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Characterization and Development of Ceramics with Inorganic Additives

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Abstract: Date palm tree (DPT) and pine tree (PT) needles in forests form a combustible mat, posing fire risks during summer in Pakistan that damage vegetation, wildlife habitats, and biodiversity and impact local livelihoods. In this article, sintered ceramic specimens were prepared at different weight concentrations (DPT5, DPT10, DPT20, and DPT 30 and PT5, PT10, PT20, and PT30) of date palm tree leaf ash and pine tree needle ash as secondary additives in ceramic manufacturing along with primary material kaolinite (China clay). Raw materials composition was analyzed using X-ray diffraction (XRD), taking loss on ignition, water absorption, bulk density, saturated surface dry density (SSD), weight per unit area, and thermal cycling as measurement indexes. The result indicates that loss on ignition increases while increasing the quantity of secondary additives and the maximum increase for DPT30 was 19.6% and for PT30, it was 22.1%. As the secondary additives increase, the water absorption rate also increases and the maximum increase for DPT30 and PT30 is 4.5%. Meanwhile, with the increase in secondary additives, the density decreased; for DPT 30, it was 1457.7 kg/m^3 and for PT30, it was 1829.8 kg/m^3. Thermal performance was investigated by heating and cooling cycles. It was observed that thermal performances increase with the increase in secondary additives. The results reveal this novel approach has the potential to form a ceramic and good properties can be achieved. The prepared specimens have the potential to be used in the fields of electronics, aerospace, construction, and building engineering, alleviating environmental strain, curbing the exhaustion of China clay reserves, and most importantly, lowering the risk of forest fires in Pakistan.

Keywords: inorganic waste; ceramic properties; date palm tree ash; pine tree needle ash; microscopic characteristics

Citation: Awais, M.; Mansoor, A.; Shah, I.; Hussain, M.; Asif, M. Characterization and Development of Ceramics with Inorganic Additives. *Inventions* **2024**, *9*, 121. https://doi.org/10.3390/inventions9060121

Academic Editor: Zhengyi Jiang

Received: 29 October 2024
Revised: 27 November 2024
Accepted: 2 December 2024
Published: 5 December 2024

1. Introduction

Gone are the days when ceramics were used only for household items and kitchenware. Now, ceramics are being used for steam jet engines, vehicle engines, electricity conductors, electric insulators, refractories, ceramics tiles, and many other advanced applications. In the context of material science, ceramics are defined as any solid made of clay and several additives. In Pakistan, the forest fire peak season typically begins in mid-December and lasts around 27 weeks. There were 1922 fire alerts reported between the 16 October 2023 and the 14 October 2024, only considering high-confidence alerts. From 2001 to 2023, Pakistan lost 5.52 kha of tree cover from fires [1]. These dry waste leaves are one of the major factors for forest fires, particularly in the summer season. This approach not only reduces fire in forests but also as these agricultural wastes are produced in significant quantities, converting them into ash, which is known as inorganic matter in biomass for manufacturing ceramic tiles, is an attractive waste disposal method. The resulting clay mixture is fired at a high temperature to increase the hardness and durability of ceramics [2]. E.H. Dagnew's [3] study concentrated on using burned bottom ash in place of clay (kaolin). Samples of dry-pressed ceramic wall tiles were made by mixing clay (kaolin) with bottom ash ranging from 0 to 60 wt.%. The results showed that the clay with a 30 wt.% addition of incinerated bottom ash had a higher flexural strength of 24.83 MPa and a water absorption of more than 10%. Q. Yuan et al. [4], utilizing fly ash from the incineration of industrial solid waste (IWA) from regenerated paper mills, created innovative unglazed ceramic tiles. Ceramic tiles with IWA additives (0–30 weight percent) and firing temperatures (1100 °C, 1200 °C, and 1300 °C) were the subject of experimental studies. Promising characteristics of these tiles were a 5.9% water absorption rate, an estimated 33.86% energy savings, and adherence to heavy metal leaching restrictions. G.A. Benedet et al. [5] studied the sustainable repurposing of waste ceramic materials, specifically rice husk ash (RHA), as a secondary mineral source in clay-based ceramic manufacturing. The results showed that adding more than 15% RHA to clay ceramics caused excessive water absorption, making it inappropriate. In order to create hollow ceramic blocks for non-load-bearing masonry, an RHA percentage of 8.3% was selected. A. Zimmer and C. Bergmann [6] tried using 20–80% coal fly ash in their ceramic tile-making project. The results show that the maximum amount of fly ash in ceramic tile that meets the minimum flexural strength (green) criterion for handling in industrial settings is 60 weight percent. The 60 wt.% fly ash ceramic tile met the technical qualities requirement with a 30 MPa flexural strength, a 12% water absorption rate, and a 7.5% shrinkage rate. Additionally, since fly ash is not a flexible substance, they looked into the impacts of adding feldspar and limestone individually to increase the plasticity of coal fly ash tile. Limestone can be added to unfired tiles to boost their green flexural strength and decrease shrinking. Nevertheless, it degrades the qualities of porosity, water absorption, and flexural strength. The addition of 30 percent feldspar within fly ash tiles has the capacity to markedly diminish porosity (5%), decrease water absorption (2%), and considerably augment flexural strength (>35 MPa). The primary drawback associated with the inclusion of feldspar is its tendency to elevate linear shrinkage. Consequently, the quantity of feldspar incorporated into coal fly ash tiles is paramount for optimizing tile performance while mitigating the risk of deformation-related defects. H. Wang [7] studied the production of ceramic tiles; 70 wt.% high-alumina coal fly ash was utilized. This formulation enabled the fly ash tile to attain a flexural strength of 67 MPa and an apparent porosity of 0.13%, which presents substantial potential for the ceramic industry and contributes to reducing coal fly ash waste. K. Namkane et al.'s [8] study incorporated 20–80 wt.% of bottom coal ash into the clay matrices of tiles, revealing that all sample tiles could be classified as BIb group according to the ISO standards governing water absorption when subjected to firing at 1175 °C. The optimal composition for bottom ash tiles comprises 40 wt.% of bottom ash and 60 wt.% of clay, as this combination exhibits the lowest linear shrinkage and minimal deformation, achieving a flexural strength of 24.8 MPa, which is viable for ceramic tiles, albeit lower than commercial alternatives. Furthermore, the investigation indicated that tiles containing coal bottom ash are susceptible to variations in firing temperatures, which can adversely influence the aesthetic qualities related to planarity and result in a darkening of the ceramic tiles' coloration. C.J. Lynn et al. [9] conducted a comprehensive review and synthesis of the principal findings from various research investigations. Generally, the recycling of sewage sludge ash into both glazed and unglazed tiles emerges as a feasible approach devoid of significant production complications. The water absorption rates of unglazed ceramic tiles frequently surpass the stipulated limits; however, such effects are minimal in low-ash-content tiles, and the application of glazing has been shown to effectively mitigate water absorption. The bending strength and abrasion resistance meet the requisite standards, though they tend to diminish with an increase in the sewage sludge ash content within the tiles. Additionally, there are no observable effects on chemical resistance and no significant implications for firing shrinkage, and a reduction in loss on ignition was noted due to the combustion of organic matter prior to the tile firing phase. Mohammed S. Ali [10] used rice husk ash (RHA) from 10 to 50 wt.% to produced environment friendly ceramics. They studied the hardness, tensile strength, compressive strength, and porosity of the produced ceramics. They found that there was an increase in porosity with an increase in the content of RHA from 10 to 50 wt.%. Hardness and compressive and tensile strength increased with an increase in the content of the RHA from 30 wt.% to 50 wt.%, and there was a decrease in hardness and compressive and tensile strength with an increase in the content of the rice husk ash from 10 wt.% to 50 wt.%. M.F. Serra [11] produced Mullite ($3Al_2O_3{\cdot}2SiO_2$) ceramics using rice husk ash and studied the grain size, porosity, thermal behaviour, density, and shrinkage of the produced Mullit. K. Vidhya, S Kandasamy et al. [12] conducted research on the impacts of ash discharged from powerhouses on the environment. They proposed that ash can be used as an admixture to make ecofriendly bricks, which will reduce the exploitation of natural clay deposits. Jingjie Cao et al. [13] used coal fly ash to produce eco-friendly ceramics and found the bulk density and porosity increased as fly ash content was increased. The investigation of the microstructures and density of the ceramics was also discussed along with durability properties of the ceramics with secondary additives. K. Namakane et al. [14] continued their investigation by incorporating sand and leonhardite, which are prevalent byproducts of coal mining, to augment the plasticity of ceramic tiles, given that bottom ash is characterized as a non-plastic substance. The maximum proportion of waste content that successfully fulfils the requisite properties may attain as much as 42.8 wt.% (comprising 21.4 wt.% of bottom coal ash and 21.4 wt.% of leonhardite). Furthermore, this ceramic tile can be utilized as floor tiles, as it conforms to the BIIa classification of flexural strength (22–30 MPa), and demonstrates a resistance to chemical aggression that aligns with unglazed Class A tiles, indicating its suitability for environments exposed to household chemicals and swimming pool salts. Haiying et al. [15] studied the reclamation of untreated Municipal Solid Waste Incineration (MSWI) fly ash for incorporation into ceramic tiles. The findings indicate that the integration of 20 wt.% of MSWI fly ash represents an optimal proportion for maximizing waste recycling while producing ceramic tiles that comply with the relevant Chinese standards. The inclusion of 20% MSWI fly ash by mass in the tiles resulted in the attainment of a compressive strength of 18.6 MPa and a water absorption rate of 7.4% at a firing temperature of 960 °C. Moreover, it was observed that when the firing temperature exceeded 1000 °C, the heavy metals present in the ceramic tile were effectively immobilized. Nevertheless, cadmium (Cd), mercury (Hg), lead (Pb), and zinc (Zn) concentrations surpassed permissible limits when leachability analysis was conducted on an unglazed tile. L. Barbieri et al. [16] attempted to synthesize porcelainized tiles through the addition of 3–15 wt.% untreated MSWI bottom ash and vitrified bottom ash (comprising 50% MSWI bottom ash and 50% glass cullet). The results indicated that all tile specimens containing either untreated or vitrified bottom ash satisfied the requisite standards for floor tiles. The water absorption was determined to be below 0.1%, with bending strength values ranging from 45 to 53 MPa, alongside an observed enhancement in linear shrinkage. D.F. Lin et al. [17] studied waste ash, like sewage sludge ash (SSA) and Municipal Incinerator Bottom Ash (MIBA), which resulted in increased water absorption and reduce bending strength and wear resistance in ceramic tiles, with complex interactions influenced by kiln temperature and mix percentages. MIBA reduces tile shrinkage; SSA increases it. L. Leandro dos Santos et al. [18] studied waste ash as a secondary additive such as ash from algaroba firewood and the results showed enhanced ceramic properties by improving mechanical resistance, reducing water absorption, and maintaining necessary characteristics while mitigating environmental impact through partial clay replacement. E. Monedero et al. [19] evaluated agro-industrial biomass ashes, including tree ash, as potential additives in construction materials, influencing properties like strength and durability in ceramic manufacturing. Results indicates ashes enhance properties of construction materials and agro-industrial biomass is a viable resource. L. Pérez-Villarejo et al. [20] incorporated tree ash in ceramic manufacturing as a secondary additive and found an increase in porosity and water absorption while decreasing apparent density and compressive strength, with optimal ash content up to 20% meeting strength standards. Water absorption increased with higher ash content. E. Rambaldi [21] employed

