COMPOSITES APPLICATION IN RE-DESIGN OF A NOVEL TANDOOR OVEN

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ABSTRACT

Tandoor ovens are known cooking utilities with long histories of development and use in various cultures around the world. Nowadays, Tandoor ovens are an integral component in the mobile food truck industry due to their high efficiency for burning small quantity of fuel and retaining a large portion of the heat during cooking. This article presents a structural design case study towards the application of composite materials in order to improve the mechanical and thermal properties of mobile food trucks' oven, considering bending modulus, toughness, specific heat capacity and thermal conductivity performance criteria. It is shown that the addition of wood dust increases the thermal capacity of the clay for preserving more heat during the cooking process, resulting in less energy consumption. The experimental data also demonstrates that adding iron powder to clay enhance the bending modulus of the resulting material and thus, can be used as a suitable alternative in the structure of food truck ovens subjected to different types of thermal and mechanical loadings.

Keywords: *Composite materials, Tandoor ovens, Design optimization*

1 INTRODUCTION

Tandoor ovens are cooking utilities with long histories of development and use in various cultures around the world. They are vital in the preparation of some culinary dishes and are highly relevant to the food industry today. Regardless of the size, shape or region of origin, all tandoor ovens have the same operating principles. Namely, the ovens are made of e.g. clay in a cylindrical shape, with some sort of insulating material, such as concrete or mud, on the outside. The fire from the burning of the fuel in the bottom of the chamber, heats both the walls of the oven and air inside to a temperature of about 480°C. Tandoor ovens have particularly become popular in mobile food trucks, due to their convenient and easy-to-use applications and variety of cooking options that they offer. However, the utilization of Tandoor ovens in the mobile food trucks is also associated with some shortfalls. Namely, 1) they can lose thermal energy during the baking process, due to a large volume and high rate of food turnover to customers, 2) the consumption of propane throughout the day for maintaining the oven's inner temperature constant is costly, 3) they are heavy and difficult to relocate, and 4) given the mobile nature of the ovens, they are susceptible to undergoing impulse loads, which can cause fracture and mechanical failure of the brittle materials currently used in the oven. In this article, towards a new application of composite materials, a re-design of material system of the Tandoor ovens is considered to address some of the aforementioned issues.

2 MATERIALS AND METHODS

2.1 Proposed composite Tandoor oven design

Figure 1 demonstrates the proposed structural design of a typical tandoor oven. The inner layer is made of pure clay. While its porous surface is perfectly suitable for sticking breads to the inner wall of the tandoor, it has been for centuries a trusted and safe material to be in direct contact with food in hot temperatures. Despite the mentioned advantages of clay, it does not transfer the thermal energy properly due to its low thermal conductivity, yielding excess energy and fuel consumption to heat up the entire inner surface of the tandoor. To address this shortcoming, the use of a thin cylindrical layer of 304 stainless steel is proposed to more evenly distribute the thermal energy across the oven, leveraging the high thermal conductivity of this material. The third layer is a thick layer of composite clay which is implemented for better heat retention. Compared to pure clay, the composite clay is expected to have a higher specific heat capacity (Hiremath, C., 2014). Therefore, a thick wall of wood dust-clay composites can hold the heat required to bake more food. In addition, integrating wood dust with the pure clay reduces the thermal conductivity which prevents the loss of thermal energy through the oven's outer layer during the cooking process (Folaranmi, J., 2009). On the other hand, the addition of iron powder to clay is supposed to enhance the mechanical properties of the resulting composite material system, such as the material resistance to failure. Based on how the tandoor oven needs to be reinforced, the type of the additive material used in the composite layer is selected. Finally, a thin layer of fiberglass is used as an insulator to minimize the thermal energy loss from the oven's wall.

