Water	River Sand	Gravel	RA	RA-PP	Water Saturation
REF	400	220	393	1035	-	-	10
50RA	400	230	393	552	552	-	50.6
50RA-PCM	400	240	393	541.6	-	541.6	7.4

2.3. Sample Manufacturing

All the samples were prepared in a laboratory environment. In accordance with the EN 12390-1 (2003) standard [31], the dimensions of the specimens were determined. Nine cube specimens, measuring 50 mm × 50 mm × 50 mm, were crafted for the purpose of characterizing the water absorption by immersion and the concrete's density (four specimens), as well as for conducting compressive strength tests (five specimens). Additionally, three cubic specimens with dimensions of 40 mm × 40 mm × 160 mm were thoughtfully prepared for flexural strength testing.

Following the flexural strength test (three specimens), the cubic specimens underwent a drying process in an oven set to a temperature of 60 °C. The drying continued until a constant mass was achieved, signifying that the mass change was less than 0.1% within a 24 h period. Subsequently, the capillary water absorption test was diligently carried out as scheduled.

2.4. Test Methods

This study aimed to comprehensively investigate the workability, physical performance, and mechanical properties of the three concrete specimens. The main tests conducted in this research encompassed slump, density, water absorption within 24 h, water absorption by immersion, capillary water absorption, compressive strength, and flexural strength.

To assess the workability of the fresh concrete, the standard EN 12350-2 [32] was followed. This test evaluated the workability and allowed for adjustments in the quantity of water used to achieve an optimal workability. Subsequently, all the concrete specimens underwent a curing period of 28 days in water to ensure proper hydration and the development of mechanical properties, in accordance with the standard EN 12390-2 [33].

The density and the water absorption within a 24 h period were determined following the guidelines outlined in the NP 581 standard [26], using the same experimental process as described in Section Density and Absorption of the Aggregates. The water absorption by immersion test, assessing the concrete's ability to absorb water when submerged, was conducted in accordance with the LNEC E 394 (1993) standard [34].

Furthermore, the compressive strength test was carried out according to the EN 12390-3 standard [35]. Since the specimens were cubic, with dimensions of 50 mm, a pressing speed of 2.9 kN/s was employed. The flexural strength test was performed following the EN 12390-5 standard [36]. After the flexural strength test, the specimens were collected and placed in an oven at 60 °C until a constant mass was achieved, in preparation for the capillary water absorption test.

Subsequently, the capillary water absorption of the concrete was tested in accordance with the LNEC E 393 (1993) [37]. This test measured the amount of water absorbed by the specimen at various time intervals, totaling 150 h.

These executed test procedures provided a comprehensive evaluation of the concrete's workability, physical characteristics, and mechanical properties, contributing to a thorough understanding of its relevant performance attributes.

3. Results and Discussions

3.1. Slump and Total Water Mix

Figure 2 illustrates the relationship between the slump and the total water mix. In the case of the REF mixture, the slump measured 14 cm, with a total water mix of 230 kg/m^3. However, when 50% of RA replaced the gravel component, it became necessary to increase the total water content by 22% to maintain the slump of the 50RA mixture within the desired range of 13 to 14 cm. Consequently, when the slump of the 50RA mixture reached 13 cm, the total water mix increased to 280.7 kg/m^3. This increase in water demand can be attributed to the considerable water absorption capacity of the dry RA. Additionally, the irregular surface of the RA aggregates, along with the presence of fine particles adhering to them, contributes to the higher water requirement.

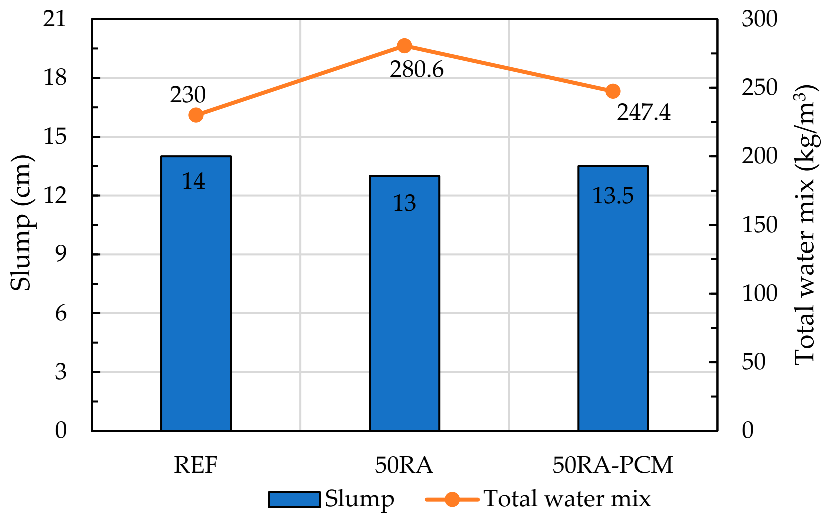

Figure 2. The relation between the slump and the total water mix.