2–5 wt.% untreated bottom ash and 5–10 wt.% vitrified bottom ash (incorporating glass) to partially substitute Na-feldspar sand within the matrix, thereby investigating the potential for the fabrication of monoporosa tiles and porcelain tiles. The findings indicate that municipal solid waste incineration (MSWI) bottom ash is technically viable to produce ceramic tiles. In the case of porous single firing tiles, the incorporation of 5 wt.% untreated bottom ash does not significantly influence water absorption and linear shrinkage. The vitrified bottom ash was not subjected to testing owing to its lack of cost-effectiveness for production applications. With respect to porcelain tiles, vitrified bottom ash tiles demonstrate a notable enhancement in water absorption and linear shrinkage when compared to the control tile at firing temperatures exceeding 1160 °C. It is noteworthy that MSWI bottom ash is associated with the release of heavy metals and the solubilization of alkaline metals. Consequently, a leachability assessment was performed to determine its suitability for recycling within tiles. The results indicate that all fired tiles continue to release a minimal quantity of leachate; however, this quantity remains below the threshold value established for inert waste. The development of ceramic tiles with inorganic additives has gained significant attention due to the potential for enhanced properties and sustainability.

Collectively, these studies illustrate the successful utilization of agricultural waste materials such as date palm tree leaf ash and pine tree needle ash in ceramic manufacturing, emphasizing their environmental benefits. These waste materials not only augment the essential characteristics of ceramics but also lower manufacturing expenses by reducing the utilization of raw materials and energy. The ongoing research is focused on the assessment of physical, mechanical, and thermal attributes of ceramics, with particular attention to the incorporation of date palm tree leave ash and pine tree needle ash as waste additives. Produced specimens were compared with conventional ceramics. Produced specimens can be used in the construction, aircraft, and electronics industries according to their observed properties.

2. Materials and Methods

2.1. Characterization of Ceramic Raw Material

In the current study, Kaolinite (China clay, $Al_2Si_2O_5(OH)_4$) was obtained from a local market in Pakistan as the primary material, while ash of wasted pine tree (PT) needles and date palm tree (DPT) leaf were used as the secondary additives in the manufacturing of Ceramic specimens. X-ray diffraction (XRD) was utilized to determine the primary mineral phase present in DPT ash, PT ash, and Kaolinite. Prepared specimens were tested as per ASTM C373-88 [22] and ASTM C326 [23] standard.

