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Exploring the potential of peach (Prunus Persica L.) nut-shells as a sustainable alternative to traditional aggregates in lightweight concrete

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Abstract

This study investigates the potential application of peach shells as lightweight aggregates in the production of non-structural lightweight concrete (LWC). The recycling and reutilization of agri-food waste presents an opportunity to address the challenges associated with waste disposal and limit the exploitation of natural resources, contributing to sustainable development goals and combatting climate change. The peach shells were subjected to heat treatment at various temperatures (160, 200, and 240 °C) to reduce the hydrophilicity of the cellulose fraction, and their chemical and physical properties were examined in relation to the performance of lightweight concrete, in terms of density, compressive strength and thermal conductivity. Two binding mixtures, one with lime only (mixture "a") and the other with both lime and cement (mixture "b"), were studied. The experimental results indicated that the prepared lightweight concrete specimens exhibited better performance as the roasting temperature increased, starting from 200 °C. Conversely, specimens prepared with peach shells roasted at 160 °C exhibited a decreased performance compared to those prepared with only air-dried peach shells. Samples prepared with the mixture "a" have better insulating properties and lower density, but lower mechanical resistance. The enhanced properties observed in the lightweight concrete specimens prepared with higher roasting temperatures highlight the potential of utilizing peach shells as an effective and sustainable alternative to traditional lightweight aggregates.

Keywords: sustainability; green building; recycle; food waste; lightweight concrete; lime concrete; fruit shells; coarse aggregate replacement

1. Introduction

The impact of the construction industry on the environment is an important issue that needs to be addressed to achieve sustainable development [1,2]. The construction sector is a significant contributor of environmental pollution. Currently, it is responsible for consuming approximately 32% of natural resources and producing approximately 25% of the solid waste generated worldwide [3–5]. In addition, it is a primary source of carbon emissions [6]. Construction industry activities are linked not only to environmental issues but also to socioeconomic and cultural aspects [7–9]. It plays a vital role in any economy by providing employment opportunities, boosting gross domestic product (GDP), and creating strong infrastructure that drives progress [9,10]. The rapid increase in global population has led to a growing demand for urbanization [11], emphasizing the need to identify low-cost building materials that can meet this growing demand while remaining accessible and affordable [9]. Currently, approximately three billion people live in slum conditions because of slow urbanization, which is exacerbated by continued global population growth. The construction sector accounts for approximately 50% of global energy consumption [9,12,13], highlighting the pressing need to develop eco-friendly building materials. With the rising demand for urbanization, buildings must be energy-efficient to meet ever-increasing energy requirements [14,15]. Advanced and effective insulation materials, for example, can help reduce the environmental impact of buildings by increasing their efficiency and reducing their energy consumption [15]. By adopting sustainable building practices, the construction industry can provide safe and affordable housing for city dwellers, promote economic growth, create job opportunities, and improve the overall wellbeing of individuals and communities. The adoption of green building methods can contribute to Sustainable Development Goals by addressing global challenges [8].

An effective way to reduce the consumption of natural resources and mitigate environmental problems related to raw material extraction is to use industrial waste from the construction industry itself or from other productive sectors such as the agro-industrial sector. Agri-food waste is often regarded as an environmental issue; however, recent developments have revealed its potential for use as a sustainable solution in the construction industry [16–20]. In particular, agri-food waste can be used as lightweight aggregate in the production of lightweight concrete (LWC) [21,22]. LWC is a versatile building material that offers numerous advantages over traditional concrete [23–25]. As the name suggests, this type of concrete is significantly lighter than traditional concrete and requires fewer materials to achieve the same level of structural integrity, thereby reducing the overall weight of the structure. Furthermore, LWC exhibits better thermal insulation properties than traditional concrete owing to its lower density, which reduces the amount of energy required for heating and cooling, resulting in lower energy consumption and environmental impact [26]. The thermal conductivity is typically lower than 1 W/m°C and the dry density is up to 2000 kg/m3. Therefore, LWC is used when low weight and insulating properties are relevant. In addition, LWC provides improved acoustic insulation, reduces noise pollution, and provides a quieter and more comfortable living environment. The use of bio-based lightweight aggregates represents a feasible approach for achieving more sustainable construction. When agri-food waste is used as an aggregate, it not only uses up what would otherwise be landfill waste but also reduces the need for natural aggregates, which are often heavy, energy-intensive, and have a significant carbon footprint as they require significant transport to the building site. Moreover, the use of agri-food waste as an aggregate in lightweight concrete directly benefits the local communities. The community would benefit from the economic value of these low-value resources, as using them for construction would generate employment opportunities, particularly in rural areas and small towns where agricultural and food waste is abundant.

