



Article

Preparation and Properties of a Composite Carbon Foam, as Energy Storage and EMI Shield Additive, for Advanced Cement or Gypsum Boards

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Abstract: This article explores the cutting-edge advancement of gypsum or cement building boards infused with shape-stabilized n-octadecane, an organic phase change material (PCM). The primary focus is on improving energy efficiency and providing electromagnetic interference (EMI) shielding capabilities for contemporary buildings. This research investigates the integration of these materials into construction materials, using red-mud carbon foam (CCF) as a stabilizer for n-octadecane (OD@CCF). Various analyses, including microstructural examination, porosity, and additive dispersion assessment, were conducted using X-ray microtomography and density measurements. Thermal conductivity measurements demonstrated the enhancement of composite boards as the OD@CCF content increased, while mechanical tests indicated an optimal additive content of up to 20%. The thermally regulated capabilities of these advanced panels were evaluated in a custom-designed room model, equipped with a homemade environmental chamber, ensuring a consistent temperature environment during heating and cooling cycles. The incorporation of OD@CCF into cement boards exhibited improved thermal energy storage properties. Moreover, the examined composite boards displayed efficient electromagnetic shielding performance within the frequency range of 3.2–7.0 GHz, achieving EMI values of approximately 18 and 19.5 dB for gypsum and cement boards, respectively, meeting the minimum value necessary for industrial applications.

Keywords: phase change material; shape-stabilized n-octadecane; red-mud carbon foam; advanced cement boards; advanced gypsum boards; density measurements; thermal conductivity; environmental chamber; electromagnetic interference shielding



Citation: Gioti, C.; Vasilopoulos, K.C.; Baikousi, M.; Ntaflos, A.; Viskadourakis, Z.; Paipetis, A.S.; Salmas, C.E.; Kenanakis, G.; Karakassides, M.A. Preparation and Properties of a Composite Carbon Foam, as Energy Storage and EMI Shield Additive, for Advanced Cement or Gypsum Boards. *J. Compos. Sci.* **2024**, *8*, 251. <https://doi.org/10.3390/jcs8070251>

Academic Editor: Francesco Tornabene

Received: 21 April 2024

Revised: 20 June 2024

Accepted: 24 June 2024

Published: 1 July 2024



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1. Introduction

The ongoing need for sustainable building solutions has spurred the search for novel materials capable of improving energy efficiency and tackling emerging issues like electromagnetic interference (EMI) shielding. Traditional construction materials like cement, gypsum, concrete, and brick have long been staples in wall construction. However, recent attention has shifted towards developing materials that not only meet structural requirements but also possess thermal energy storage capabilities [1]. This focus on thermal energy storage aligns with the broader effort to enhance energy efficiency and sustainability in building practices. Moreover, the demand for buildings equipped to counteract the effects of electromagnetic waves has grown more urgent in our increasingly technology-driven surroundings. The rapid evolution of electronic devices has raised concerns about electromagnetic radiation, as it can disrupt device functionality and potentially pose risks to

human well-being [2]. In light of these challenges, integrating advanced materials with diverse properties has emerged as a promising avenue toward achieving multifunctionality in building solutions.

Within this context, the incorporation of phase change materials (PCMs) into building elements such as gypsum and cement boards has garnered considerable interest. This interest arises from their ability to store and release thermal energy, thereby enabling effective temperature regulation within building environments [1,3,4]. The cost-effectiveness and adaptability of PCM products have catalyzed inventive approaches in the construction sector. They are increasingly recognized for their ability to enhance energy efficiency and regulate thermal conditions within constructed spaces [1,5,6]. The adoption of these materials has been extensively studied within engineering and scientific communities. This thorough examination is primarily due to their capability to absorb and release thermal energy during phase transitions, offering a promising approach for enhancing indoor temperature management [1]. Nonetheless, the practical implementation of PCMs encounters hurdles stemming from their inherent drawbacks, including low thermal conductivity and the possibility of leakage when in a liquid state during phase transition [7]. To effectively tackle these obstacles, the adoption of a shape-stabilizing (SS) support matrix has emerged as a highly effective strategy. This matrix serves as a safeguarding enclosure for the PCM, guaranteeing its containment and stability in a molten state, particularly at higher temperatures. As a result, it prevents leakage and reduces corrosion in structural materials [8]. Porous materials based on carbon, including carbon foam, expanded graphite, graphene oxide, graphene aerogel, and activated carbon, offer an encouraging framework for the integration of functional additives such as PCMs. This integration results in enhanced thermal conductivity and electromagnetic interference (EMI) shielding capabilities, offering compelling opportunities for various applications [8–12].

The integration of phase change materials (PCMs) and electromagnetic interference (EMI) shielding additives into gypsum and cement building boards represents a significant leap forward, offering practical implications across various commercial applications. The incorporation of PCMs into building materials like gypsum boards enhances their thermal regulation capabilities by absorbing and releasing thermal energy during phase transitions, thus aiding in the regulation of indoor temperatures. This innovation leads to improved building energy efficiency by minimizing reliance on heating and cooling systems [13,14]. Increased energy efficiency, particularly valuable in regions experiencing extreme temperature variations, is a game-changer for commercial properties aiming for higher energy efficiency ratings and potentially qualifying for green building certifications [15]. Furthermore, by augmenting the thermal mass of gypsum and cement boards, PCMs extend the period over which thermal energy is released or absorbed, beneficial in maintaining stable indoor temperatures in data centers, laboratories, and manufacturing facilities [16].

The addition of EMI shielding additives into building boards also plays a critical role in safeguarding against electromagnetic interference, crucial in environments housing sensitive equipment or systems reliant on uninterrupted electronic operation. This advancement ensures the reliability of electronic and wireless communication systems in commercial settings, including offices, hospitals, and research facilities [17]. Beyond thermal and electromagnetic considerations, this integration significantly contributes to meeting safety standards and regulatory requirements, addressing thermal insulation, fire resistance, and electromagnetic compatibility concerns. These advanced building boards offer a comprehensive solution that streamlines the construction process, reduces compliance-related risks, and enhances the overall safety and efficiency of commercial buildings.

In summary, the combination of PCMs and EMI shielding additives into gypsum and cement building materials heralds a new era in construction technology. It not only improves thermal regulation and energy efficiency but also extends thermal mass capabilities, ensures reliable EMI protection, and streamlines compliance with safety and regulatory standards, thereby offering a multifaceted advantage across a wide array of commercial applications.

Significant studies in the literature have delved into integrating carbon-based materials with shape-stabilized PCMs into composite cement or gypsum boards [1,18]. Chin et al. showed that concrete panels incorporated with paraffin-oil palm kernel shell-activated carbon exhibit increased thermal lag and reduced peak temperature during the phase transition of composite PCM [19]. Qian and Li reported the preparation of cement composites with n-octadecane stabilized on a diatomite/carbon matrix [20]. The developed heat-storage cement mortar has been found to mitigate fluctuations in interior temperature, showcasing significant potential for energy savings and enhanced thermal comfort in the built environment. Chen et al. reported that the incorporation of SAT-urea eutectic salts encapsulated with modified commercial-activated carbon in gypsum could slowly reduce the thermal conductivity and significantly improved the thermal inertia of the composites [21]. Finally, in our recently published work [22], the incorporation of activated carbon/RT18HC into gypsum boards resulted in composite gypsum boards with improved thermal storage and EMI shielding properties, compared to standard gypsum boards.

In this study, we present a novel investigation into the advancement of building materials with dual functionalities by incorporating gypsum and cement boards with shape-stabilized organic phase change materials (ssPCMs). This ssPCM consists of n-octadecane (OD) stabilized on carbon red-mud foam (CCF). Our previous research has extensively examined the thermal and electromagnetic interference (EMI) shielding properties of OD@CCF composites, demonstrating their effectiveness in thermal management and EMI reduction in electronic devices [8]. Our current research focuses on assessing the impact of different percentages of this additive on the thermal storage capacity and EMI protection capabilities of gypsum and cement panels. We conducted experiments under real conditions to simulate real weather scenarios using a custom-designed environmental chamber, following the experimental approach of Zhang et al. [23]. Our current study focuses on assessing the impact of varying percentages of this additive on the thermal storage capacity and EMI shielding abilities of gypsum and cement boards. We conducted experiments under real-world conditions, simulating realistic weather scenarios using a custom-designed environmental chamber. By integrating n-octadecane encapsulated in carbon red-mud foam into the matrix of these building components, we not only aim to regulate indoor temperatures effectively, but also to strengthen structural resistance to electromagnetic interference. This approach offers a comprehensive solution to the dual challenges of energy conservation and electromagnetic shielding in modern architectural designs.

2. Materials and Methods

2.1. Materials

The materials used to produce ceramic carbon foam (CCF) and shape-stabilized n-octadecane on CCF (OD@CCF) were commercially sourced and are extensively detailed in our previous publication [8]. The raw materials required for cement production were supplied by Energy Houses (ENHSS, Serres, Greece), a collaborating business partner based in Greece. Gypsum and starch were provided by KNAUF (Amfilochia, Greece), a globally recognized company, to ensure that the final product closely resembled commercial standards.