2.2. Preparation of Sample

Figure 1 shows the preparation schematic of the fired ceramic specimen. Firstly, PT needles and DPT leaves were fired to extract ash, which later was sieved using a sieve (mesh size of 75 µm) to extract the fine particles of ash and to mix it as secondary additives with Kaolinite at different weight ratios such as 5%, 10%, 20%, and 30% using sodium silicate (Na_2SiO_3) as a binder. The raw materials were mixed for 2 min to achieve a uniform dry mixture. Test specimens of 60 mm in diameter and 7 mm in thickness were made using a die. Specimens were pressed at 25 tons using a hydraulic press. Each green body sample was marked with its waste concentration as shown in Table 1. All specimens were then baked using a Memmert (UN110) baking oven to a temperature of 150 °C; later, they were heated to a high temperature of 1350 °C for 24 h in a sintering furnace.

Table 1. Mixture proportion of raw materials by weight (%).

Raw Material	K	DPT5	DPT10	DPT20	DPT30	PT5	PT10	PT20	PT30
Kaolin (K)	100	95	90	80	70	95	90	80	70
Date palm tree (DPT)	-	05	10	20	30	-	-	-	-
Pine tree (PT)	-	-	-	-	-	05	10	20	30

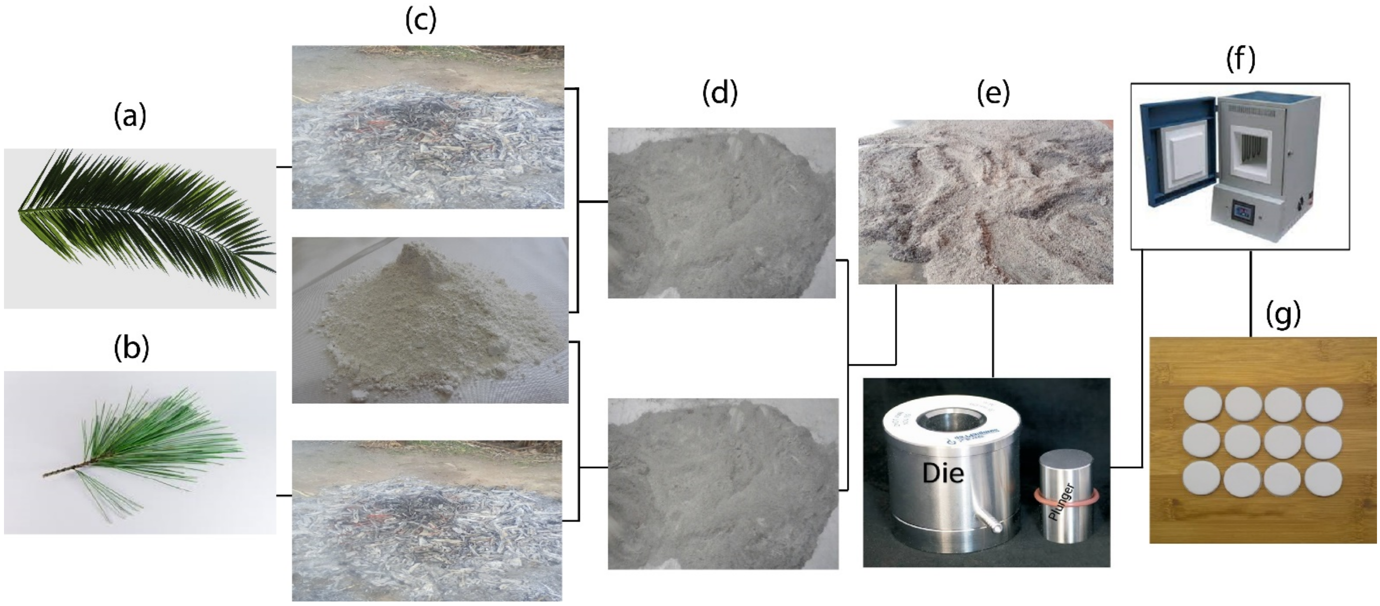

Figure 1. Ceramic specimen preparation schematic. (**a**) Date palm tree (DPT) leaf. (**b**) Pine tree (PT) needles leaf. (**c**) Extraction of different ashes for mixing. (**d**) Mixing of ashes. (**e**) Sludge preparation by moulding process. (**f**) Electric furnace for sintering process. (**g**) Final ceramics specimens.

In Table 1, symbol K represents Kaolin (hydrated aluminum silicate) with 0% waste added, while symbols DPT5, DPT10, DPT20, and DPT30 and PT5, PT10, PT20, and PT30 show an ash added concentration of date palm tree (DPT) and pine tree (PT) needles at 5%, 10%, 20%, and 30% by weight as additives in ceramic manufacturing.

Furthermore, ash was analyzed thorough XRD. The ashes have valuable components that make them suitable as a secondary additive in ceramic manufacturing. The chemical composition of ashes is shown in Table 2.

Table 2. Raw material composition.

Raw Materials	Composition							
Kaolinite (K)	Magnesium sodium phosphate compound	Sodium chloride compound	Villiaumite	Potassium aluminum silicate hydroxide	Borate phase	Chromium fluoride		
	26.8%	20.4%	15.6%	15.5%	13.1%	8.7%		
DPT ash	Lithium Oxide	Sulphur compounds	Vanadium	Bromide–chloride compounds	Potassium	Copper	Manganese, nickel, palladium, tin	Cobalt–tin–indium oxide
	42.1%	29.3%	6.9%	6.3%	5.9%	4.1%	3.6%	1.9%
PT ash	Copper sulphate pentahydrate	Magnesium silicate	Selenium compound	Copper oxide	Tin oxides compound	Barium compound	Barium gallium oxide hydroxide	
	33.9%	26.1%	18.7%	12.6%	4.4%	2.6%	1.7%	

2.3. Characterization of Sintered Ceramic

The manufactured ceramic specimens were tested as per the ASTM C373-88 and ASTM C326 standards. To ascertain the attributes of the fired specimens, different tests were conducted: mechanical properties (compressive strength and loss on ignition), reliability analysis (water absorption, Bulk density, and Saturated surface dry density), and thermal cycling.

Water absorption, bulk density, and SSD were analyzed according to ASTM 373-88 and loss on ignition (LOI) was calculated according to ASTM C326 standard by using Equation (1).

$$\text{Loss on ignition} = \frac{W_b - W_a}{W_b} \times 10 \quad (1)$$

where W_b and W_a are the weights of the brick before and after heating, respectively.

Figure 2 depicts the arrangement utilized for conducting the heating/cooling thermal cycle test, where the thermal efficiency of a specimen was evaluated. The heating setup had wooden box with a 200-watt bulb mounted at the top, a wooden box with aluminum foil reflected paper coated inside and outside of the wooden box, and a computer recording system connected with a data logger. In this test, a 200-watt bulb was used as the heating source, and the duration of the heating process was 160 min; after heating, the heat source was switched off and specimens were naturally allowed to cool down for another 75 min at room temperature. Each specimen was subjected to six thermal cycles. During this process, sample, surface temperature, and inner air temperature were calculated.