This study focused on exploring the potential of Rosaceae nutshells as an eco-friendly alternative to traditional aggregates in LWC. In particular, the potential of peach (Prunus persica L.) shells as lightweight aggregates was assessed. Peaches are widely cultivated [27], and their shells are considered low-value agro-industrial residues [28]. According to the "Food and Agriculture Organization (FAO)", global peach production was approximately 24 million tons in 2020. The pulp of Rosaceae fruits is highly valued by agro-industries because of its versatility in making juices, canned fruits, jams, and sweet snacks. All these productive sectors generate a significant amount of waste pits, which make up approximately 10% of the total mass produced [29]. Currently, the main alternative to landfilling fruit shells is the incineration of biomass heating systems. However, this activity requires temporary storage of the shells in large piles outdoors, with consequent problems such as space availability, environmental hygiene issues, and the development of odorous fumes due to uncontrolled fermentation of the pulp residues and decomposition of the organic material [30]. The second and more important factor is the serious environmental effects caused by the incineration of these materials. The combustion of agricultural residues such as wood, leaves, trees, and grass generates approximately 40% of CO2 emissions, 20% of fine particles, and 50% of polycyclic aromatic hydrocarbons (HAPs) [31]. The use of peach shells as aggregates for sustainable building is linked to some of their characteristics, which make them very interesting. First, their degradation under natural conditions is difficult and slow, unlike that of other food waste by-products [32,33]. Furthermore, they have considerable porosity, which results in a considerable reduction in the thermal conductivity [34]. Finally, being a widely available and low-cost waste material, its reuse and valorization are perfectly in line with the 2030 Agenda for Sustainable Development [35]. However, the main concern is the high water absorption of the cement mix by the biomass aggregates. Increased water absorption leads to swelling, cracking, and the subsequent loss of durability and mechanical strength [36–38]. This phenomenon can be reduced by the heat treatment of materials using a roasting procedure [34]. In this study, peach shells were roasted at 160, 200, and 240 °C to evaluate the effect of aggregate pretreatment on the performance of LWC. Heat treatment imparts an increase in dimensional stability to the fruit shells owing to lower water absorption. This phenomenon is due to the degradation of the hydroxyl groups of the cellulosic fraction, which results in a decrease in the water absorption capacity of the biomass [39,40]. Therefore, heat treatment of peach shells can be an effective method for improving the performance of peach shell concrete (PSC).

In this study, two lime-based cement mixtures are investigated. This binding material has been used in civil engineering [37,41,42], and only a few studies have evaluated its potential as an alternative to Portland cement [43,44]. Lime offers several environmental advantages compared to cement-based materials. Its raw material, limestone, is burned at lower temperatures than cement; therefore, lime requires less energy. Furthermore, part of the CO2 generated during its production is reabsorbed by hardened lime [45]. In addition, lime-based concrete is more porous, resulting in a decrease in density and thermal conductivity. Therefore, it is an eco-friendly material compared to concrete, even though it leads to materials that are much less mechanically resistant.

This study presents a novel approach for sustainable lightweight concrete production by exploring the potential utilization of peach shells as coarse aggregates. To the best of our knowledge, this is the first comprehensive investigation of the incorporation of roasted peach shells into lime-based concrete mixtures to enhance sustainability and reduce environmental impact. We aim to contribute to the development of innovative and eco-friendly construction materials by harnessing the inherent properties of peach shells and their abundance as agricultural waste. By systematically evaluating the physical, mechanical, and durability properties of peach-shell-based lightweight concrete, we aim to provide valuable insights into its feasibility and performance.

2. Methodology

2.1. *Raw materials properties and Specimens preparation*

2.1.1. Binder Mixture

The main binder used was hydrated lime (Litokol S.p.A., 42048 Rubiera, Italy). To improve the mechanical properties, a few sets of specimens were prepared with the addition of Typica I 52.5 grade Portland cement (Litokol S.p.A., 42048 Rubiera, Italy). The physical and chemical properties of the binders are listed in Table 1.

Table 1

Physical and chemical properties of the binders

	Hydrated lime	Cement 52.5
Chemical analysis (wt%)		
SiO_2	-	19.8
CaO	75.68	63.89
Al_2O_3	-	4.43
Fe_2O_3	-	3.08
SO_3	-	3.77
MgO	-	1.02
Na_2O	-	0.09
K_2O	-	0.67
TiO_2	-	0.18
Physical Properties		
Bulk density (kg/m^3)	450	770
Specific gravity (g/cm^3)	2.24	2.75
Compressive strength 7 days (N/mm^2)	-	30
Compressive strength 28 days (N/mm^2)	-	52.5

2.1.2. Coarse and fine aggregates

Crushed shells were used as alternative coarse aggregates (Fig. 1). The peaches were sourced from a local orchard in Modena, Italy, and bought from a nearby supermarket. The pulp was separated from the pits, cleaned before use, and the residual dried pulp and dust on their surfaces were removed. The pits were preliminarily air-dried for 30 days, to remove residual moisture, after which the external shell was separated from the internal kernel through coarse grinding. A crushing machine was used to crush the dried shells, and they were then sieved with 4.5 and 9.5 mm sieves. Three sets of roasted peach shells were prepared by placing them in glass container and heated in an inert atmosphere (N_2) for two hours at 160, 200, 240 °C, respectively (PS160, PS200 and PS240, respectively). One set was kept simply air dried (PS). Natural alluvial silica sand was used as the fine aggregate (Litokol S.p.A., 42048 Rubiera, Italy). The physical properties of the aggregates are listed in Table 2, and the proximate chemical compositions of the fruit shells are listed in Table 3.