In contrast, when 50% of RA–PP replaced the natural aggregates, there was a noteworthy 11.8% reduction in the water mix content compared to the 50RA's. This decrease can be justified by the fact that the functionalized RA aggregates contained pores filled with the PCM, resulting in a cleaner surface. The PCM covering the surface of the aggregates also decreased the friction between them, leading to a lower demand for water.

Comparing the 50RA-PP with the REF mixture, there was a 7.6% increase in the total water consumption. This could be attributed to the irregular shape of the RA aggregates, a factor that has been discussed in prior studies [38]. Furthermore, there might have been pores present in some of the RA aggregates that did not fully absorb the PCM, necessitating additional water for the mixture.

These findings contribute to a better understanding of the water requirements in mixtures containing recycled aggregates and phase-change materials, highlighting the influence of an aggregate's characteristics on the overall water demand.

3.2. Density and Water Absorption of Concretes

In accordance with the NP 581 standard [26], the density and water absorption were assessed within a 24 h time-frame. Figure 3 provides a representation of the results, indicating minimal disparities in the dry density among the three concrete mixtures. Specifically, the dry density of the REF was marginally greater, approximately 4.5% higher than that of the 50% recycled aggregate (50RA) mixture, and roughly 7.4% higher than that of the 50% recycled aggregate with PCM (50RA-PCM) mixture. A closer examination of the data in Table 1 reveals that this discrepancy can be attributed to the inherently higher dry density of the gravel in comparison to the recycled aggregate (RA). The variations in dry density observed among the mixtures reflect the distinct characteristics of the aggregate components used in their formulations.

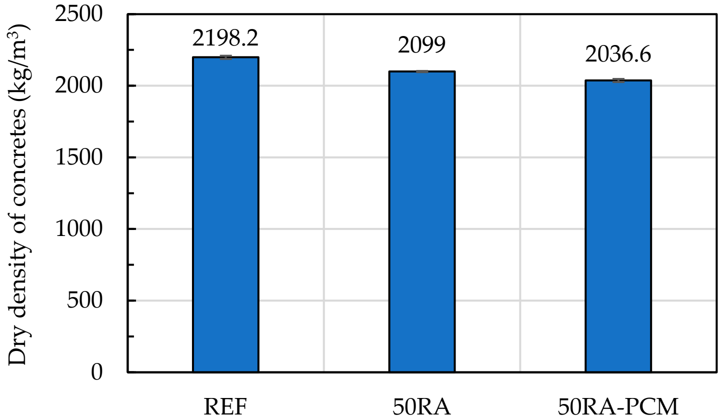

Figure 3. Dry density of the concretes (kg/m^3).

Furthermore, as part of the same assessment process, the water absorption properties of the concrete were determined. Figure 4 illustrates the outcomes of the water absorption tests for all the concrete mixtures. It is easy to observe that the absorption of the REF is the smallest of all the water absorptions, with a slight difference between the 50RA and the 50RA-PCM. Specifically, the water absorption of the 50RA was approximately 33.8% higher than that of the REF, while the water absorption of the 50RA-PCM was approximately 27.9% higher than that of the REF. This observation suggests the presence of a greater number of pores within the 50RA and 50RA-PCM concrete specimens. Simultaneously, the data in Table 2 corroborates the fact that the water absorption of the recycled aggregate (RA) is significantly higher than that of the gravel, providing an explanation for this phenomenon.

These findings underscore the influence of an aggregate's composition on water absorption properties and point to the potential presence of porous structures within the recycled aggregate-containing concrete mixtures.