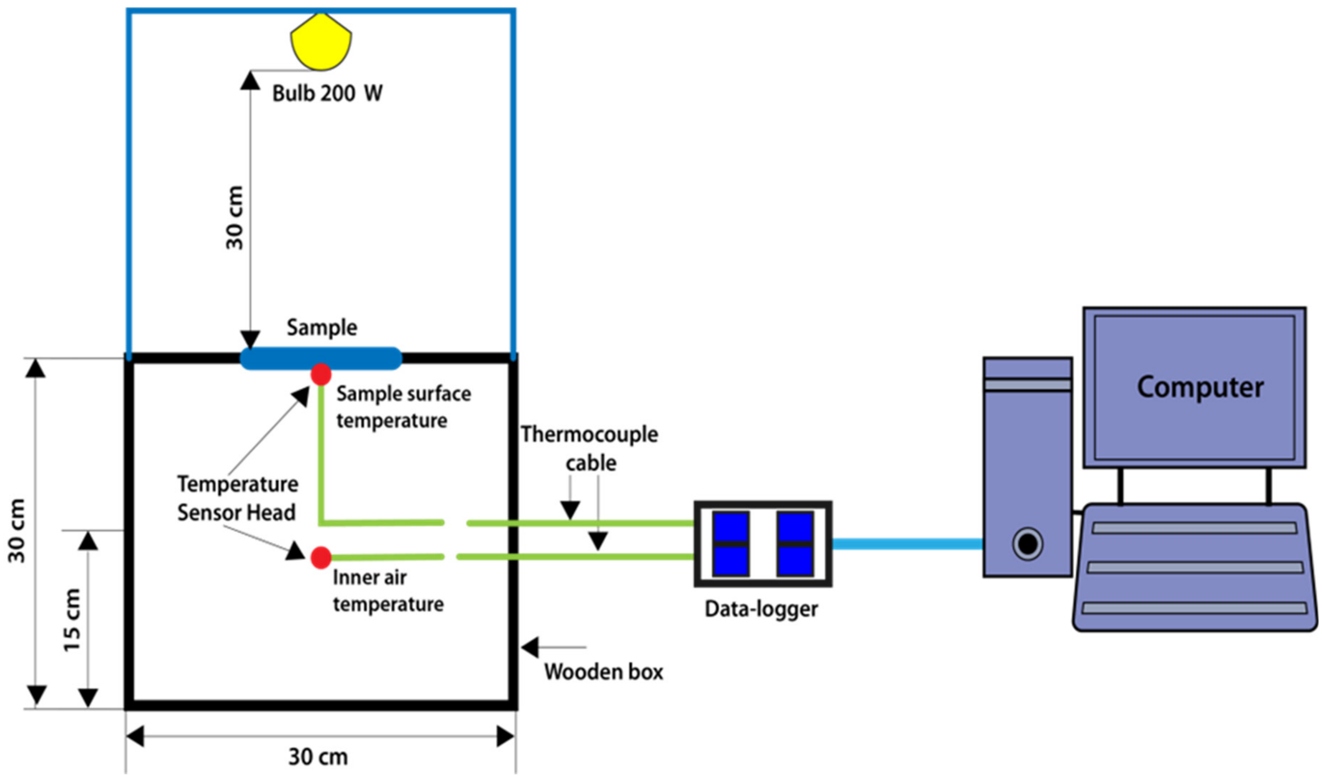

Figure 2. Schematic of heating/cooling thermal cycle test setup.

3. Results and Discussion

3.1. Properties of Brick Raw Materials and Nutshell Powder

X-Ray Diffraction (XRD)

Kaolinite is a clay mineral with a well-known crystalline structure. Figure 3 shows kaolinite has distinct sharp peaks, particularly between 20° and 40° 2θ, indicating a high degree of crystallinity. These peaks correspond to their layered silicate structure. DPT leaf ash and PT needle ash both show sharp peaks. The presence of these sharp peaks suggests that there are crystalline phases within the ash, and it is possible to assess their potential for use in ceramics production.

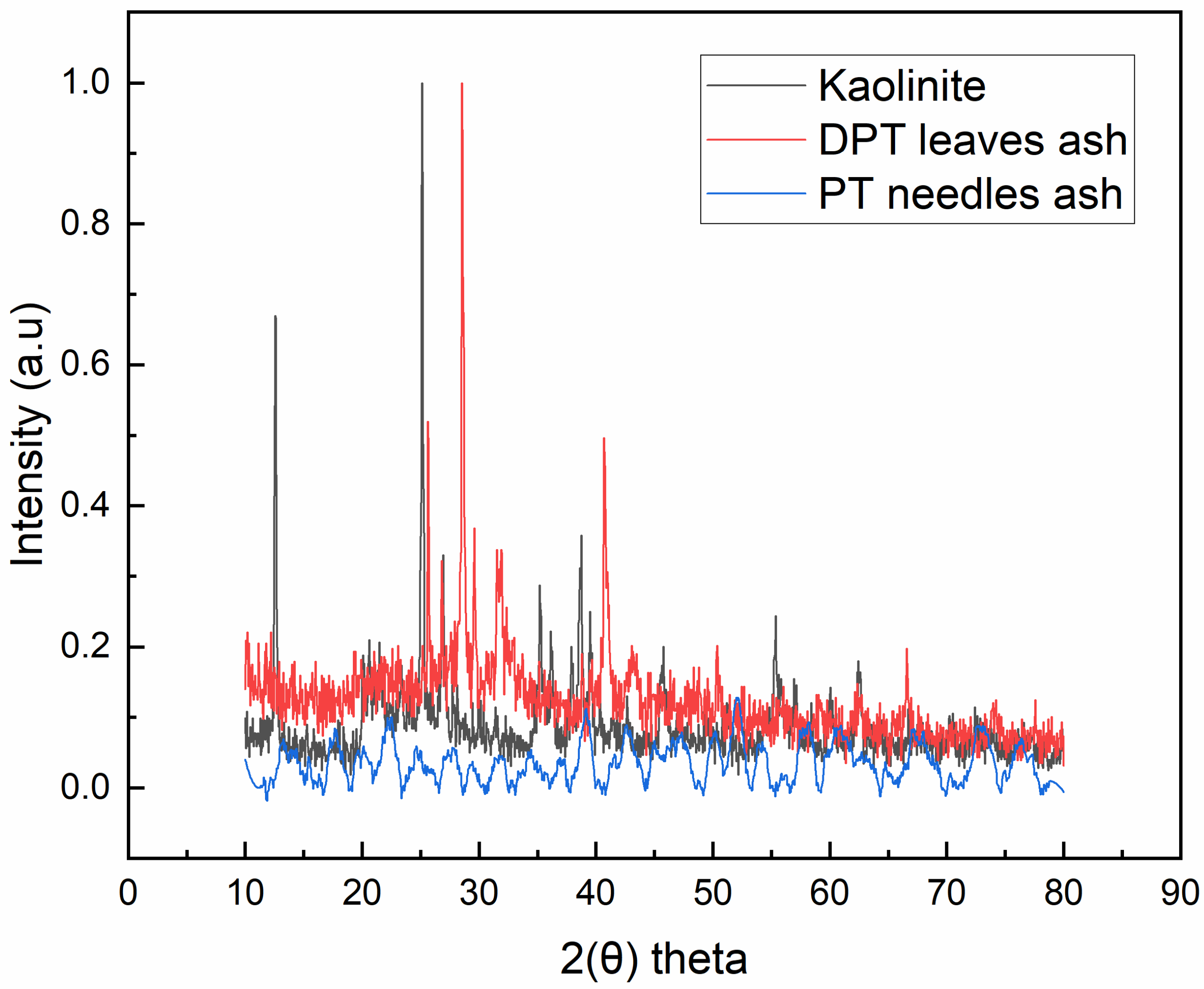

Figure 3. XRD of pine tree (PT) leaf ash, date palm tree (DPT) leaf ash, and Kaolinite (K).