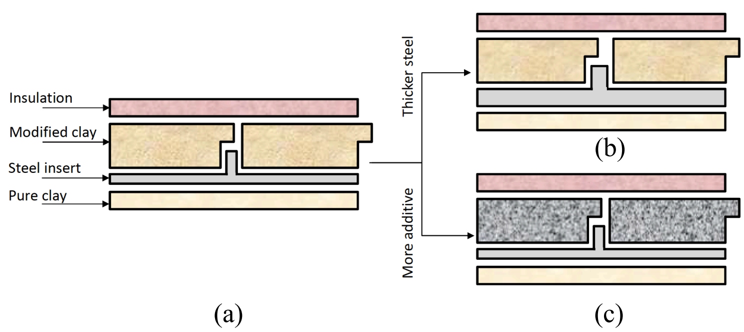
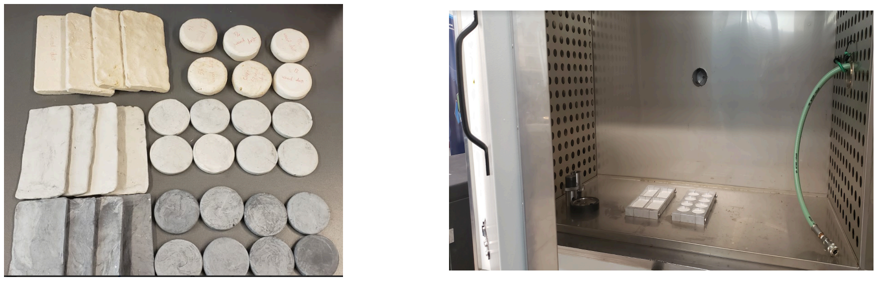


Figure 1: (a) The proposed material design of the tandoor oven; (b) the tandoor wall with a thicker layer of steel for faster heat distribution; (c) the tandoor wall setting with more additive material for better heat conservation or higher material strength.

2.2 Experimental Evolutions

For testing the thermo-mechanical performance of the proposed design, two shapes of specimens were used in this study. Cylindrical samples with the diameter of 6.35 cm and depth of 2.54 cm were used for thermal and physical experiments (Figure 2.a). For mechanical tests, samples with rectangular cube shapes (12.7 x 6.35 x 2.54 cm) were prepared. Two types of additives were used for comparison purposes: wood dust and iron powder. After adding the additive materials, both pure and composites clay samples were baked in the oven at the temperature of 130°C for a period of 45 minutes. The baked clays then go under mechanical and thermal tests to measure the corresponding properties (Figure 2.b).



(a) (b)

Figure 2: (a) Baked clay samples (bottom: clay with iron powder additive, center: pure clay, top: clay with wood dust additive); and (b) the clay samples in moulds being baked in the oven.

2.2.1 Thermal Conductivity and Volumetric Heat Capacity

LaserComp FOX50 instrument was used to measure the samples' thermal conductivity and volumetric heat capacity (Figure 3.a). The sample was positioned between two temperature-controlled plates. The plates created a user-defined temperature difference across the sample. The resulting heat flux (Q/A) from steady-state heat transfer through the specimen was measured by the device. The thermal conductivity was then calculated using the following equation:

$$\lambda = \frac{Q}{A}\frac{L}{\Delta T} \tag{1}$$

Where λ ($\frac{W}{m.K}$) is the thermal conductivity, $\frac{Q}{A}$ is the heat flux, L is the sample thickness and ΔT is the temperature difference between the two plates. Similar approach was used to measure the samples' volumetric heat capacity:

$$C_v = \frac{Q}{L.\Delta T} \tag{2}$$

2.2.2 Bending Modulus and Toughness

A three-point flexural test was used to determine the bending (flexural) modulus (tendency of the material to resist bending) and toughness (the amount of energy absorbed before material's failure) of the clay samples. The test was carried out using a universal testing machine (Instron series 5969) and 3-point bending fixture (ASTM D790) setup (Figure 2.b). The support span length was adjusted to 4.5 cm based on the samples dimension. The test then began with the a cross-head speed rate of 0.5 mm/min and continued until fracture occurred. The flexural modulus for rectangular bars can be calculated using the following equation:

$$E_f = \frac{L^3 m}{4bh^3} \tag{3}$$

where E_f (MPa) represents flexural modulus, L is support span, m is the gradient of the straight-line portion of the load deflection curve, b is the width of the sample, and h is depth or thickness of the sample.

The toughness of the samples was measured by calculating the area under strain stress curve before the fracture point.