3.3. Water Absorption by Immersion

Figure 5 illustrates the water absorption values obtained through the water absorption by immersion test following the LNEC E 394 (1993) standard [34]. When comparing the results in Figure 5 with those in Figure 4, it is evident that both datasets exhibit similar trends. Specifically, the reference mixture (REF) demonstrates the lowest water absorption by immersion rate, approximately 23.5% lower than that of the 50% recycled aggregate (50RA) mixture and about 18.1% lower than that of the 50% recycled aggregate with PCM (50RA-PCM) mixture.

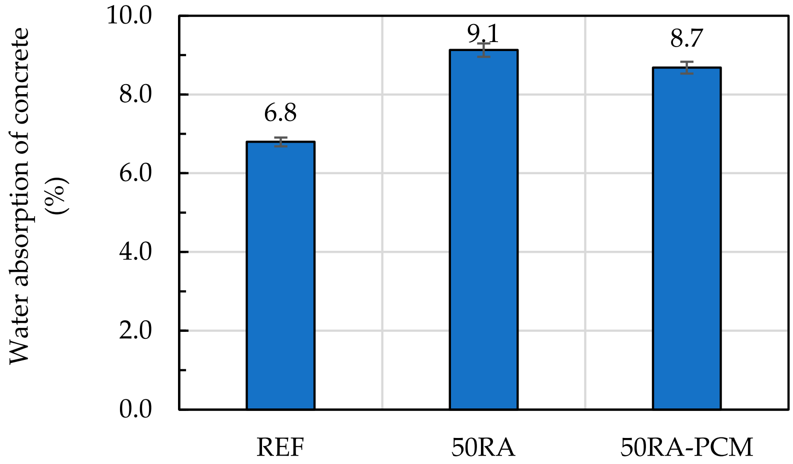

Figure 4. Water absorption of the concretes in a 24 h time-frame (%).

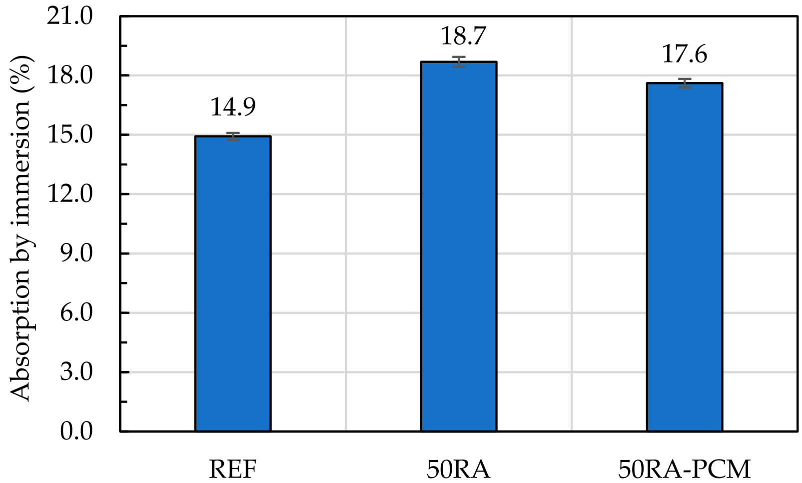

Figure 5. Water absorption by immersion (%).

Furthermore, the water absorption by immersion for the 50RA-PCM is approximately 5.9% less than that of the 50RA mixture. These findings align with the results observed previously and further substantiate the notion that the reference mixture (REF) consistently displays lower water absorption characteristics when contrasted with concrete mixtures incorporating RAs. When comparing this to the concrete incorporation of the non-functionalized RA, it becomes evident that the concrete incorporation of the functionalized RA tends to reduce water absorption by immersion to a certain extent.

3.4. Capillary Water Absorption

According to the standard LNEC E 393 [37], the capillary water absorption of three concretes was examined over a duration of 150 h, and the water absorption measurements were recorded at several time intervals. The results are presented in Figure 6. Furthermore, when considered alongside the principles governing capillary water absorption [39], these findings suggest that the 50% recycled aggregate with PCM (50RA-PCM) mixture possesses fewer minuscule voids, cracks, or surface capillary pathways.

The capillary water absorption curves of both the reference mixture (REF) and the 50% recycled aggregate (50RA) mixture exhibited a similar trend during the initial 41 h of testing. However, after this point, the capillary water absorption of the 50RA mixture gradually exceeded that of the REF mixture. Nevertheless, it is important to note that, following this phase, all the concrete mixtures exhibited a continued uptake of water until they essentially reached a state of constant mass.