3.2. Properties of Fired Ceramic Specimens

3.2.1. Loss on Ignition (LOI)

Weight loss upon ignition increases when pore-inducing agents are added. The incorporation of a component (whether organic or otherwise) into the clay blend leads to the development of porosity within the system during the drying and firing stages, facilitated by processes such as dihydroxylation and carbonate decomposition. The formation of voids results in a decrease in weight, as air is lighter than both the clay material and the pore-forming agents. Moreover, it stimulates the densification of the material, which could influence the compressive properties of the fired specimens, potentially compromising their structural stability [24]. Figure 4 represents the average result of five specimens with standard deviations (SDs) for DPT and PT of 0.5 and 0.4. The result reveals that by increasing the ash percentage of date palm tree (DPT) to 5, 10, 20, and 30% the loss on ignition of the tiles increases to 6.6, 13.8, 16.4, and 19.6%, respectively. In the same way, when increasing the ash percentage of pine trees (PTs) to 5, 10, 20, and 30%, the Loss on Ignition of the tiles increased to 15.9, 19.6, 20.2, and 22.1%. The DPT specimen showed a steady increase in weight loss, which indicates the presence of a consistent level of organic material and pore-inducing potential. On the other hand, PT ash causes higher weight loss, which suggests that it contains a greater portion of volatile components or more effective pore-forming substances.

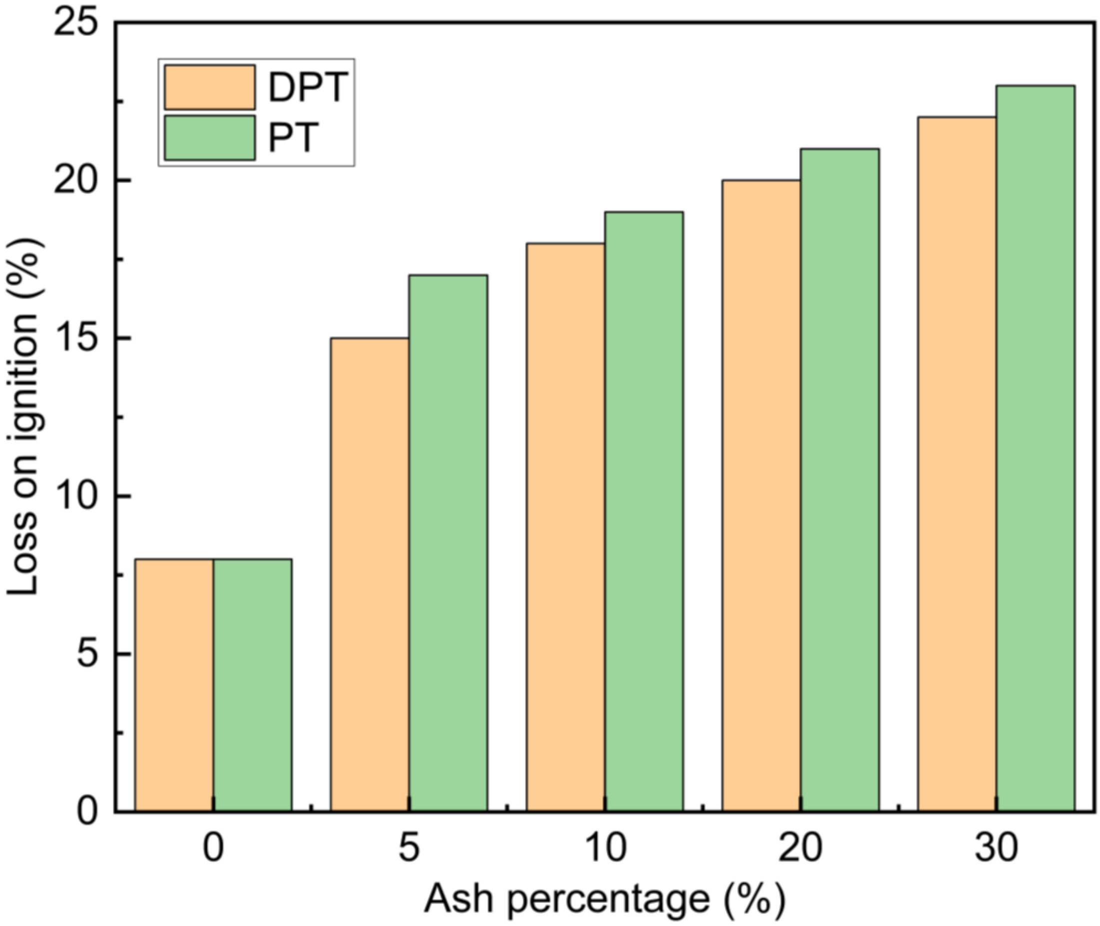

Figure 4. Loss on ignition vs. additives percentages.

3.2.2. Water Absorption

Ceramics tiles are categorized by water absorption rate, with impervious (extremely dense) having a water absorption rate of less than 0.5%, vitreous (high density) having a water absorption rate between 0.5 and 3%, semi-vitreous (medium density) having water absorption rate between 3 and 7%, and non-vitreous (low density) having a water absorption rate greater than 7%. The tested specimen shows a steep rise in water absorption rate when DPT leaves and PT needles were used as secondary additives. The water absorption for the baseline case was observed to be less than 0.5%. All fired specimens had water absorption rates between 0.5% and 7%. Figure 5 represents the average result of the five specimens with a standard deviation for DPT and PT of 0.3. The result reveals that by increasing the ash percentage of date palm trees (DPTs) to 5, 10, 20, and 30%, the water absorption of the tiles increases to 1.4, 2.2, 3.1, and 4.5%, respectively. When the pine tree leaf ash increases to 5, 10, 20, and 30%, the water absorption of tiles increases to 0.7, 0.8, 1.1, and 4.5%, respectively. The introduction of DPT ash and PT needle ash into the ceramic specimens was observed to cause a rise in the water absorption rate as the additive percentage increased. It can be analyzed from the results that as the ash percentage increases, more organic decomposable materials are introduced, which upon firing, leave behind voids creating pathways for water to infiltrate that enable the material to retain the water in it. Water absorption is directly proportional to additive percentage. At a lower ash percentage (5–20%), PT ash shows a slower increase as compared with DPT, which suggests PT ash is less effective at creating porosity due to differences in organic content, particular size, and chemical composition.