Table 2

Physical properties of coarse and fine aggregates

	Coarse aggregate				**Fine aggregate**
Physical property	**PS**	**PS160**	**PS200**	**PS240**	**Sand**
Particle size (mm)	*4.5 – 9.5*	*4.5 – 9.5*	*4.5 – 9.5*	*4.5 – 9.5*	*1*
Specific gravity (kg/dm^3)	*1.28*^{a}	*1.24 ± 0.05*	*1.21*^{a}	*1.19*^{a}	*1.5*
Bulk density (kg/m^3)	*556 ± 2*	*528 ± 1*	*520 ± 2*	*514 ± 3*	*1560*
Water absorption (24h) (%)	*15.2 ± 0.3*	*16.1 ± 0.5*	*8.7 ± 0.3*	*7.8 ± 0.2*	*1.1*
Shape	*Flaky*	*Flaky*	*Flaky*	*Flaky*	*Tout-venant*

PS = Peach Shells, ^{a}SD<0.05

Table 3

Proximal chemical composition of Peach shells

	PS	**PS160**	**PS200**	**PS240**
*Moisture (%)**	*4.2 ± 0.7*	-	-	-
Mass loss (%)	-	*5.1 ± 0.6*	*5.5 ± 0.3*	*6.4 ± 0.5*
Ash (%)	*1.0 ± 0.2*	*1.8 ± 0.3*	*2.3 ± 0.1*	*3.0 ± 0.2*
C (%)	*47.7 ± 0.5*	*48.3 ± 0.9*	*50.9 ± 0.7*	*59.0 ± 0.7*
H (%)	*5.7 ± 0.1*	*5.5 ± 0.2*	*5.6 ± 0.1*	*5.2 ± 0.3*
N (%)	*0.2*^{a}	*0.3*^{a}	*0.3*^{a}	*0.3*^{a}
O (%) (from difference)	*45.4 ± 0.8*	*44.1 ± 0.11*	*40.9 ± 0.9*	*32.5 ± 0.12*
Protein content (%)	*1.2*^{a}	*1.9*^{a}	*1.9*^{a}	*1.9*^{a}
Fat (%)	*0.1*^{a}	*0.1*^{a}	*0.1*^{a}	*0.1*^{a}

PS = Peach Shells, ^{a}SD<0.05

*On dry basis

The methods recommended by the Association of Official Analytical Chemists were used to determine the levels of moisture, ash, crude protein, and residual oil. Moisture content was determined by drying the samples at 105 °C to a constant weight. The ash content was determined using a laboratory furnace at 550 °C and the temperature was gradually increased. Nitrogen content was determined using the Dumas method and converted to protein content by multiplying by a factor of 6.25. The residual fat fraction was recovered using the Soxhlet method, exhaustively extracting 10 g of each sample using petroleum ether (boiling point range 40 – 60 °C) as the extractant solvent. Each measurement was performed at least in triplicate, and the results were averaged.

It is important to note that various factors have a significant impact on the chemical composition and physical properties of vegetable matrices, such as geographical origin, level of ripeness, and specific cultivar they originate from [46].

Figure 1 shows the values of mass loss (Δm%) and specific gravity (kg/dm^3) against roasting temperature.

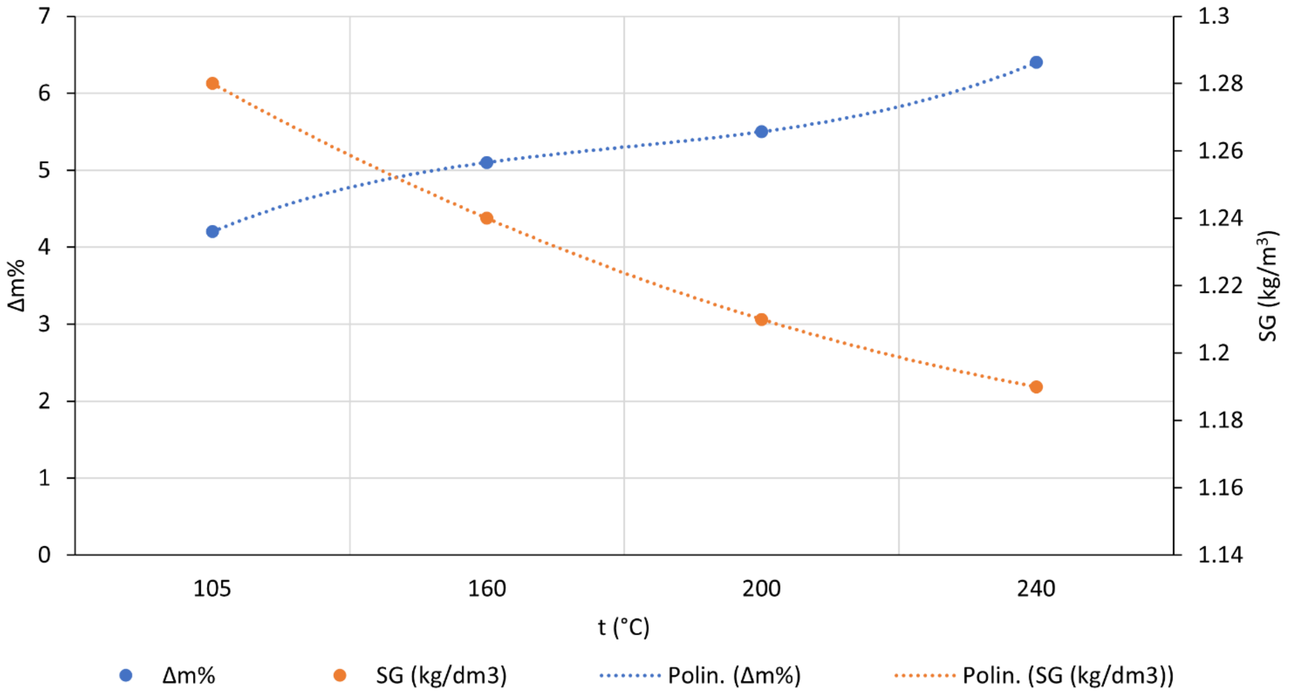

Fig. 1. Mass loss (Δm%) and specific gravity (kg/dm^3) values against the roasting temperature (°C) of peach shells.