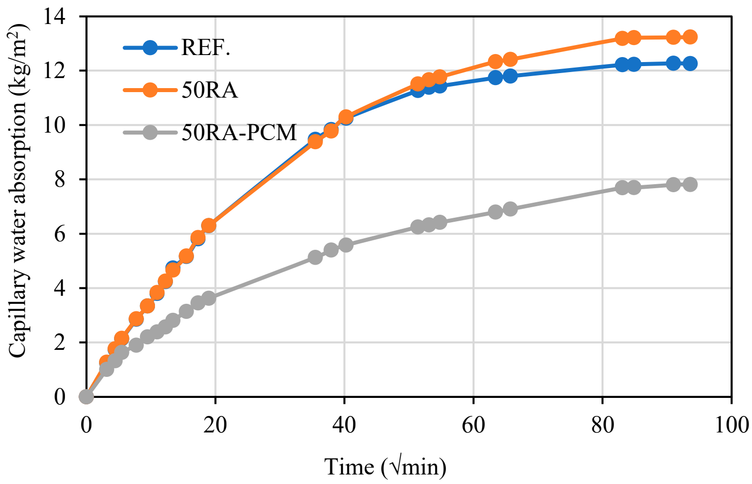

Figure 6. Capillary water absorption (kg/m^2).

Additionally, the capillary water absorption coefficients were calculated, and the results are presented in Table 5. Notably, the 50RA-PCM mixture exhibited a notably lower capillary water absorption coefficient, signifying its superior resistance to capillary water absorption. In contrast, the 50RA mixture demonstrated the highest capillary water absorption coefficient, surpassing that of the 50RA-PCM by approximately 43.4% and exceeding the REF mixture by 8.9%. These phenomena can be elucidated by the presence of the PCM within the capillary pores of the recycled aggregate. The PCM effectively obstructed the occurrence of capillary phenomena to a significant extent, leading to a reduced capillary water absorption coefficient.

Table 5. Capillary water absorption coefficient (kg/(m^2·h$^{0.5}$)).

Mixtures	Capillary Water Absorption Coefficient (kg/(m^2·h$^{0.5}$))
REF	0.116
50RA	0.1274
50RA-PCM	0.0721

These findings underscore the significant differences in capillary water absorption properties among the tested concrete mixtures, with the 50RA-PCM mixture displaying the most favorable performance in terms of the capillary water absorption coefficient.

3.5. Compressive Strength

After subjecting all the specimens to a 28-day curing period in water, the compressive strength was assessed in accordance with the EN 12390-3 standard [35]. As illustrated in Figure 7, it becomes readily apparent that the compressive strength of the REF mixture significantly outperforms that of the 50RA mixture by a margin of 37.1% and that it surpasses the compressive strength of the 50RA-PCM mixture by a substantial 64.3%. These results highlight a discernible reduction in compressive strength when a recycled aggregate was employed in the mixture.

Furthermore, the compressive strength of the concrete incorporating functionalized RA decreased by 16.5% compared to the 50RA. It is worth noting that, with the same content of RA, the concrete incorporating the functionalized RA presented small compressive strength. This can be justified by the PCM adhering to the surface of the RA possibly resulting in less-effective bonding between the cement matrix and the aggregates, potentially contributing to the observed decrease in compressive strength [18,40].

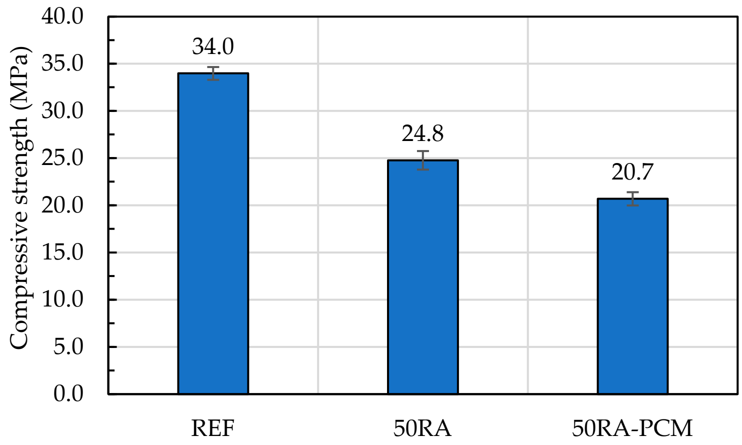

Figure 7. Compressive strength of the concretes (MPa).