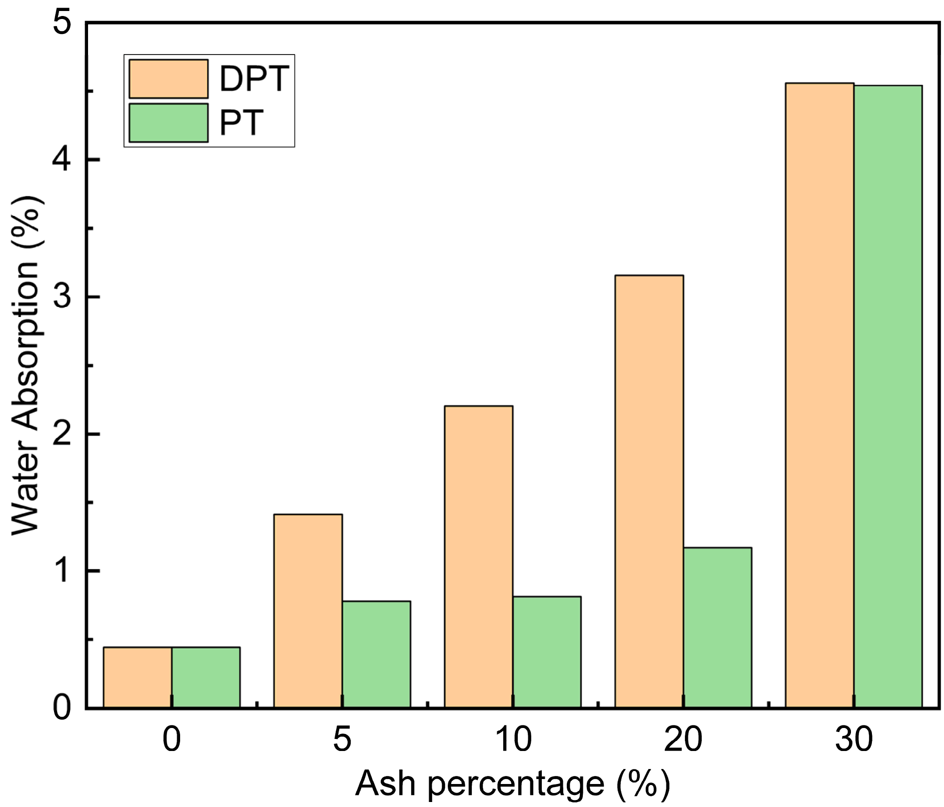

Figure 5. Water absorption vs. percentages of additives.

3.2.3. Bulk Density

Figure 6 represents the average result of five specimens with standard deviations for DPT and PT of 1.6 and 1.8. The result reveals that by increasing the ash percentage of date palm tree leaves (DPTs) to 5, 10, 20, and 30%, the density of the ceramic specimen decreases from 1797.8, 1768.2, and 1655.5 (kg/m^3) to 1457.7 (kg/m^3) and by increasing the percentage of pine tree ash (PT) to 5, 10, 20, and 30%, the density of the ceramic specimens decreases from 2138.8, 2010.9, 1836.3, and 1829.8 (kg/m^3), respectively. At 0% additives, the dry density is 2454.7 (kg/m^3), the base line (BL) value. When DPT and PT ash is added, during the firing process in which organic component volatilizes create pores, these air-filled pores are significantly lighter than the solid material they replace, which results in a decreasing density. DPT ash causes more reduction in density at higher percentages, likely due to higher organic content. PT ash specimen causes a less steep reduction. As density decreases, ceramic specimens offer various benefits in construction, including diminished structural dead load, improved ease of handling, and reduced transportation expenses.

3.2.4. Saturated Surface Dry Density (SSD)

Figure 7 represents the average result of five specimens with a standard deviation for DPT and PT of 1.8. The result reveals the effect of percentages of ash on the SSD of the ceramic specimens. The SSD of ceramics with 0% ash for the baseline (BL) had a value of 2465.6 kg/m^3. It was observed that by increasing the percentage of date palm tree (DPT) ash from 5 to 30%, the SSD of the ceramic specimens decreased from 1823.2 kg/m^3 to 1478.6 kg/m^3. PT ash shows slightly higher initial SSD compared to DPT ash at the same percentage, which indicates it may produce smaller pores at a lower concentration. By increasing the percentage of pine tree leaf ash by 5 to 30%, the SSD of the ceramic specimens also decreased from 2155.5 kg/m^3 to 1687.3 kg/m^3. Increased porosity reduced the bulk density of the materials including SSD, which is consider the saturated weight of the ceramic. A reduction in SSD indicates lightweight ceramic properties can be achieved.

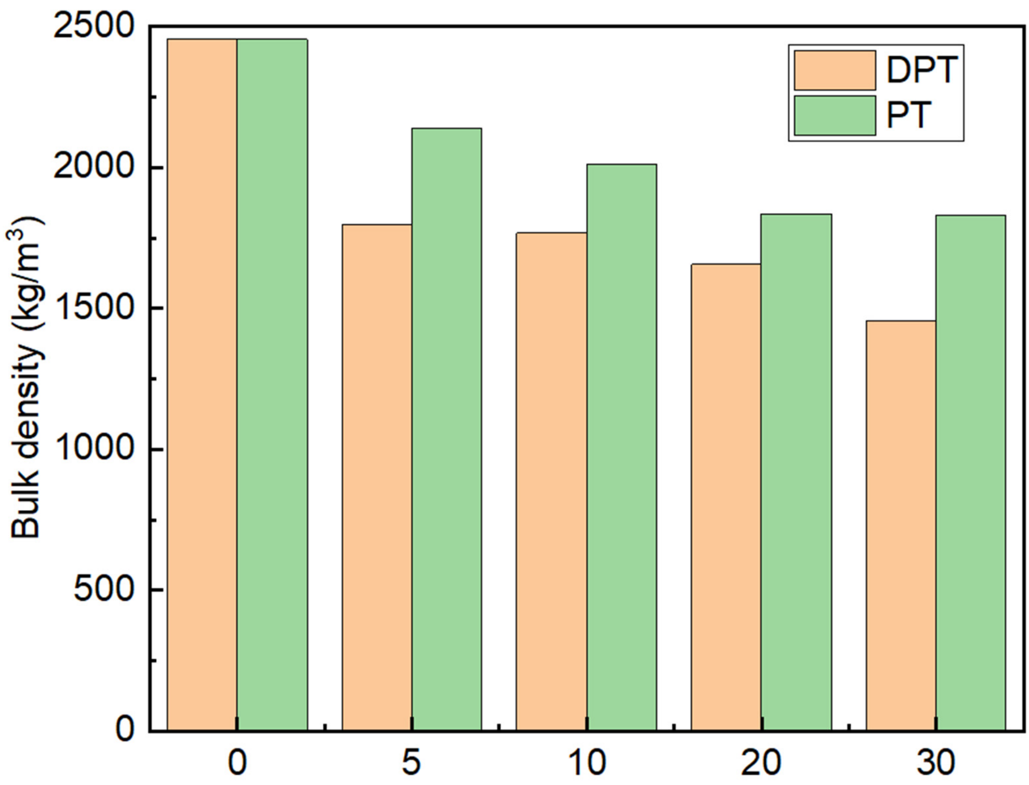

Figure 6. Bulk density vs. percentages of additives.