2.2. Preparation of CCF and OD@CCF Hybrid

Comprehensive details regarding the experimental procedures for preparing these materials can be found in our previously published research [8]. The CCF matrix was synthesized through the technique of replicating polymeric foam, which employs a polyurethane sponge as a mold, resin for the carbon precursor, and red mud as an additive.

2.3. Preparation of Cement Boards

The experimental procedure devised for manufacturing the cement boards received guidance from a Greek collaborative partner, Energy Houses (ENHSS, Serres, Greece), which supplied the necessary raw materials and offered technical insights throughout

the production process. In accordance with both company and international standards, the raw materials included cement powder, polypropylene fibers, acrylic polymer emulsion resin, perlite, water, and composites containing encapsulated n-octadecylamine with foams (OD@CCF) in various proportions. The cylindrical composite samples ($D = 30$ mm, $h = 30$ mm) were then broken into smaller pieces to ensure their uniform dispersion within the cement boards. The experimental procedure involved weighing the aforementioned raw materials in specified quantities for each composition (detailed in Table 1) and then subjecting them to continuous manual stirring for at least fifteen minutes to ensure thorough homogenization. Afterward, the mixture was spread onto a wooden mold and left to dry at room temperature for at least twenty-four hours, yielding specimens with dimensions of $200 \times 200 \times 37$ mm. The cement board without additives is denoted as CB, while those with composite additions are referred to as CB/OD@CCF- x , where x represents the volume percentage of the OD@CCF additive.

Table 1. Composition of ingredients used in the manufacturing of cement boards.

Sample	Cement (g)	Water (g)	Perlite (mL)	Polypropylene Fibers (g)	Resin (mL)	OD@CCF (g)
CB	624	624	2080	2.08	10.4	-
CB/OD@CCF-10	624	624	1936	2.08	10.4	144
CB/OD@CCF-20	624	624	1780	2.08	10.4	300
CB/OD@CCF-30	624	624	1648	2.08	10.4	432

2.4. Preparation of Gypsum Boards

To produce the gypsum boards, all solid materials were thoroughly mixed manually until achieving a uniform consistency. Water was gradually added while vigorously stirring the mixture. The blending process continued for approximately five minutes before pouring the resulting slurry into a mold, resulting in gypsum boards with dimensions of $200 \times 200 \times 12.5$ mm. The slurry was left undisturbed in the mold for a minimum of 24 h at room temperature to allow for drying. The specific compositions of the prepared gypsum boards are detailed in Table 2. The reference gypsum board is denoted as GB, while composite boards are labeled as GB/OD@CCF- x , where ' x ' represents the volumetric percentage of the OD@CCF additive.

Table 2. Composition of ingredients used in the manufacturing of gypsum boards.

Sample	Gypsum (g)	Water (g)	Starch (g)	OD@CCF (g)
GB	550	448	28.5	-
GB/OD@CCF-10	495	448	28.5	55
GB/OD@CCF-20	440	448	28.5	110
GB/OD@CCF-30	385	448	28.5	165

2.5. Measurements of Density

The bulk densities (ρ) of the gypsum and cement boards were initially estimated in the original specimens using the formula $\rho = m/V$, where ' m ' represents weight and ' V ' stands for the volume of the boards. However, to enhance measurement accuracy, a modified Archimedes water displacement method was employed, following a standardized procedure [24]. This method involved initially measuring the bulk volume and then determining the bulk density for small-sized porous specimens. Before immersion into a cylinder with known dimensions, the samples were sealed with wax. Both density measurement techniques yielded similar ρ values, showing no significant deviations.

2.6. Micro-CT Imaging through X-ray Computed Microtomography

X-ray computed microtomography (micro-CT) was utilized to examine the internal structure of composites containing different concentrations of additive (10%, 20%, and 30%). Imaging was conducted using a Bruker SkyScan 1275 scanner (Billerica, MA, USA). This scanner is equipped with a distortion-free 3 Mp active flat-panel detector. The imaging parameters included an accelerating voltage of 60 kV, a current of 60 μ A, and the use of a 1 mm thick Al filter. The object distance was set at 20 mm, resulting in a pixel size of 10 μ m. A 360° scan was performed with a rotation step of 0.20°, leading to a scan duration of approximately 25 min. The reconstruction of the scanned images was carried out using Bruker's NRecon—v2.1.0.1 software. Subsequent image analysis was conducted using CTan v1.20.8.0 and Dataviewer 1.5.6.2 software tools.

2.7. Thermal Properties

Differential Scanning Calorimetry (DSC) analyses were conducted within a nitrogen (N_2) atmosphere using the DSC 214 NETZCH Polyma instrument (Selb, Germany). The heating and cooling rates were set at 2 °C/min, with temperature ranges from 0 °C to 40 °C and vice versa. To evaluate the thermal transport properties of gypsum board specimens, including thermal conductivity (k) and heat capacity (C_p), a C-Therm TCi Thermal Conductivity analyzer (Fredericton, Canada) was employed. The assessment utilized the Modified Transient Plane Source (MTPS) method (ASTM D7984) [25], where a one-sided thermal sensor applied a brief low-energy current pulse lasting 0.8 s to the specimen. This method ensured that thermal convection did not influence the measurement of thermal conductivity (k). The resulting temperature variation indicated a resistance change in the sensor, resulting in a voltage drop, which was then used to evaluate the thermal transport properties of the material under investigation. Thermal conductivity (k) and thermal effusivity (e) were directly measured, providing a comprehensive insight into the heat transfer characteristics of the samples. Final values were determined by averaging five measurements for each specimen using the polymer test method, with Pyrex glass serving as the standard ($k = 1.143$ W/m·K). Subsequently, heat capacity (C_p) was calculated using the equation $C_p = e^2/k \cdot \rho$, where ρ represents the density of each specimen.

2.8. Mechanical Properties

The flexural strength or modulus of rupture (MOR) of gypsum boards (GB, GB/OD@CCF) was evaluated through three-point bending tests conducted on the Autograph AGS-H testing machine (Shimadzu, Kyoto, Japan), in compliance with the ASTM C293/C293M-16 standard [26]. In greater detail, the dimensions of each test specimen were meticulously recorded to an accuracy of ± 0.01 mm. The specimen of gypsum, with dimensions of 200 mm $\times$ 50 mm $\times$ 12.5 mm, was precisely placed in the center of the 100 mm span between the support rods of the testing apparatus. The bend was applied at a constant rate of 2.0 mm/min, and the load at the point of breakage was documented. The calculation of the bending (flexural) strength (σ) was then carried out using Equation (1).

$$MOR = \frac{3WL}{2bd^2} \quad (1)$$

In this equation, W (N) represents the load at the point of fracture, while L stands for the distance between the support rods, W denotes the width of the specimen, and h indicates its thickness. Each subgroup provided five specimens ($n = 5$) for testing.

The mechanical properties of the cement boards (CB, CB/OD@CCF) were evaluated by measuring the compressive deformation behavior of cubic specimens $x = y = z \sim 50$ mm, using the same testing machine. The compressive strength ($CS = \text{Load}/\text{Area}$ (N/mm²)) of every cement board was conducted according to standard ASTM C109/C109M-20 [27]. Compressive stress–strain (%) curves were derived from the load–displacement curves, and subsequently, the compressive strength and modulus of elasticity of the samples were calculated. The results are the average of measurements made on at least 5 specimens.

2.9. Thermal Performance Measurements

We utilized a custom-built environmental chamber [28] for conducting thermal performance measurements. The chamber, illustrated in Figure S2, was crafted from polystyrene foam panels with dimensions of 1000 mm in length, width, and height. A specialized slot at the top of one of the side panels was designed to fit a fan heater and a mobile air conditioning unit. Beneath the primary compartment, there were four subordinate chambers designated for testing, each measuring 200 mm in length, width, and height. Constructed from polystyrene foam panels, these smaller enclosures featured an open-top design on one side of the panel to simplify the placement of test samples. The temperature within each testing chamber was monitored using Type K thermocouples, centrally positioned for accurate readings, alongside additional thermocouples affixed to the exterior and interior surfaces of the test samples. A thermocouple located in the center of the main chamber offered a holistic view of the temperature dynamics within. Control over the chamber's temperature was achieved through the activation of the fan heater and the portable air conditioner to raise or lower the temperature, commencing from the chamber's top. This arrangement permitted the evaluation of the test samples' thermal behavior under varied temperature scenarios, with temperature readings collected at 5 min intervals.

2.10. Electromagnetic Interference (EMI) Shielding Properties

The examination of electromagnetic interference (EMI) shielding efficiency was conducted utilizing a P9372A Keysight Streamline Vector Network Analyzer (Keysight, Santa Rosa, CA, USA) paired with two sets of standard microwave waveguides with a 15 dB gain (specifically, WR 187 and WR 147, procured from Advanced Technical Materials Inc. (ATM), Patchogue, NY, USA). These setups facilitated coverage across a comprehensive C frequency bandwidth from 3.2 to 7.0 GHz, a spectrum relevant for long-range telecommunication applications such as satellite communications, Wi-Fi connectivity, cordless phones, and weather radar operations. For the testing process, samples were precisely aligned at the center within each pair of waveguides, allowing for the detailed measurements of their scattering parameters (S-parameters; S11, S12, S22, S21).