The trend of $\Delta m\ vs\ t\ (°C)$ is commonly observed in wood roasting processes, although it varies numerically depending on the matrix being studied.

In Table 3, the Δm and specific gravity (SG) values are correlated with the roasting temperature ($°C$) using a polynomial best-fit operation. The resulting equations (Eq. 1 and 2) facilitate the interpolation of mass loss for any temperature of interest within the range 105-240 °C, enabling a comparison of the effects induced on the other variables that can be useful for any applications.

$$\Delta m\%: y = 0.1667x3 - 1.2500x2 + 3.4833x + 1.8 \tag{1}$$

$$SG: y = -3E - 14x3 + 0.005x2 - 0.055x + 1.33 \tag{2}$$

2.1.3. Lime-concrete design and specimen preparation

Normal tap water was used in this study. The mix proportions of all specimens are listed in Table 4. For each shell, the mix proportion of the related concrete was kept constant (PS = LWC with dried Peach Shell; PS160 = LWC with Peach Shell roasted at 160 °C; PS200 = LWC with Peach Shell roasted at 200 °C; PS240 = LWC with Peach Shell roasted at 240 °C). Specimens were removed from the mold after 24 hours. They were stored in a laboratory room with a relative humidity of 95 ± 5 % and a temperature of 20 ± 2 °C until the test age. Binder mixture "a" only includes lime, while mixture "b" involved the addition of cement. Three sets of specimens were prepared: one for the compressive strength test, one for the demolded, air-dry, and oven-dry density evaluation, and one for the thermal conductivity test. Each set contained three cubic specimens (100 × 100 × 100 mm3), and the average values were obtained for each test result.

The specimens were prepared as follows: river sand, lime, and cement were poured into a blender and dry-mixed for 1 min. Water was added and the mixture was mixed for 3 min. The lightweight aggregates were finally added to and mixed for 5 min. After mixing, fresh mixtures were then poured into the mold and compacted. The specimens were placed in the laboratory room and were removed from the molds after approximately 24 h.

Table 4

Mix proportion of LWC samples

Sample	Lime*	Cement*	Sand*	Lightweight aggregate*	w/b ratio$^\#$
PS_a	*585*	-	*625*	*350*	*0.45*
PS160_a	*585*	-	*625*	*339*	*0.45*
PS200_a	*585*	-	*625*	*330*	*0.45*
PS240_a	*585*	-	*625*	*325*	*0.45*
PS_b	*390*	*195*	*625*	*350*	*0.4*
PS160_b	*390*	*195*	*625*	*339*	*0.4*
PS200_b	*390*	*195*	*625*	*330*	*0.4*
PS240_b	*390*	*195*	*625*	*325*	*0.4*

PS = Peach Shells
*kg/m^2
$^\#$water-binder ratio

2.2. Experimental methods

2.2.1. Morphological analysis of the aggregates

The field emission scanning electron microscope (SEM) instrument (Nova Nano-SEM 450, 20 kV) was used to evaluate the microscopic morphology of coarse light-weight aggregates.

2.2.2. Demolded, Air-dry and Oven-dry densities

Demolded, air-dry and oven-dry densities were determined following ASTM C567. The demolded mass was measured after demolding (after 24h of curing), and the air-dry mass was measured after 28-day of curing. The test method for oven-dry density is more complex. The specimens were immersed in water (at about 20 °C) for 48 h, then the surface water was removed with filter paper, and the saturated surface-dry mass was measured. Then, it was suspended in water with a wire, and the apparent mass of the suspended-immersed specimens was determined. The samples were then oven-dried at 110 °C for 72 h. The oven-dry density was calculated from Eq. (3):

$$O\_m = \frac{D \times 997}{F - G} \tag{3}$$

where Om is the measured oven-dry density (kg/m3); D is the specimen mass (kg); F is the mass of saturated surface-dry specimen (kg); G is the apparent mass of suspended-immersed specimen (kg).

2.2.3. Mechanical test

The compressive strength test was performed after 28- and 56-day using a Technotest compression test machine (Technotest, Modena, Italy). The average value of at least three specimens was used as the test result. It was performed in conformity with the European standard for structural concrete (EN 12390-3:2009), although our concrete had no structural purpose. Lime mortar (EN 1015-11:1999) would be more suitable for the intended use, but the presence of coarse aggregates prevents its application.