3.6. Flexural Strength

Three specimens, each with dimensions of 40 mm × 40 mm × 160 mm, were cured for 28 days in water. Subsequently, the flexural strength test was realized following the EN 12390-5 standard [36], and the results are presented in Figure 8.

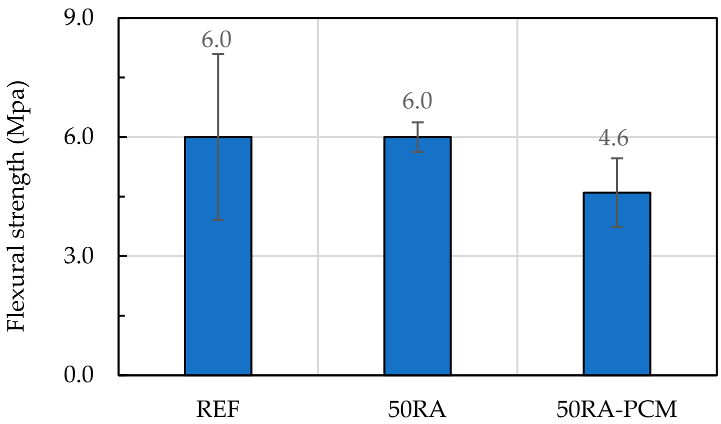

Figure 8. Flexural strength of the concretes (MPa).

It is noteworthy that the REF mixture and the 50RA mixture exhibited identical flexural strengths of 6 MPa. However, there were relatively substantial variations observed among the three REF samples, indicating some degree of variability in their flexural strength performance. In contrast, the flexural strength of the 50RA-PCM mixture was measured at 4.6 MPa, which represents a 23% reduction compared to the other compositions.

These results provide insights into the flexural strength characteristics of the tested concrete mixtures, highlighting the potential impact of incorporating PCMs on the flexural strength, especially in the case of the 50RA-PCM mixture.

4. Conclusions

In conclusion, the utilization of phase-change materials (PCMs) simultaneously with RAs to study the physical and mechanical properties of concrete represents a promising avenue for addressing critical issues related to energy consumption and construction waste management. In this study, the incorporation of a recycled aggregate and the incorporation of a functionalized recycled aggregate in concrete were studied from the following aspects:

Workability. From the observed relationship between the slump and the water consumption of fresh concrete, it is evident that the presence of a recycled aggregate (RA) significantly influences the total water demand during the mixing process. RAs necessitate a greater amount of water to achieve the desired slump.

Conversely, in the case of a functionalized RA, the PCM effectively occupies the pores within the RA, reducing the overall water demand during mixing. Consequently, this modification results in a more controlled and reduced water requirement, enhancing the workability of the concrete mixture.

Physical properties of concrete. The dry density values of the concretes presented the effects of the dry density of the aggregate. That is, the greater the dry density of aggregate, the greater the dry density of concrete.

From the test results regarding water absorption, water absorption by immersion, and capillary water absorption, the concrete incorporating 50% of recycled aggregate showed a great water absorption performance. This can all be explained by the fact that RAs have a greater water absorption rate. The concrete incorporating 50% of functionalized RA presented a small capillary water absorption coefficient. This can be justified by the fact that the PCM fully filled the pores of the RA, which effectively prevented the occurrence of capillary phenomena in the concrete to a large extent, resulting in a reduction in the capillary water absorption coefficient of the concrete in question.

Mechanical properties of concrete. Based on the mechanical test results, it is evident that the 50RA-PCM mixture displayed relatively lower compressive and flexural strength values. The primary factor contributing to this phenomenon was the presence of the PCM adhering to the surface of the RA, which altered the bond between the cement matrix and the aggregate. Consequently, this alteration reduced the internal friction within the concrete, leading to the observed reduction in both compressive and flexural strength.

These findings underscore the importance of considering the potential impact of PCMs on the mechanical properties of concrete, particularly in terms of its bonding effects on the aggregates and overall friction within the mixture. This study further provides basic research data support for the combination of construction and demolition waste and phase-change materials to improve the thermal properties of concrete, as well as a basis for the use of phase-change materials in various types of material applications in the future.

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