3. Results and Discussion

In our earlier research [8], we extensively examined the structural and physicochemical attributes of both the carbon–red-mud foam matrix (CCF) and the composite OD@CCF. Our analysis revealed, then, that CCF possesses a remarkably porous structure, featuring pores of elliptical and spherical shapes ranging from 50 to 500 μm . The cell walls exhibit partial graphitization of carbon alongside various oxide phases. Of particular note, the hybrid foam OD@CCF exhibited exceptional efficiency in encapsulating paraffins, with a loading capacity of 48.8% w.t. of octadecane. In the forthcoming sections, we will delve deeper into the characteristics of gypsum and cement composite boards integrated with the OD@CCF additive at different concentrations.

3.1. Density Results and Microtomography Analysis of Composite Boards

Figures 1 and 2 illustrate the images of both the reference gypsum or cement board (GB or CB) and the GB/OD@CCF or CB/OD@CCF composite boards, respectively.

Table S1 presents the results of density measurements, while Figure 3 illustrates the plotted data against the percentage content of OD@CCF for GB/OD@CCF composites. The data in Figure 3a reveal a slight decrease in gypsum board density with increasing additive content. Specifically, integrating 30% OD@CCF into gypsum boards reduced the density from 0.96 to 0.92 g cm^{-3} , showing a relatively consistent trend considering the error margins. This decrease aligns with previous findings, as evidenced by the density of the current shape stabilizer, carbon foam, which was recorded at 0.54 g cm^{-3} [8], significantly lower than the initial density of the reference gypsum board (0.96 g cm^{-3}). Incorporating such lightweight additives contributes to the overall density reduction of the composite boards, although they still satisfy the minimum density criterion of 0.60 g/cm^3 as mandated by

the European standard UNE-EN 13279-1 for gypsum binders and plasters [29,30]. Similar density reduction trends during additive incorporation have been observed in the literature. For instance, in our prior research [22], adding 30% activated carbon PCM to gypsum boards led to a density decrease from 0.96 to 0.81 g cm⁻³. Additionally, Jameel et al. [31] noted a density decrease in gypsum boards enhanced with chopped carbon fibers, reaching 1.258 to 1.098 g cm⁻³ for a 0.3% volume fraction.

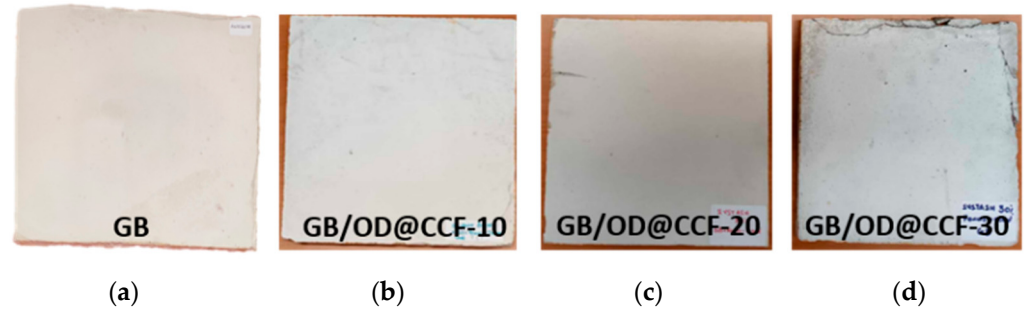


Figure 1. Photos from the (a) reference gypsum board (GB) and GB/OD@CCF composite boards with (b) 10, (c) 20, and (d) 30% OD@CCF additive.

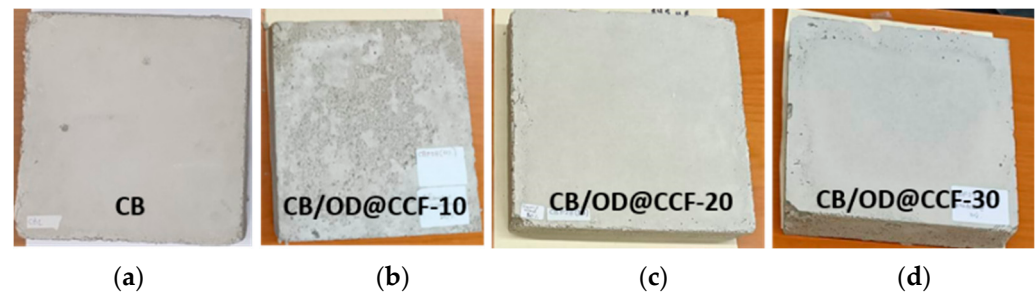


Figure 2. Photos from the (a) reference cement board (CB) and CB/OD@CCF composite boards with (b) 10, (c) 20, and (d) 30% OD@CCF additive.

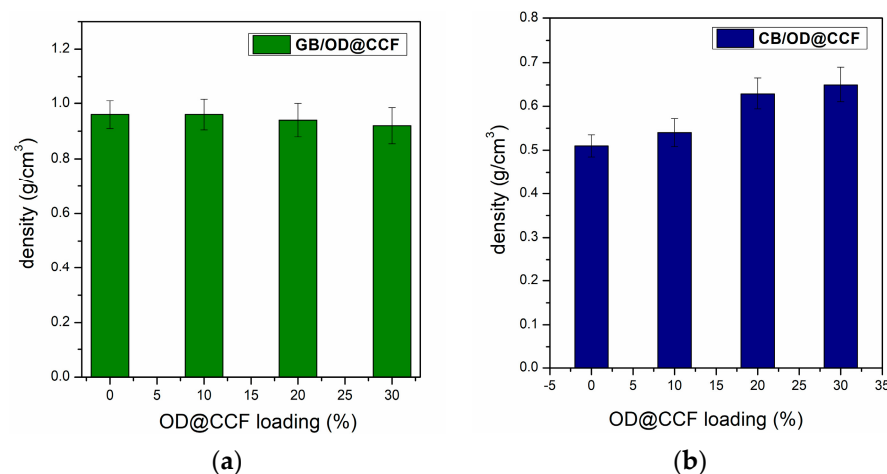


Figure 3. Density variation of (a) GB/OD@CCF and (b) CB/OD@CCF composites as a function of the percentage content of OD@CCF additive.

Conversely, in CB/OD@CCF composites, density increases with rising additive content (Figure 3b), attributed to the higher density of PCM compared to the components of cement boards. The solid-phase density of the current PCM, raw octadecane, stands at 0.88 g cm⁻³ [32], contrasting with the measured density of the reference cement board at 0.51 g cm⁻³. A similar trend was observed by Ye et al. [33], who reported an increase in cement board density from 0.32 to 0.43 g cm⁻³ upon adding 40% w.t. RT28HC stabilized on expanded perlite.

Finally, comparing the building boards (GB and CB), the addition of OD@CCF increased up to ~28% of the density of CB, while in the case of GB, the density decreased up to 4% (Figure S3a).

To substantiate the findings and investigate the cement and gypsum structure, X-ray computed microtomography (μ CT) analysis was carried out, providing vital information on how the addition of various concentrations of additives affects the microstructural properties of the composites. The images on a microscale, as depicted in Figures 4 and 5, highlight unique attributes that change with differing degrees of additive application. In these images, a color scale bar is used to denote the range of X-ray absorption values, which, in turn, represent the different density levels within the wall-board materials, escalating from lower (shown as black) to higher (shown as white) values. The black marks observed throughout these images indicate areas of diminished intensity (air pockets), showcasing the porous nature of the boards. Specifically, in the imagery associated with the cement boards, the CB reference board illustrations predominantly include areas colored in black and purple (refer to Figure 4a). For 10% additive OD@CCF, the microtomography images (Figure 4b) display a reduction in black and purple areas, accompanied by the emergence of new yellow and green areas (higher index components). These areas are more intense in the images of composite boards with higher OD@CCF content, 20 and 30% w.t. (Figure 4c and d, respectively). These latter components likely correspond to OD@CCF particles, indicating their homogeneous integration into the cement board even at the higher loading (30%). These findings are also in agreement with the density measurements, where the density of the cement board increases with increment of OD@CCF loading.