2.2.4. Thermal Conductivity of Lime-concrete specimens

A KD2 Pro thermal properties analyser (Decagon Inc., Pullman WA 99163, USA) was used for thermal conductivity measurements. It is a portable device fully compliant with ASTM D5334-08 and is used to measure the thermal properties of materials based on probe/sensor methods (transient line heat source), as confirmed by Decagon Devices Inc. Operator Manual version 11. It consists of a portable controller and sensors probe to be inserted into the medium to be measured. The measurement consists of heating the probe for a certain time and monitoring the temperature during heating and cooling. The influence of the ambient temperature on the samples must be minimized to obtain more accurate values. The measurement range of thermal conductivity of KD2 Pro is 0.02 to 2.00 W/(mK). In this study, three cubic specimens for each sample (100 × 100 × 100 mm3), at 28 days of curing were selected to measure thermal conductivity at dry conditions. The samples were oven-dried for 24 hours at 100 °C prior to testing.

3. Results and Discussion

3.1. Lightweight aggregates

The peach shell samples naturally dried and roasted at 160, 200 and 240 °C are shown in Figure 2.

As previously mentioned, we obtained peach pits independently by purchasing ripe fruits from the supermarket and separating the wood fraction. However, for industrial supplies and applications, there are several dealers in the region who sell chopped fruit shells, which are currently used as biomass fuel [47].

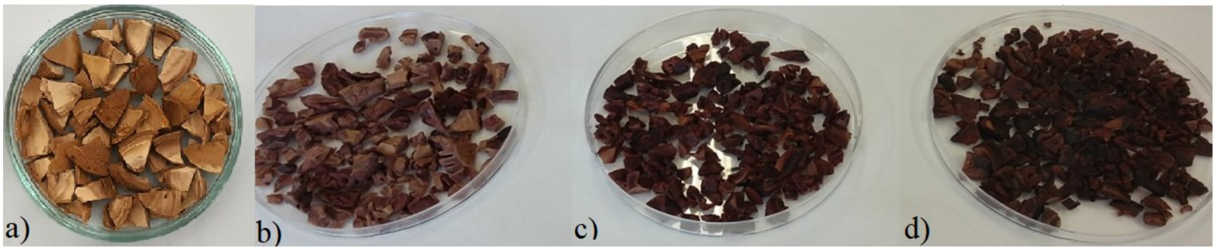

Fig. 2. Peach shell samples: naturally dried (a), roasted at 160 °C (b), 200 °C (c), 240 °C (d)

The physical and mechanical properties of LWC are strongly influenced by the nature, composition, and physical properties of the lightweight aggregates used [36,48,49]. The specific characteristics of the aggregate have a significant impact on the type of application and use of the final product [50]. Therefore, a thorough understanding of the properties and characteristics of peach shells is essential for their potential use as lightweight aggregates. Additionally, it is important to examine how the chemical and physical properties of the peach shells are affected by variations in the roasting temperature to establish a correlation between the pre-treatment process and the performance of the LWC.

Table 2 presents the physical properties of the peach shell samples, including particle size, specific gravity, bulk density, water absorption, and shape. The results clearly show how different roasting temperatures can affect the physical properties of peach shells. The specific gravity decreased as the roasting temperature increased, with PS having the highest value of 1.28 and PS240 having the lowest value of 1.19. Similarly, the bulk density decreased as the roasting temperature increased, with PS exhibiting the highest value of 556 kg/m3 and PS240 exhibiting the lowest value of 514 kg/m3. The bulk density of lightweight aggregates plays a critical role in determining the mechanical and insulation properties of LWC [37]. This feature is closely related to the size, shape, moisture content, and porosity of the aggregates. The strong decrease in specific gravity and bulk density is mainly related to the strong loss of moisture and volatile organic compounds (VOCs) that occurs following heat treatment. The water absorption initially increased from the PS sample to PS160, while it drastically decreased at the following temperatures, reaching a minimum at PS240. This observation proves the reduction in the hydroxyl functional groups of the cellulosic fraction, which are responsible for the interaction of the woody matrix with water molecules [51]. It is likely that the temperature of 160 °C was not high enough to trigger these degradation processes, resulting in a strong dehydration effect on the material without any reduction in its water absorption capacity. This observation is not completely unexpected, as it is known that H2O loss following the thermal treatment of lignocellulosic matrices becomes significant after 200 °C [52,53]. The water absorption characteristics of lightweight aggregates are typically and significantly greater than those of traditional coarse aggregates, primarily because of their higher porosity, and different chemical composition. In particular, fruit shells are composed primarily of three key natural polymers – cellulose, lignin, and hemicellulose – which are typical components of lignocellulosic biomass [52,54,55]. Compared to lignin, which acts as an adhesive between cellulose and hemicellulose and is highly hydrophobic [56,57], cellulose has a distinct ability to absorb water. Therefore, it is essential to develop approaches that can reduce the water affinity of the cellulose fraction and, consequently, limit the water absorption of lightweight aggregates. In fact, water absorption can negatively impact important properties of LWC, such as density, strength, durability, and time-dependent deformation [36,37].

Table 3 highlights the proximal chemical composition of the peach shell samples, including the samples roasted at different temperatures. It provides a general overview of the differences in the chemical constituents, demonstrating the impact of roasting on organic material and elemental composition. As expected, the mass loss increased as the roasting temperature increased, with PS240 exhibiting the highest mass loss. Similarly, the ash content increased with higher roasting temperatures due to the partial removal of organic content. The carbon content progressively increased with increasing roasting temperature, whereas the oxygen content decreased, indicating the removal of oxygen-containing functional groups. This clearly explains the decrease in water absorption with increasing roasting temperature.