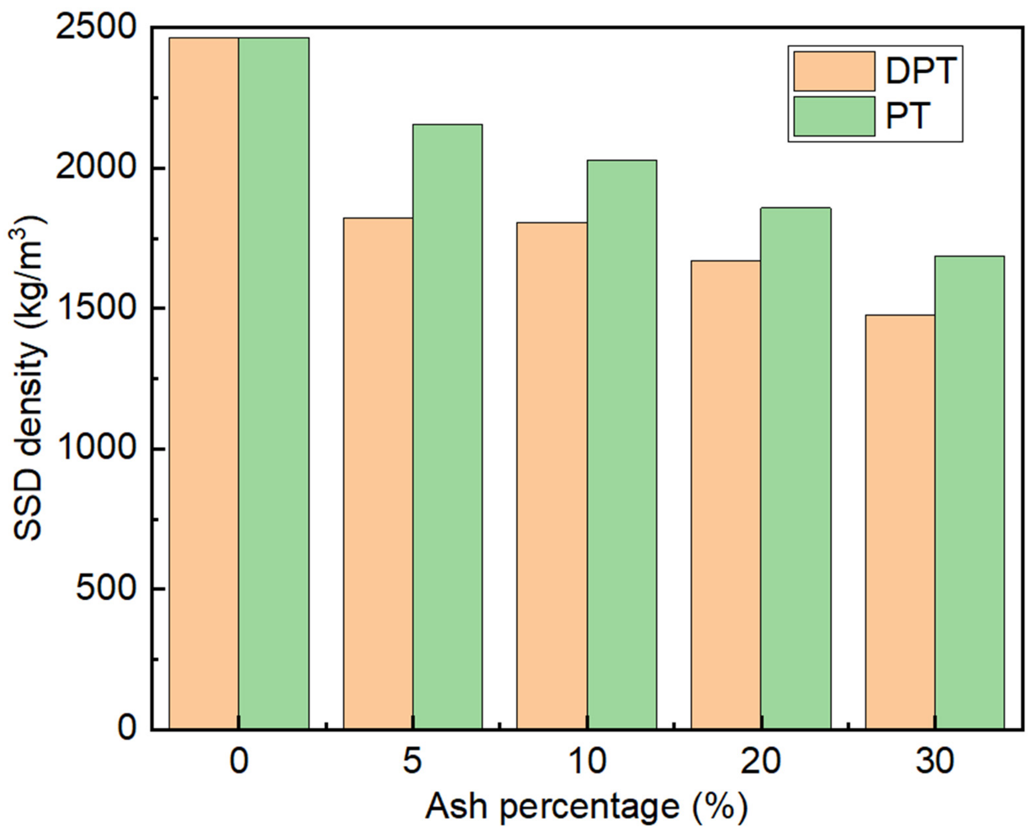

Figure 7. SSD vs. percentages of additives.

3.2.5. Weight per Unit Area

Figure 8 represents the average result of five specimens with a standard deviation for DPT and PT of 1.8 and 1.9. The result shows at 0% addition that the weight per unit area is 18.3 kg/m^2, and with the addition of 5 and 10% of DPT leaf ash, the weight per unit area increases from 15.8 and 16 kg/m^2 and then decreases at 20% and 30% to 15.9 to 8.8 kg/m^2, respectively; with the addition of PT leaf ash at 5 to 10%, the weight per unit area increases from 15.9 to 17.3 kg/m^2 and then decreases at 20% to 15.7 kg/m^2 and again increases at 30% to 15.8 kg/m^2. The minor increase and decrease in PT leaf specimens may indicate unburned residues left during the sintering process. This remaining mineral content compensates for the reduction caused by porosity. However, the fluctuation in weight unit per area remains well within the baseline (0%) specimen limit.

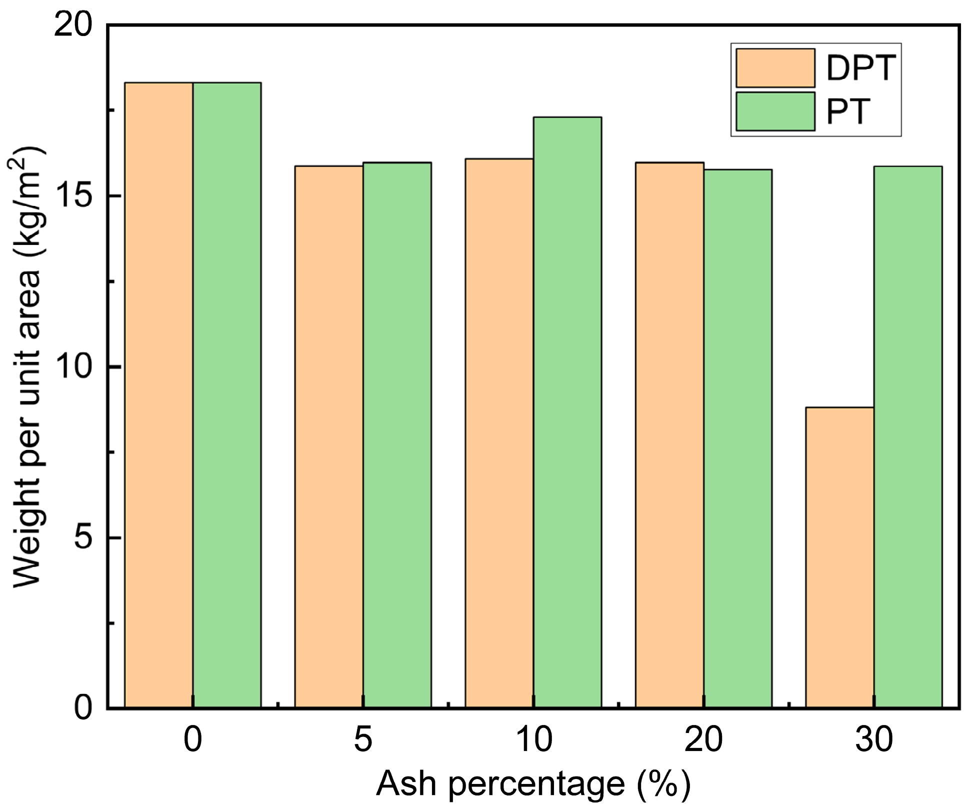

Figure 8. Weight per unit area vs. secondary additives.

3.2.6. Thermal Cycling

The peak surface temperature of a specimen, denoted ($T_{max\text{-}S}$), along with the peak air temperature within the containment box, referred to as ($T_{max\text{-}A}$), were calculated through the averaging of outcomes from six thermal cycles. Table 3 summarizes these results. The ($T_{max\text{-}S}$) values for DPT and PT were 43 ± 1.1, 50.4 ± 1.0 °C, 49.3 ± 1.0 °C, 48.2 ± 0.9 °C and 43 ± 1.1, 44 ± 1.3 °C, 46.5 ± 1.3 °C, and 52.1 ± 1.4 °C, respectively, and the corresponding ($T_{max\text{-}A}$) values were 30.8 ± 0.4, 33.8 ± 0.5 33.1 ± 0.4, 32.4 ± 0.3, and 30.8 ± 0.4, 31.6 ± 0.2, 32.8 ± 0.4, and 34.1 ± 0.6.