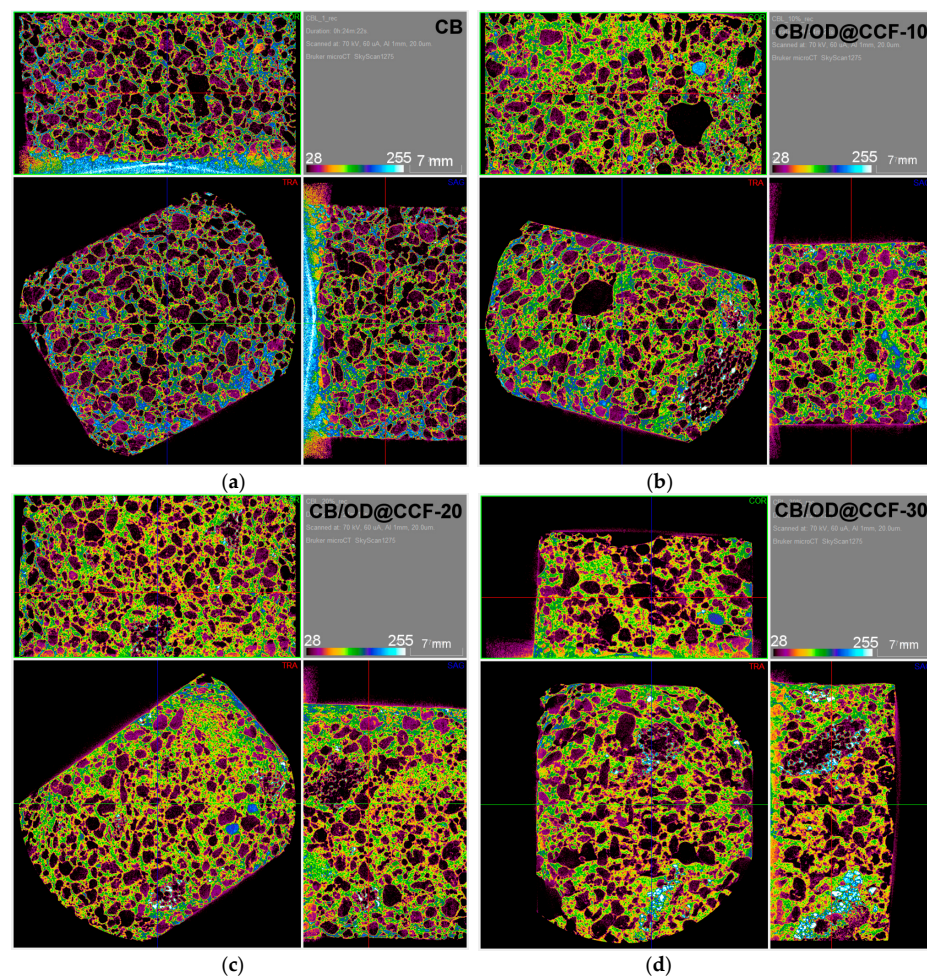


Figure 4. X-ray computed microtomography (micro CT) images from CB reference board (a) and CB/OD@CCF composite boards with 10% (b), 20% (c), and 30% (d) OD@CCF content.

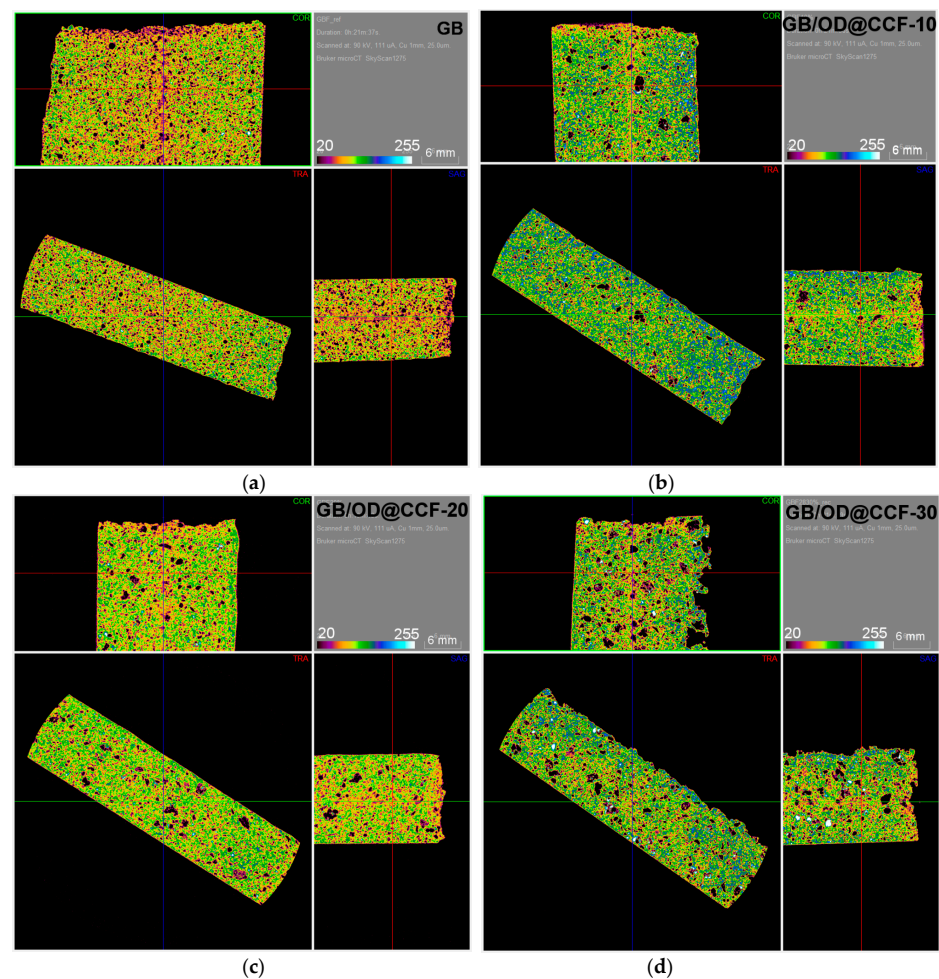


Figure 5. Images from X-ray computed microtomography (micro-CT) of GB reference board (a) and GB/OD@CCF composite boards containing 10% (b), 20% (c), and 30% (d) OD@CCF.

In the case of gypsum boards, the corresponding microtomography images are shown in Figure 5. The images for the GB reference board predominantly feature yellow- and green-colored areas as well as few purple- and black-colored areas (Figure 5a). For 10% additive OD@CCF, the microtomography images (Figure 5b) display more black-colored areas (lower index components, air voids) accompanied by the emergence of blue (higher index components). After a careful observation of black areas, it is obvious that they also consist of purple-colored areas, and these components may be attributed to OD@CCF particles having lower intensity than gypsum components. Similar features are also shown in the images of composite boards with higher OD@CCF content, 20 and 30% w.t. (Figure 5c and d, respectively), and the OD@CCF particles seem to be homogeneously dispersed in the gypsum matrix, even at higher loadings (30%).

3.2. Thermal Properties

Figure 6 displays the Differential Scanning Calorimetry (DSC) curves for (a) composite gypsum boards GB/OD@CCF and (b) composite cement boards CB/OD@CCF with varying percentages of OD@CCF content. Figure S1 displays the respective curves for pure octadecane. The melting (T_m) and solidification (T_s) temperatures, along with their corresponding enthalpies (ΔH_m and ΔH_s), are presented in Table S1. Analysis indicates that for both gypsum and cement boards, the melting temperature of octadecane falls within the range of 26.4–28.3 °C, while the solidification temperature ranges from 22.7 to 24.5 °C. Furthermore, the melting enthalpy rises progressively from the lowest to the highest OD@CCF loading, as expected (increasing from 6.3 J/g to 22.5 J/g for gypsum

boards and from 6.0 J/g to 14.8 J/g for cement boards). Conversely, the solidification enthalpy decreases from -5.2 J/g to -22.0 J/g for gypsum boards and from -8.3 J/g to -13.5 J/g for cement boards. These findings are plotted in Figure 7.

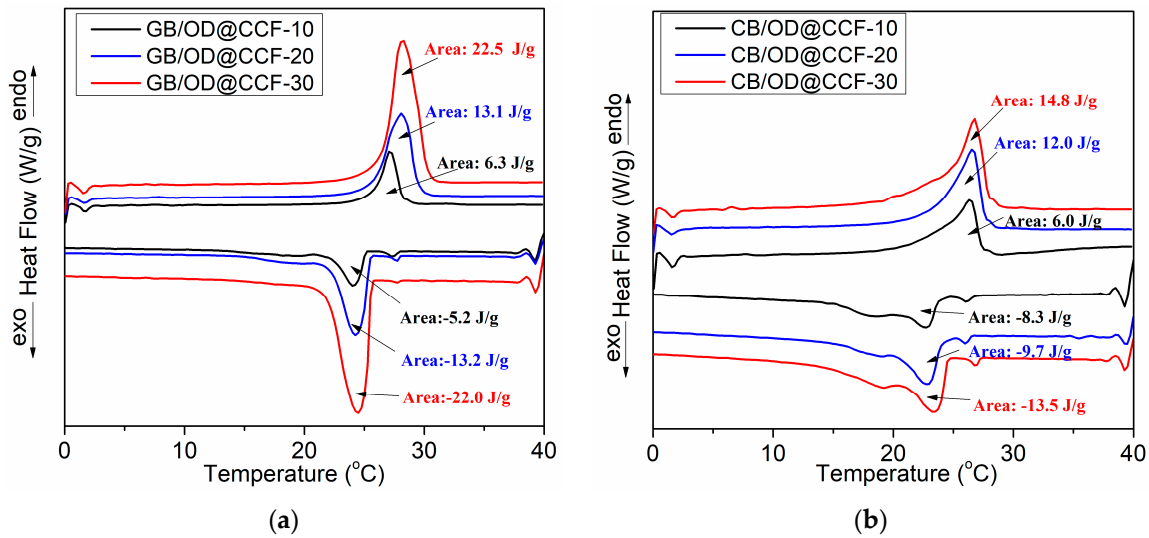


Figure 6. DSC curves of (a) GB/OD@CCF and (b) CB/OD@CCF with various % OD@CCF.