3.2. Morphological analysis of Peach Shells

The surfaces of peach shells (PS) are shown in Fig. 3a, 3b, and 3c. We reported only the images related to naturally dried PS because we did not identify significant differences between the roasted samples. Furthermore, we only presented images relating to the outer surface, which allowed the evaluation of material porosity. In fact, the internal surface was extremely smooth and compact; therefore, it seemed more important to focus only on the outer surface, as it probably contributed more to the properties of the aggregates and, consequently, to the behavior of the specimens.

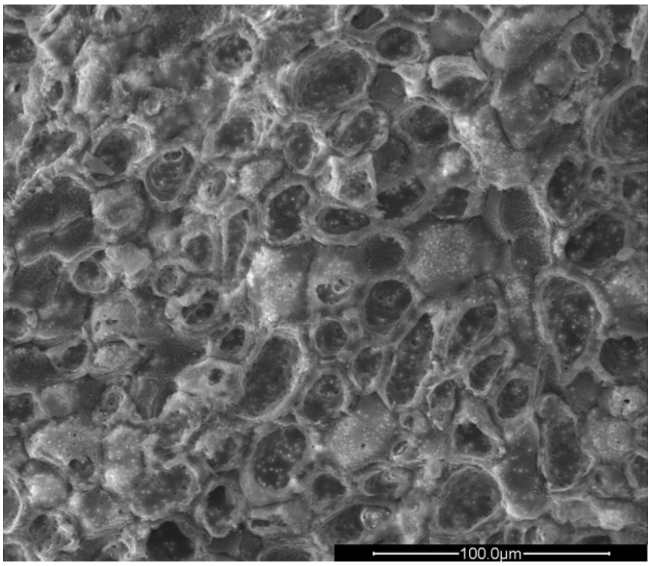

Fig. 3a. SEM image of crushed peach shells (PS), 1000x

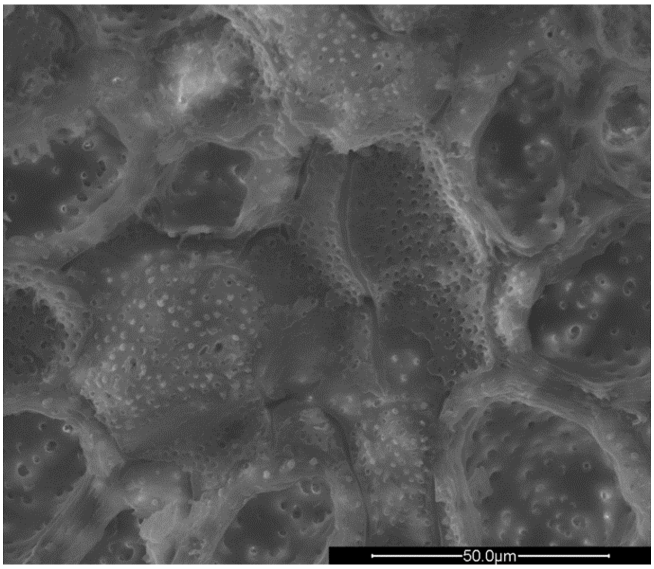

Fig. 3b. SEM image of crushed peach shells (PS), 2000x

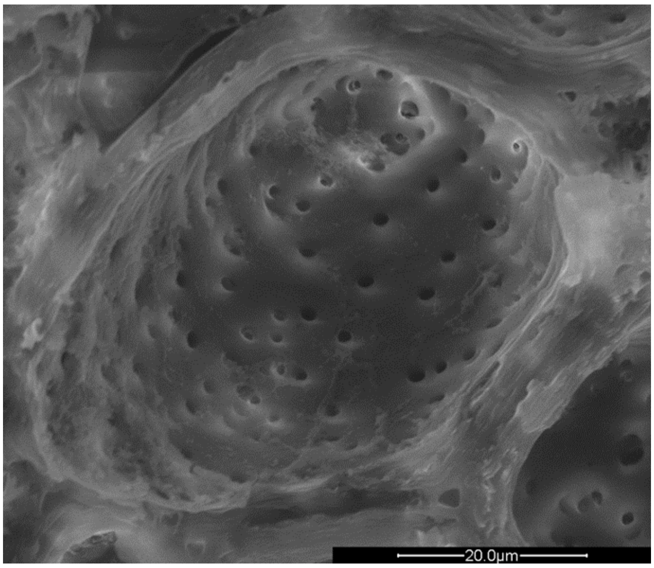

Fig. 3c. SEM image of crushed peach shells (PS), 4000x

The surface appears rough, irregular and have many ovoidal cavities. The grater diameter of the cavities is approximately 50 µm, and the smaller is about half, 25 µm. Microporosities extend over the entire external surface and inside the cavities. Their size was approximately 2.0 µm. The high number of microporosities gives the peach shells a low density but, at the same time, leads to a greater absorption of water by inclusion.