The thermal performance of DPT and PT is depicted in Figure 9. As demonstrated in Figure 9a,b, in comparison with 0% additive, DPT5, DPT10, DPT20 and PT5, PT10, and PT20 demonstrated an obviously higher inner surface temperature during a 160 min heating process, and they also exhibit a higher inner surface temperature during the 75 min cooling process, as demonstrated. These results reveal the energy absorption and release characteristics of the DPT and PT specimens during heating and cooling stages. Figure 9c,d portray the development of inner air temperature within the heating box using DPT and PT. The trends in obtained inner air temperature development resemble those presented in Figure 9a,b. This further validates the endothermic and exothermic characteristics and thermal conductivity performance of ceramic specimens containing additives. Thus, it is concluded that it can be used as heat sink in electronic and aerospace industries.

Table 3. Maximum surface temperatures ($T_{max\text{-}S}$) °C and maximum air temperature ($T_{max\text{-}A}$) °C of ceramics with addition of DPT, PT ash.

DPT Specimen	0%	5%	10%	20%
$T_{max\text{-}S}$	43 ± 1.1	50.4 ± 1.0	49.3 ± 1.0	48.2 ± 0.9
$T_{max\text{-}A}$	30.8 ± 0.4	33.8 ± 0.5	33.1 ± 0.4	32.4 ± 0.3
PT Specimens	**0%**	**5%**	**10%**	**20%**
$T_{max\text{-}S}$	43 ± 1.1	44 ± 1.3	46.5 ± 1.3	52.1 ± 1.4
$T_{max\text{-}A}$	30.8 ± 0.4	31.6 ± 0.2	32.8 ± 0.4	34.1 ± 0.6

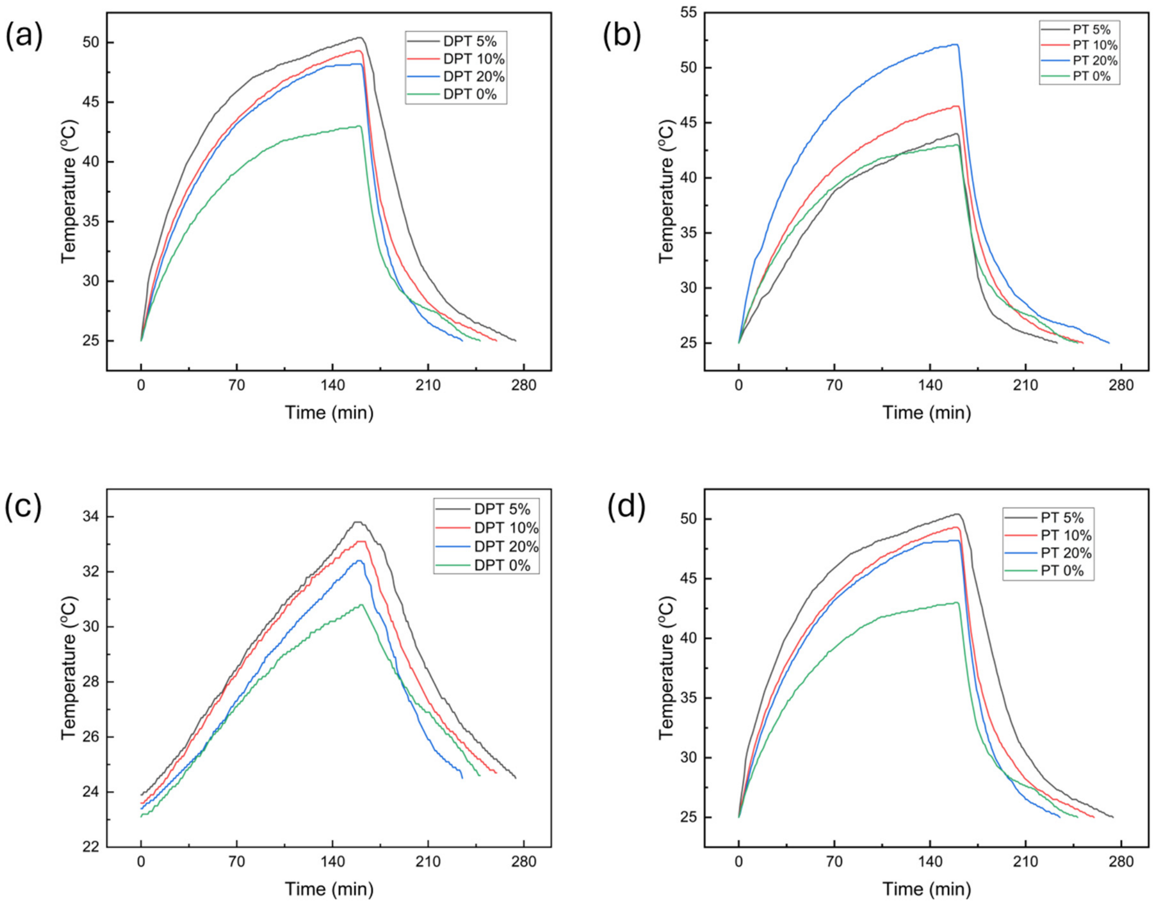

Figure 9. Thermal cycling of bricks: (**a**) DPT inner surface temp; (**b**) PT inner surface temp; (**c**) DPT inner air temp; (**d**) PT inner air temp.

4. Conclusions

It is viable to prepare sintered ceramics with the use of date palm tree leaf ash and pine tree needle ash, and good properties can be achieved. Loss on ignition increases with the amount of date palm and pine tree leaf ash increasing from 5% to 30%. The increase for DPT30 was 19.6% and for PT30, it was 22.1%. Water absorption increases with an increase in the secondary additive. This increase was 4.5% for DPT30 and PT30. The density decreases to 1457.7 kg/m^3 for DPT30, and 1829.8 kg/m^3 for PT30 with an increase in secondary additive. Thermal performance was investigated by heating and cooling cycles. It was observed that thermal performance increased with the increase in secondary additives; thus, the material can be used in applications where a higher heat transfer rate is required, e.g., electronics. These results have the potential to form a basis for setting a uniform criterion for the extensive utilization of these indigenous resources in the fields of electronics, aerospace, construction, and building engineering, alleviating environmental strain, curbing the exhaustion of China clay reserves, and most importantly, lowering the risk of forest fires.

Author Contributions: Conceptualization: M.A. (Mirza Awais) and I.S.; methodology: M.A. (Mirza Awais), A.M. and M.H.; writing—original draft: M.A. (Mirza Awais) and M.H.; data curation: M.H. and M.A. (Muhammad Asif); writing—review and editing: I.S., M.A. (Muhammad Asif) and A.M.; visualization: M.A. (Muhammad Asif); supervision: I.S.; project administration: A.M. and I.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: All the data related to this research is available in this article.

Conflicts of Interest: All authors declare that there are no conflicts of interest.

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