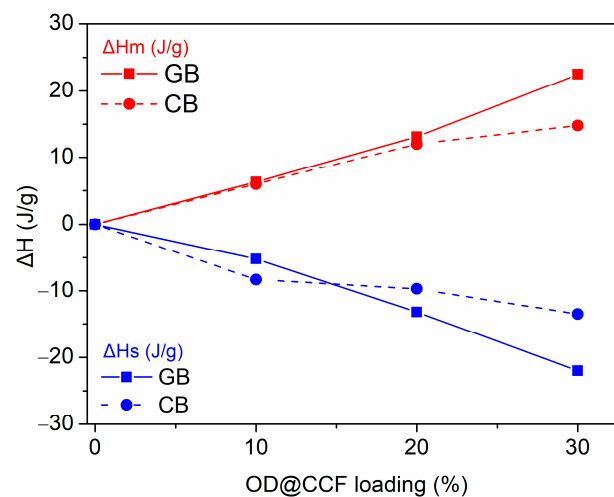


Figure 7. Variations in ΔH_m and ΔH_s values of composite boards GB and CB at different percentages of OD@CCF content.

The results from thermal conductivity (k) and specific heat capacity (C_p) measurements for the reference gypsum and cement boards and their composites GB/OD@CCF and CB/OD@CCF are presented in Table S2. Moreover, Figure 8 depicts the graphical correlation between thermal conductivity and specific heat capacity with increasing percentages of OD@CCF additive. The data analysis reveals noticeable variations in these parameters corresponding to the incremental increase in additive content. Specifically, a positive correlation is evident, indicating an improvement in both thermal conductivity and specific heat capacity with higher additive content. This positive correlation is interpreted as the OD@CCF component making a positive contribution to the heat transfer capabilities within the composite gypsum and cement boards. The data suggest that as the percentage of OD@CCF additive increases, there is a concurrent enhancement in both thermal conductivity and specific heat capacity, highlighting the positive influence of the additive on the heat transfer properties of the composite material. This improvement can be attributed to two main factors. Firstly, carbon foam contributes to an overall en-

hancement in the thermal conductivity of the composites. Secondly, the well-dispersed and inter-connected carbon foam particles within the gypsum or cement matrix create additional channels for heat transfer [34]. Similar findings are reported in the literature. For instance, in our previous work [22], the incorporation of activated carbon/RT18HC in gypsum boards increased the thermal conductivity and specific heat capacity from 0.33 W/(m·K) and 1455 (J/Kg·K) to 0.53 and 1833 (J/Kg·K), respectively, for a 30% w.t. additive. Zhang et al. [35] noticed that diatomite/paraffin incorporation into gypsum boards reinforced with 1% carbon fibers resulted in an increment of thermal conductivity from 0.86 to 0.93 W/(m·K). In addition, according to the same team, expanded graphite/paraffin gypsum-based composites with 20% w.t. additive increased the thermal conductivity from 0.742 W/(m·K) to 1.137 W/(m·K) [23]. Concerning cement composite boards, in our case, the thermal conductivity values are measured in the range of 0.06–0.08 W/(m·K), which are in agreement with the literature for perlite concrete thermal conductivity properties (0.07–0.08 W/(m·K)) [36], showing a ~33% increment for 30% additive. According to previous published works, carbon-based nanomaterials can significantly improve cement's thermal conductivity [37–39]. Also, Ye et al. [33] reported the increment of cement board's thermal conductivity by adding expanded perlite-stabilized RT28HC; specifically, the 40 % w.t. additive reached 0.149 W/(m·K) from 0.11 W/(m·K). Octadecane exhibits 0.2 W/(m·K) [32], which also can improve, in our case, the lower thermal conductivity of perlite cement boards.

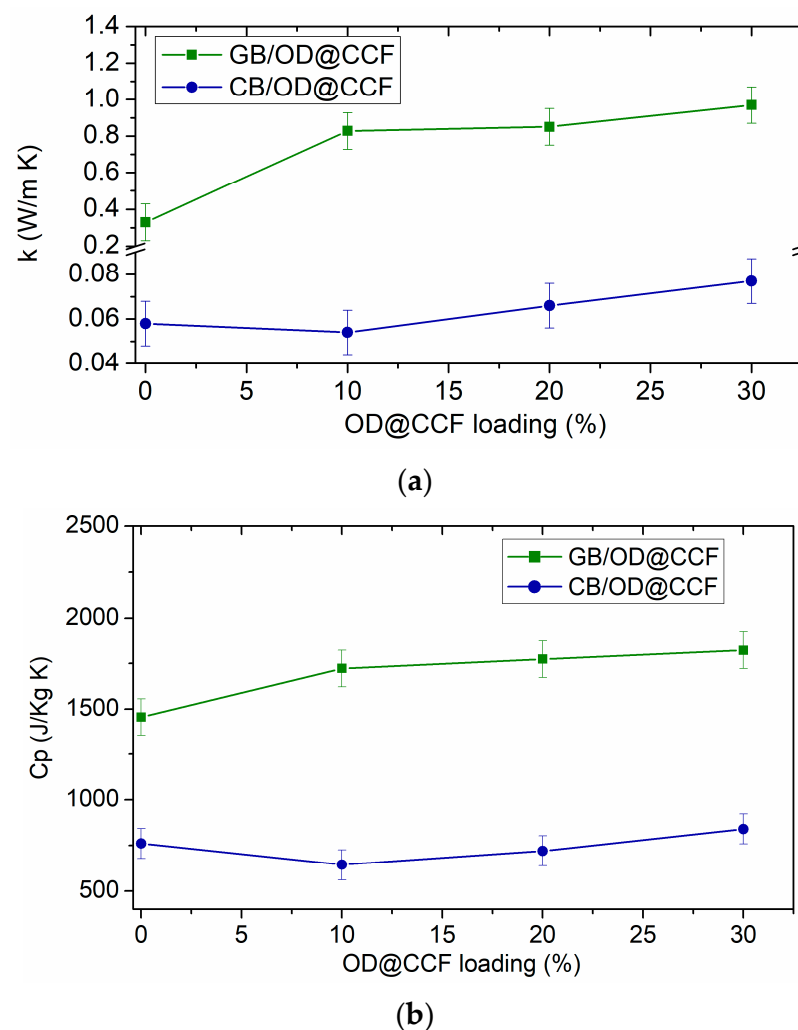


Figure 8. (a) Thermal conductivity, denoted as 'k', and (b) specific heat capacity, abbreviated as 'Cp', for gypsum and cement boards with varying percentages of OD@CCF additive.

In comparing the building boards (GB and CB), the inclusion of OD@CCF boosts thermal conductivity and specific heat capacity by approximately 33% and 10%, respectively, for CB, and by 193% and 25% for GB (Figure S3b,c).

3.3. Mechanical Properties

Flexural strength could be considered among the most important mechanical property of gypsum boards. Flexural strength is crucial because gypsum boards are often subjected to bending stresses during handling, transportation, and installation. Higher flexural strength ensures that the board can withstand these stresses without breaking or cracking, leading to improved durability and ease of use. On the other hand, the most important mechanical property of cement building components is typically compressive strength. Compressive strength measures the ability of the material to withstand axial loads or forces that tend to compress it. It is a critical property for such structural materials because they are often used in load-bearing applications, such as walls and foundations. High compressive strength ensures that these components can support the loads they are subjected to without crumbling or failing. It provides stability and structural integrity to buildings and other structures constructed using these blocks. While other mechanical properties such as tensile strength, flexural strength, and shear strength are also important, compressive strength is particularly crucial for ensuring the overall stability and safety of structures built with cement building components.

The results of mechanical testing on gypsum and cement boards with varying OD@CCF contents are presented in Figures 9 and 10, respectively. Analysis of load–deformation data from bending tests on GB/OD@CCF boards (Figure 9) indicates a clear relationship between additive percentage and composite board mechanical properties. At lower concentrations (up to 20%), a positive correlation is observed, indicating that OD@CCF inclusion enhances material strength, likely owing to enhanced interactions between molecules and the effects of reinforcement. However, with increasing OD@CCF content, a decline in mechanical strength is evident, possibly due to possible disturbance of the gypsum structure caused by elevated OD@CCF concentrations. As shown in Figure 9b, the optimal OD@CCF content for gypsum boards is found to be 10%. At this concentration, the modulus of rupture measures at 3.14 MPa, significantly higher than the 2.64 MPa for the reference gypsum board. This suggests that the mechanical strength of the composite board peaks at 10% OD@CCF content in bending tests.