3.3. Density and compressive strength of the LWC samples

Based on the ACI Committee 213 Guide for Structural Lightweight Concrete, LWC can be classified by its density, typically ranging from 320 to 1920 kg/m^3 [58]. This density-based classification produces three material groups: *i)* low-density concretes (300 – 800 kg/m^3); *ii)* moderate-strength concretes (800 – 1350 kg/m^3); *iii)* structural concretes (1350 – 1920 kg/m^3). Additionally, these three classes are related to specific strength levels: 0.7–3.4 MPa; 3.4-17 MPa; and 17-63 MPa, respectively [59,60]. Density is crucial as it determines several characteristics and properties of concrete, including compressive strength [61]. Reducing concrete density leads to an increase in its porosity, a decrease in thermal conductivity and typically a decrease in mechanical strength.

The density data obtained are collected in Table 5.

Table 5

Demoulded, Air-dry, and Oven-dry density values of LWC samples

	Density (kg/m^3)*		
Sample	**Demoulded (24 h)**	**Air-dry (28d)**	**Oven-dry (28d)**
PS_a	*1207.4 ± 1.5*	*1107.7 ± 1.4*	*1031.9 ± 1.4*
PS160_a	*1212.7 ± 2.0*	*1112.9 ± 1.7*	*1038.7 ± 1.8*
PS200_a	*1192.9 ± 1.3*	*1093.6 ± 1.2*	*1012.4 ± 1.3*
PS240_a	*1187.4 ± 1.5*	*1088.9 ± 1.5*	*1009.7 ± 1.4*

PS_b	*1464.5 ± 0.9*	*1295.2 ± 0.8*	*1204.8 ± 0.7*
PS160_b	*1469.7 ± 1.1*	*1300.8 ± 1.2*	*1209.5 ± 1.3*
PS200_b	*1453.5 ± 1.9*	*1289.6 ± 1.8*	*1184.6 ± 1.9*
PS240_b	*1448.3 ± 1.5*	*1284.6 ± 1.4*	*1177.3 ± 1.5*

*Data are expressed as mean of three replicates ± SD

All the samples were in the density range related to moderate-strength LWC. As expected, the density value decreased as the roasting temperature increased, which is in line with the bulk density trend of the peach shells (Table 2). However, unexpectedly, the PS160 samples did not follow this trend, as the PS samples have lower density values, regardless of the binder mixture. This difference may be due to the higher water absorption observed following heat treatment at 160 °C, which probably resulted in the higher density of LWC. Therefore, a temperature higher than 200°C is required to induce a modification of the lignocellulosic matrix obtain a significant decrease in the density of LWC.

The use of lime as a binder in concrete leads to a lower density than cement-based concrete, because of its lower specific gravity and bulk density [62]. This is confirmed by the higher density values observed in the specimens prepared with the binding mixture "b", containing cement. Furthermore, the values of Table 5 are all significantly lower than those reported in other studies relating to cement-based LWC prepared with similar vegetable matrices as lightweight aggregate [34,63,64].

The density is also influenced by the amount of air trapped inside the concrete, a phenomenon that can be caused by several factors. Generally, the irregular shape of the aggregates and, in particular, the flaky shape, hinder the complete compaction of concrete, thus contributing to a higher trapped air content, higher porosity, and decreasing density [65]. Moreover, lightweight aggregates trap air inside due to their high porosity.

The results of compressive strength tests at 28 and 56 days of the LWC samples are shown in Table 6.

Table 6

Compressive strength at 28-day and 56-day of LWC samples

Compressive strength (MPa)*		
Sample	**28-day**	**56-day**
PS_a	*1.38 ± 0.20*	*1.99 ± 0.14*
PS160_a	*1.21 ± 0.11*	*1.78 ± 0.16*
PS200_a	*1.92 ± 0.17*	*2.63 ± 0.20*
PS240_a	*2.23 ± 0.15*	*2.92 ± 0.17*
PS_b	*4.01 ± 0.16*	*4.97 ± 0.21*
PS160_b	*3.75 ± 0.15*	*4.59 ± 0.16*
PS200_b	*4.68 ± 0.11*	*5.51 ± 0.12*
PS240_b	*4.99 ± 0.17*	*5.88 ± 0.16*

*Data are expressed as mean of three replicates ± SD

The compressive strength of all the specimens prepared with the binder mixture "a" have a compressive strength of less than 3.4 MPa. Therefore, these specimens are not classified as "moderate-strength concrete", because of their insufficient compressive strength. However, their application potential is not limited by this classification system. For example, for some applications, such as for non-structural mortar beds for wooden floors, density values typical of moderate-strength concrete are recommended, but compressive strength values higher than 3.4 MPa are not required [37]. On the other hand, the compressive strength of the specimens containing cement, prepared with the binder mixture "b", had compressive strength values higher than 3.4 MPa, and perfectly meet the requirements of moderate-strength concrete. There are countless potential uses for these materials [25,66], but their most practical application is as a non-structural fill for thermal and sound insulation in floors and roofs.

The compressive strength of concrete is influenced by several factors, including the properties and volume of aggregates [67,68]. In particular, porosity and water absorption have a significant influence, as they make concrete less compact and porous. The lower water absorption of the peach shells roasted at 200 and 240 °C explains the greater compressive strength of the specimens PS200 and PS240. Similarly, the greater water absorption found in peach shells treated at 160 °C compared to naturally dried peach shells justifies the decrease in compressive strength observed when passing from the PS sample to PS160.