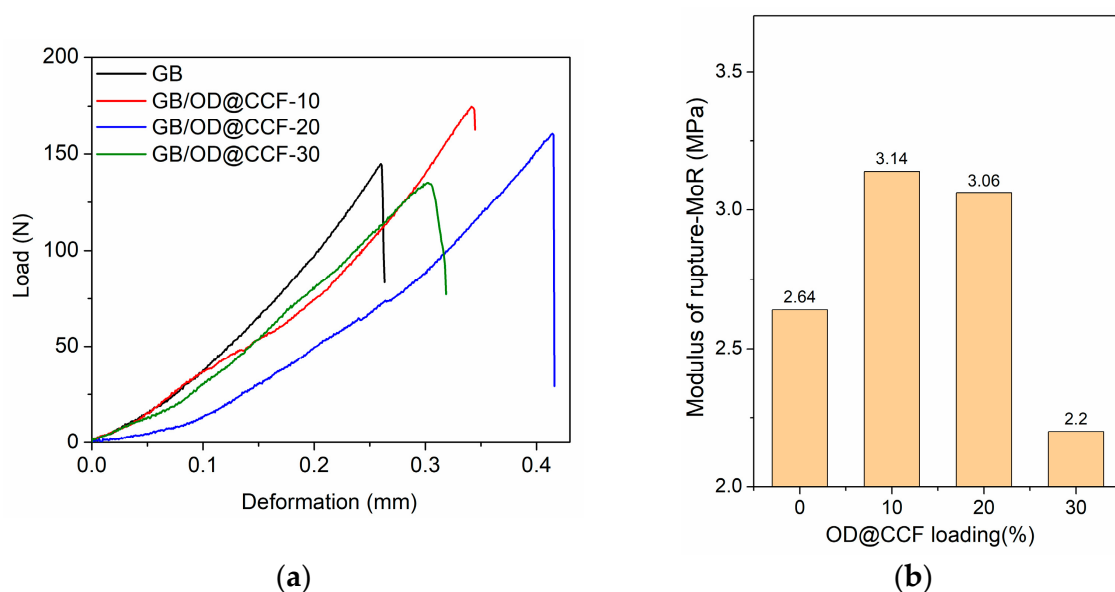


Figure 9. Curves representing (a) load–deformation and (b) modulus of rupture extracted from bending tests conducted on gypsum boards with varying loading of OD@CCF additive.

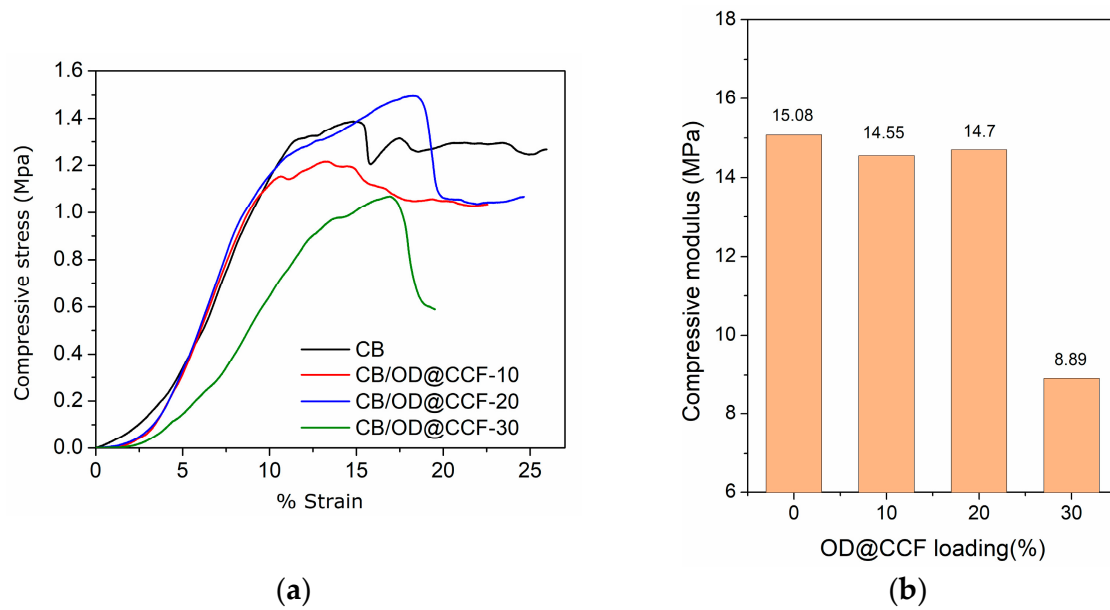


Figure 10. Results from compression tests for cement boards (CBs) with varying % content of OD@CCF additive. (a) Representative stress–strain curves and (b) compressive strength versus OD@CCF content.

The results of compression tests on cement boards (CBs) with varying percentages of OD@CCF additive are presented in Figure 10. The corresponding parameters from these tests are outlined in Table S3. A minor reduction in compressive strength is noted with increasing OD@CCF loading, decreasing from 1.09 MPa to 0.96 MPa for 10% and 20% loading, respectively. However, with a higher OD@CCF loading of 30%, this reduction is more pronounced, resulting in a compressive strength of 0.81 MPa.

In comparing the building boards (GB and CB), the inclusion of OD@CCF boosts the modulus of rupture by approximately 19% for 10% and 20% additive in case of GB, while this value is reduced by 16.6% for higher contents (30%). On the other hand, in case of CB, the compressive modulus reduced by 2.5% for 10% and 20% additive and 41% for 30% additive (Figure S3d).

3.4. EMI Shielding Properties

The effectiveness of electromagnetic interference (EMI) shielding for the created samples was evaluated based on shielding efficiency (SE) across the frequency spectrum of 3.2–7.0 GHz. The total SE can be delineated as the aggregate of reflection at the surface (SE_R), absorption (SE_A), and multiple reflections (SE_M), as detailed below [40]:

$$SE_T \text{ (dB)} = SE_R \text{ (dB)} + SE_A \text{ (dB)} + SE_M \text{ (dB)} \quad (2)$$

Typically, internal multiple reflections within the material can be disregarded if the SE exceeds 10–15 dB. Therefore, we estimated the average SE_T as

$$SE = SE_T \triangleq 10 \log_{10} \left(\frac{P_{inc}}{P_{tm}} \right) = 10 \log_{10} \left(\frac{1}{T} \right) = SE_R + SE_A \quad (3)$$

where

$$SE_R = 10 \log_{10} \left(\frac{1}{1 - R} \right) \quad (4)$$

$$SE_A = 10 \log_{10} \left(\frac{1 - R}{T} \right) \quad (5)$$

SE_R and SE_A represent the reflection and absorption components of SE, respectively. Enhanced SE indicates more effective shielding. SE, also represented as SE_T , with A, T, and R signifying absorption, transmission, and reflection, respectively, is typically measured as the logarithmic ratio of incident power (P_{inc}) to transmitted power (P_{trn}) [41,42] and thus expressed in decibels (dB).

Figure 11 depicts the S_{21} (transmission; Figure 11a) and the S_{11} parameters (reflection; Figure 11b) of the GB/OD@CCF composite samples for a series of octadecane samples shape-stabilized in carbon foam, with different OD@CCF concentrations, in the frequency range of 3.2–7.0 GHz. Figure 11b clearly illustrates that the reflection of the samples is almost zero for all the additive concentrations in the range of 0.00–30%. Consequently, the EMI shielding effect attributable to reflection (SE_R) is minimal, rendering the total shielding effectiveness (SE) as merely $SE_T = SE_A$ [refer to Equation (3)]. This observation aligns with findings from other research teams investigating carbon-based composite materials [43].

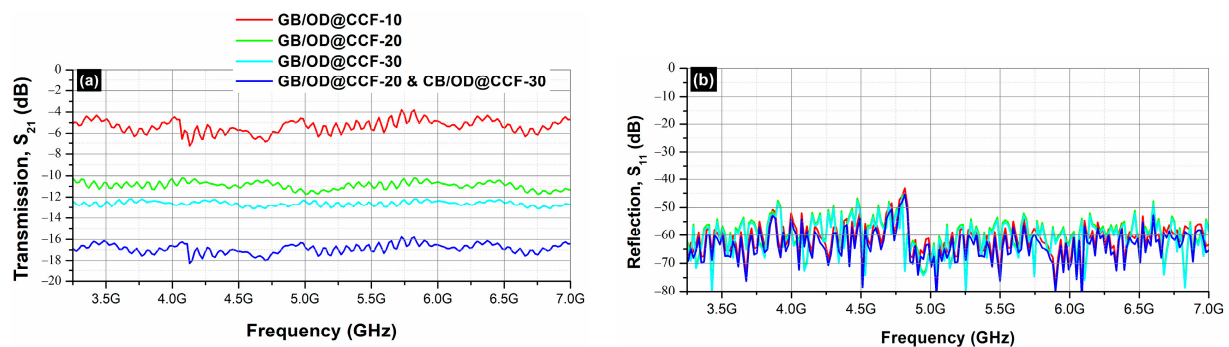


Figure 11. Transmission S_{21} (a) and reflection S_{11} (b) coefficients from 3.2 to 7.0 GHz (C-band) for different gypsum board samples.

Figure 12 depicts the absorption (Figure 12a) and total shielding efficiency (SE_T) (Figure 12b) spectra of the GB/OD@CCF composite samples for a series of concentrations of octadecane shape-stabilized in carbon foam, OD@CCF, in the frequency range of 3.2–7.0 GHz.

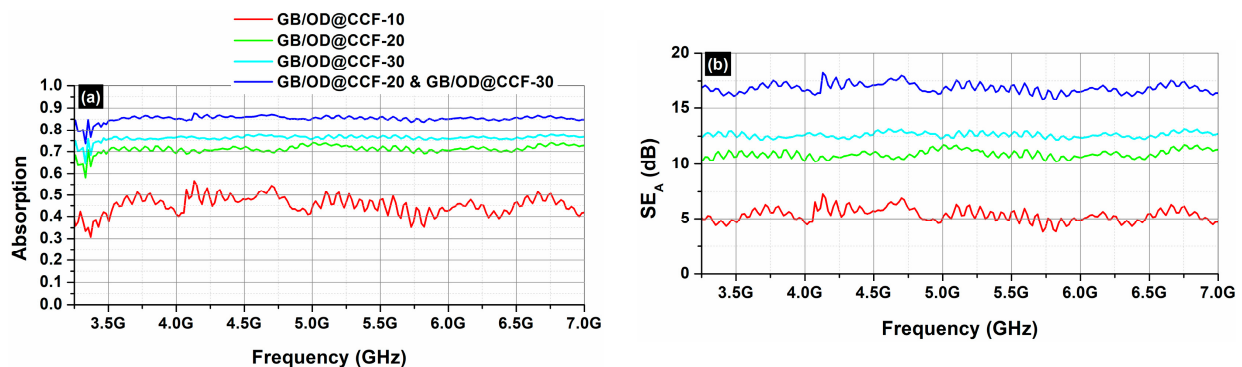


Figure 12. Electromagnetic radiation absorption (a) and SE_A (b) from 3.2 to 7.0 GHz (C-band) for different gypsum board samples.

It is obvious that absorption serves as the primary shielding mechanism, a conclusion supported by the progressively rising absorption levels observed with increasing OD@CCF content in the gypsum board composites.

At low OD@CCF loadings, the electrically conductive network within the gypsum board composites is incomplete, resulting in only a minor difference in electrical conductivity between the gypsum samples and air. This causes a large impedance match and allows a significant number of electromagnetic waves to pass through the samples [44]. As shown in Figure 12b, the SE_A remains below 5–6 dB for OD@CCF concentrations up to 10%, but

increases to between 10 and 12.5 dB for concentrations ranging from 20% to 30%. This indicates that absorption is the dominant EMI shielding mechanism in these composite samples, consistent with findings reported in the literature [43].

At this point, it should be noted that the addition of GB/OD@CCF-20 with the GB/OD@CCF-30 samples was studied in order to verify whether higher additive concentrations could reach an SE_T of ~15–20 dB, which is considered sufficient for EM shielding, e.g., electronic devices, etc. [45].

Similar samples to those described above were studied, making cement boards that can be used outdoors. Figure 13 depicts the S_{21} (transmission; Figure 13a) and S_{11} parameters (reflection; Figure 13b) of the CB/OD@CCF composite samples for a series of concentrations of octadecane shape-stabilized in carbon foam, OD@CCF, in the frequency range of 3.2–7.0 GHz.

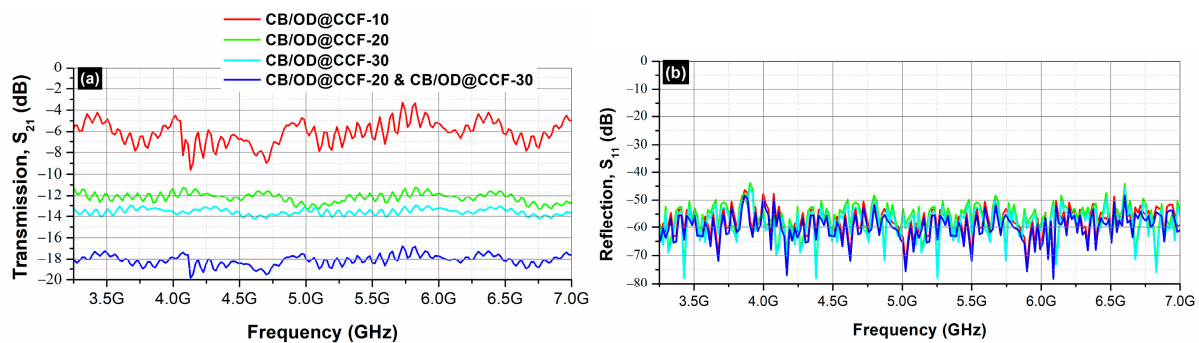


Figure 13. Transmission S_{21} (a) and reflection S_{11} (b) coefficients from 3.2 to 7.0 GHz (C-band) for different cement board samples.

Like previously, electromagnetic absorption appears to be the primary shielding mechanism, as evidenced by the steadily increasing absorption levels with higher OD@CCF content in the cement board composites.

Figure 14 depicts the absorption (Figure 14a) and total shielding efficiency (SE_T) (Figure 14b) spectra of the CB/OD@CCF composite samples for a series concentrations of shape-stabilized octadecane in carbon foam, OD@CCF, in the frequency range of 3.2–7.0 GHz.

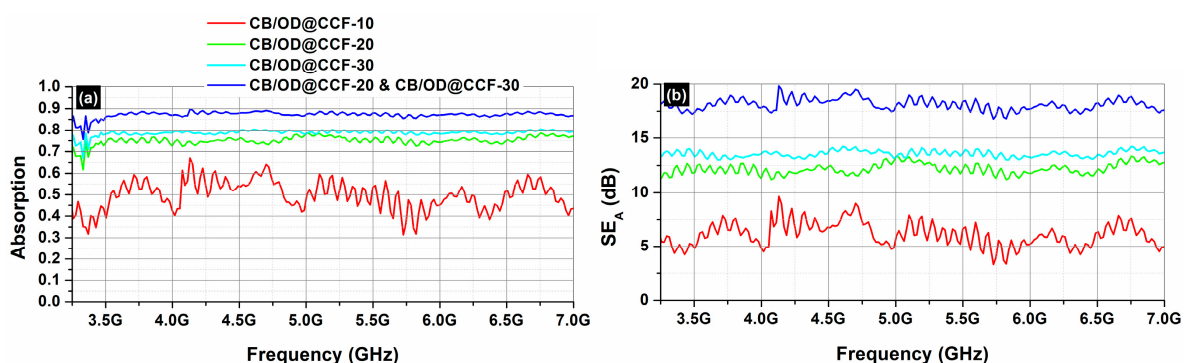


Figure 14. Absorption (a) and SE_A (b) measurements across the 3.2 to 7.0 GHz frequency range (C-band) for various cement board samples.

It is worth noticing that the SE_A levels of the cement board samples are higher than the corresponding ones of the gypsum samples, reaching a value of ~19.5 dB for the combination of CB/OD@CCF-20 with the CB/OD@CCF-30 samples (compared to ~18 dB for GB/OD@CCF-20 and CB/OD@CCF-20). Concrete and cementitious composites, in general, are very poor electrical conductors, but still conductors, at least compared to gypsum [46,47]. This is actually the reason for their enhanced EMI effect. Moreover, it has been demonstrated that the dry resistance of cement specimens is influenced by the

material's porosity and the presence of free-moving ions [48]. As shown in Figures 4 and 5, the pore sizes inside the gypsum samples are much smaller, compared to cement boards. As a result, large pathways facilitate free ion movement in CB/OD@CCF composite boards (Figure 4), which are closed in GB/OD@CCF samples, and consequently, the mean path of ion movement increases [49]. In turn, this changes the electrical conductivity of gypsum (compared to cement) boards and increases the resistance, which decreases EMI SI accordingly.

3.5. Thermal Performance Measurements

To evaluate the thermal performance of the test samples, the upper environmental chamber was subjected to an 8 h heating phase, followed by an 8 h cooling phase. Figure 15 displays the temperature curve of the environmental chamber and the temperature curves measured at the lower surface of the samples, specifically the surface within the testing room of each sample, namely gypsum boards GB/OD@CCF-10 and GB/OD@CCF-30 and the reference gypsum board (GB).