3.4. Thermal Conductivity coefficient of the LWC samples

Thermal conductivity plays a crucial role in the design and use of non-structural lightweight concretes. With the world facing a climate crisis, insulating materials have become increasingly popular [14,69]. Energy efficiency in buildings is gaining momentum, and strategies are being developed to ensure that buildings consume less energy. Boosting the thermal insulation of a building is key to achieving this goal, as it helps enhance energy efficiency, which is crucial to ensuring a sustainable future [9,70]. In fact, enhancing thermal insulation can lead to significant reductions in environmental impact and CO_2 emissions, as air conditioning, ventilation, and occupant comfort account for approximately 29% of the CO_2 emissions from the building sector.

The thermal conductivity of concrete is influenced by several factors, such as the type and content of the aggregates, the content of air voids, the distribution of pores and their geometry, the moisture content, the w/b ratio and the type of binding mixture [71]. For example, the thermal conductivity of conventional concrete is inversely proportional to the porosity content [72]. This factor is particularly significant as air has low thermal conductivity (0.025 W/mK at room temperature). Therefore, microstructural factors strongly affect this property.

The results are collected in Table 7

.

Table 7

Thermal conductivity of LWC samples

Sample	Thermal conductivity coefficient (W/mK)*
PS_a	*0.15 ± 0.01*
PS160_a	*0.19 ± 0.03*
PS200_a	*0.09 ± 0.04*
PS240_a	*0.03 ± 0.01*
PS_b	*0.20 ± 0.01*
PS160_b	*0.29 ± 0.05*
PS200_b	*0.15 ± 0.03*
PS240_b	*0.10 ± 0.04*

*Data are expressed as mean of three replicates ± SD

The results show that there is a significant difference in the thermal conductivity properties between the samples made with naturally dried peach shells (PS) and those made with thermally treated shells (PS160, PS200, and PS240). It is evident that the thermal conductivity coefficient decreased with an increase in the temperature at which the shells were treated, except for roasting at 160 °C. In fact, PS160 has a higher thermal conductivity coefficient than PS, demonstrating a significant correlation between LWC density and thermal conductivity. However, the thermal conductivity of peach shell concrete is low, because of the highly porous structure of the lightweight aggregates, which carry more air bubbles into the concrete during the mixing phase. The addition of cement (mixture "b") resulted in better compactness of the samples and a consequent worsening of their thermal insulation properties.

Moderate-strength concrete generally has a thermal conductivity coefficient between 0.2 and 0.6 W/mK [73,74]. Table 7 reveals that all samples fall within this range or exhibit even lower values, demonstrating stronger insulating properties. The samples produced using mixture "a" possess a thermal conductivity coefficient lower than 0.2. This suggests that the use of lime as a binder enhances thermal insulation. Although this binder resulted in less dense and mechanically weaker specimens, it yielded lighter and more thermally insulating

4. Summary and conclusions

The potential of peach shells as lightweight aggregates in the production of eco-friendly LWC was evaluated:

- The shells were air-dried and roasted at different temperatures (160, 200, and 240°C). Heat-treated shells at temperatures higher than 200 °C showed lower bulk density, specific gravity, and water absorption, whereas those treated at 160 °C showed an increase in these physical properties compared to untreated peach shells.
- The specimens containing only lime as a binder were more eco-friendly, as lime is more

ecological than cement, lighter, and more thermally insulating.

- The compressive strength was low, falling below the threshold of 3.4MPa required for "moderate-strength concrete". However, this did not diminish its application potential. Samples containing cement (mixture "b") had a higher compressive strength, fitting the classification of "moderate-strength concrete".
- Samples containing cement (mixture "b") had a higher coefficient of thermal conductivity, while lime-based concrete showed better insulating properties. In general, all specimens had a low thermal conductivity thanks to the high porosity of the peach pits, as evident from the SEM analysis.
- Heat treatment improved properties, such as density, compressive strength, and thermal insulation, but only at temperatures above 200°C. At 160°C, the treatment was inadequate for triggering useful changes in the cellulosic fraction of the shells. Aggregates treated at higher temperatures resulted in a significant reduction in water absorption, which improved the properties of concrete.

The findings of this study have significant implications for the construction industry by providing a sustainable solution to reduce waste, lower energy consumption, and mitigate the environmental impact of traditional construction materials. Future investigations could focus on optimizing the heat treatment parameters to achieve even greater enhancements in the properties of peach shell-based lightweight concrete, such as fine-tuning the roasting temperature and duration. Considering the low compressive strength exhibited by lime-based specimens, future studies could investigate reinforcement techniques or the addition of supplementary materials to enhance the mechanical properties while preserving the eco-friendliness of our lightweight concrete.

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Author contributions

Conceptualization [V.D.; S.P.]; methodology [V.D.; B.A.; A.U.]; software [V.D.; A.M.]; validation [A.M.; F.R.]; formal analysis [A.M.; S.P.]; investigation [V.D.; B.A.; A.U.]; resources [A.M.; S.P.; F.R.]; data curation [V.D.; S.P.]; writing—original draft preparation [V.D.]; writing—review and editing [V.D.; A.U.; B.A.]; visualization [V.D.; F.R.]; supervision [A.M.; S.P.; F.R.]; project administration [V.D.; A.M.]; funding acquisition [A.M.; S.P.].

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Conflict of interest

The authors declares no conflict of interest

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