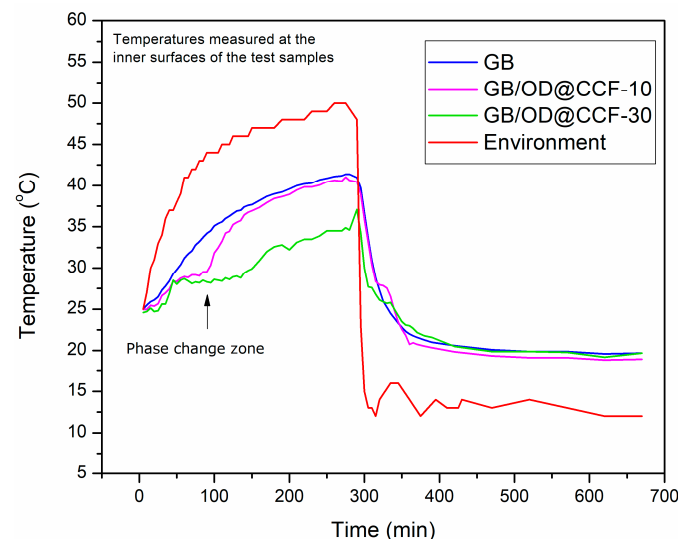


Figure 15. Thermal performance curves comparing gypsum board samples loaded with 10% and 30% OD@CCF to the reference gypsum board, GB.

In the first 45 min of heating, the rate of temperature increase (RTI) of the GB/OD@CCF-10 and GB/OD@CCF-30 samples is identical to that of the reference sample, and at this point in time, the temperature is 28 °C. After this point, the phenomenon of phase change of the stabilized PCMs begins as time passes. The absorption of the required heat for the n-octadecane change from solid to liquid is depicted by the decrease in the RTI of the two samples and the appearance of a “plateau” in their temperature curves (phase change zone). Interestingly, the duration of this plateau in each sample is obviously related to their different paraffin loading. In GB/OD@CCF-10, the phase change zone extends to 90 min, while in GB/OD@CCF-30, it extends to 135 min. When all the paraffin has become liquid, a brief sharp increase in the RTI of the two samples compared to that of the reference sample is observed, followed by a smoothing of these rates and their equalization with the reference. The difference in the absolute temperatures of the two samples compared to the reference is also noteworthy. GB/OD@CCF-10 has a difference of approximately 2 °C, and GB/OD@CCF-30 has a difference of approximately 7 °C, highlighting the effect of the loading percentage on the effectiveness of the advanced gypsum board to maintain a lower temperature within a space. The response of the samples to the subsequent sudden cooling of the environmental chamber confirms the positive effect of the higher paraffin content on the properties of the gypsum board. The rate of temperature decrease of the GB/OD@CCF-30 sample is noticeably lower than that of the GB/OD@CCF-10 sample in the phase change

zone. Furthermore, the final temperature of GB/OD@CCF-30 is approximately 2 °C higher than that of the reference.

The temperature curves of the indoor spaces of the test rooms are shown in Figure 16 along with the temperature curve of the environmental chamber. Specifically, the temperature variation is recorded in the environmental chamber and in the test rooms (indoor temperature) of the reference cement board (CB) and the cement board CB/OD@CCF-30, respectively.

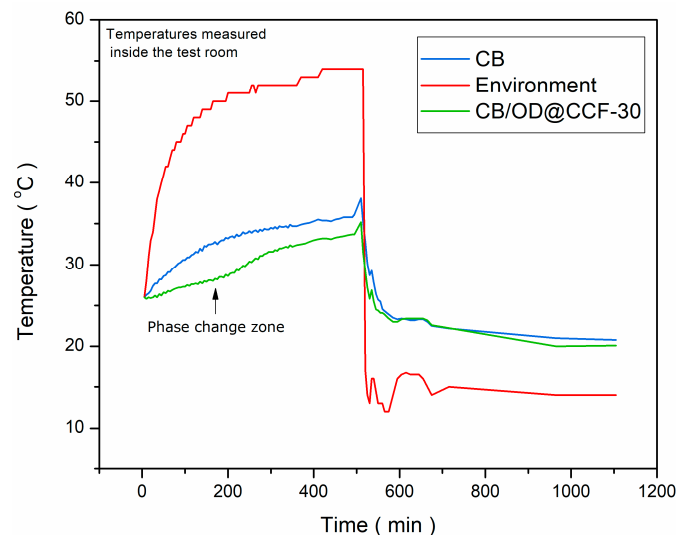


Figure 16. Curves from thermal performance measurements for cement board sample with 30% OD@CCF loading in comparison with the reference cement board.

As the temperature of the environmental chamber increases, a difference in the rate of temperature increase (RTI) is observed between the reference sample (CB) and the CB/OD@CCF-30 sample. This difference, evident near 28 °C, can be attributed to the thermal energy absorbed by the CB/OD@CCF-30 sample for the phase change of the stabilized PCM from solid to liquid. Notably, the phase change zone stabilizes the temperature in the test room around 28 °C for approximately 3 h, unlike the reference cement board (CB) test room temperature, which steadily rises to around 33 °C during the same period. Subsequently, after about 5.5 h, the RTI in both rooms becomes similar. The absolute temperature difference between the two rooms remains constant at approximately 2.3 °C. It is evident that the cement board with stabilized n-octadecane has the capability to keep the room cooler for a longer period compared to the plain reference cement board.

4. Conclusions

To summarize, this research represents a significant step forward in the development of cement and gypsum building boards infused with shape-stabilized n-octadecane within carbon-based foams, aiming to improve energy storage and electromagnetic interference shielding capabilities. Our investigation underscores the critical importance of optimizing the concentration of shape-stabilized n-octadecane in these composite materials. Determining the optimal concentration is pivotal for achieving the desired balance between enhanced energy storage, EMI shielding, and mechanical properties.

Key findings from this study include the following:

(i) Incorporating OD@CCF into gypsum and cement boards enhances thermal energy storage properties, resulting in improved thermal conductivity and specific heat capacity. Notably, temperature differentials of up to 7 °C were observed between reference gypsum and composite board inner surfaces, with a 2.3 °C improvement in the indoor test room temperature for composite cement boards.

(ii) EMI shielding properties also improve with increasing OD@CCF content, with the combination of boards containing 20% and 30% OD@CCF achieving EMI shielding absorption levels of approximately 18 dB and 19.5 dB for gypsum and cement boards, respectively.

(iii) Mechanical properties remain largely unaffected with up to 20% OD@CCF additive in both gypsum and cement boards. Particularly for gypsum boards, the modulus of rupture increases by approximately 19% compared to the baseboard. However, some mechanical degradation is observed with higher additive loading.

Overall, these positive results pave the way for practical applications and future innovations in construction materials. They offer a sustainable and technologically advanced solution for enhancing energy storage and EMI shielding in building environments.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/jcs8070251/s1>: Table S1: The melting and solidification temperatures (T_m and T_s , respectively) and enthalpies (ΔH_m and ΔH_s , respectively) derived from DSC measurements; Table S2: Thermal conductivity (k), thermal effusivity (e), specific heat capacity (C_p) and density (d) of reference gypsum or cement board and the corresponding composite boards. Table S3: Mechanical properties of CB reference and composite boards derived from compression tests. Compressive strength, compressive modulus, percentage of compressive strength (ICS) and compressive modulus (ICM) of CB respective values; Figure S1: DSC curves of pure n-octadecane; Figure S2: Pictures from the custom-made environmental chamber. (a) The chamber during the measurements; (b,c) the internal area of the chamber. Figure S3. Comparison for % effect of OD@CCF additive on CB or GB board's (a) density, (b) specific heat capacity (C_p), (c) thermal conductivity (k) and (d) mechanical properties.

Author Contributions: Supervision, M.A.K. and G.K.; project administration, M.A.K. and G.K.; funding acquisition, M.A.K. and G.K.; conceptualization, M.A.K. and G.K.; methodology, M.A.K. and G.K.; investigation, C.G., K.C.V., Z.V. and A.N.; formal analysis, C.G., K.C.V., Z.V., C.E.S., M.A.K. and G.K.; data curation, M.A.K., G.K., Z.V., C.G., K.C.V., M.B., A.N., A.S.P. and C.E.S.; validation, C.E.S.; resources, M.A.K., G.K. and A.S.P.; writing—original draft preparation, M.B., G.K. and M.A.K.; writing—review and editing, G.K., K.C.V., M.B. and M.A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was co-financed by the project “Advanced Nanostructured Materials for Sustainable Growth: Green Energy Production/Storage, Energy Saving and Environmental Remediation” (TAEDR-0535821), which is implemented under the action “Flagship actions in interdisciplinary scientific fields with a special focus on the productive fabric” (ID 16618), Greece 2.0—National Recovery and Resilience Fund—and funded by the European Union’s NextGenerationEU. Also, this work was co-financed by the European Union and Greek national funds through the Operational Program Competitiveness, Entrepreneurship, and Innovation, under the call RESEARCH—CREATE—INNOVATE (acronym: SEMI-WEB; project code: T2EDK-02073), and it was also supported by proposal number 101092339 (Exploit4InnoMat) under the call HORIZON-CL4-2022-RESILIENCE-01 (topic: HORIZON-CL4-2022-RESILIENCE-01-20; type of action: HORIZON-IA).

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Acknowledgments: The authors would like to thank the companies Energy Houses (ENHSS, Serres, Greece) and KNAUF (Amfilochia, Greece) for supplying us with raw materials for the production of cement and gypsum boards, respectively.

Conflicts of Interest: The authors declare no conflicts of interest.

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