2.2.3 Density

As the tandoor ovens are carried by mobile food trucks, a lighter oven design can considerably reduce the truck fuel consumption in the long run. Therefore, the density of the samples needs to be measured to assess their heaviness and the impact they have on the total weight of the ovens. The Electronic Densimeter MDS-300 (Figure 3.c) was utilized to measure the samples' densities based on the Archimedes' principle. The cylindrical samples were initially located on the weight sensor to measure the weights. The samples were then placed in the middle of the device's water tank to measure the under-water gravity. Using the two measured values, the sample's density was measured.

(a) (b) (c)

Figure 3: (a) LaserComp FOX50 used to measure thermal conductivity and volumetric heat capacity (web-1); (b) Instron 5969 load frame with 3 point bending fixture (ASTM D790) used to measure bending modulus and toughness (web-2); and (c) MDS-3000 equipment used to measure density.

3 RESULTS AND DISCUSSION

3.1 Thermal Properties

As represented in Table 1, the ability of the composite oven sample to conduct heat decreases as it is combined with wood dust, whereas its ability to store thermal energy increases. This is due to the fact that adding wood dust would increase the porosity of the samples which creates void spaces in the material and, thus, delays heat flow. Conversely, by adding iron powder, the sample can faster distribute thermal energy through its body. However, its capacity to conserve heat decreases due to the low heat capacity of the iron.

Table 1 Thermal properties of the tested clay samples.

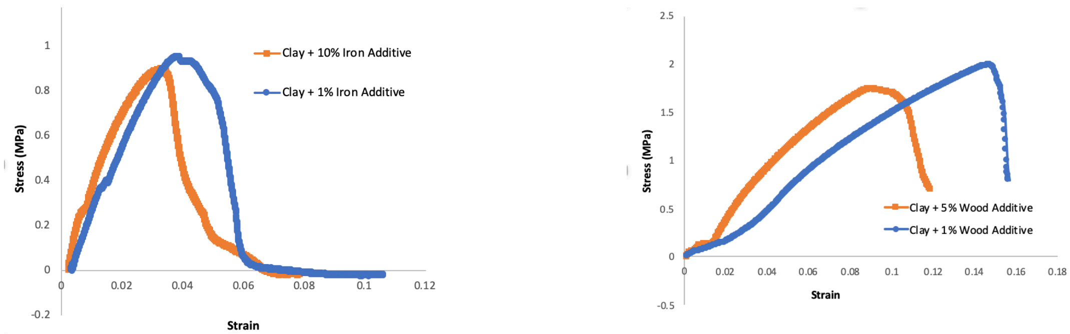
Sample	Thermal Conductivity (W/m.K)	Specific Heat Capacity (J/kg.K)
Pure Clay	0.25	753
Clay with 1% Wood Dust	0.24	776
Clay with 1% Iron Powder	1.02	722

3.2 Mechanical Properties

Table 2 presents a summary of the mechanical properties of the pure clay, composite clays with wood dust and composite clays with iron powder. The addition of wood dust has improved the bending modulus of the composite design. This improvement was more feasible when the iron powder was added. This is expected considering the very high modulus of iron material. Moreover, it is also realized that adding wood dust and iron powder decreases the toughness of the composite samples. The highest values for bending modulus (30.89 MPa) were detected in samples with 10% iron powder addition. These samples had also the lowest toughness values. Figure 4 demonstrates the stress-strain graph of the 3-point bending test for the clay samples with iron powder and wood dust additives.

Table 2 Mechanical properties of the tested clay samples.

Sample	Bending Modulus (MPa)	Specific Modulus $(MPa./(kg/m^3))$	Toughness (kJ/m^2)
Pure Clay	5.13	0.0035	0.74
Clay with 1% Wood Dust	9.935	0.0069	0.63
Clay with 5% Wood Dust	19.95	0.0148	0.53
Clay with 1% Iron Powder	20.03	0.0134	0.32
Clay with 10% Iron Powder	30.89	0.0202	0.27



(a) (b)

Figure 4: Stress-Strain response of (a) the clay samples with iron powder additives and (b) the clay samples clay with wood dust additives, under 3-point bending.

4 CONCLUSIONS AND FUTURE WORK

The addition of wood dust to pure clay increases the material's specific heat capacity and reduces its ability to conduct thermal energy. Such a composite material configuration may be used in the form of a thick layer in the Tandoor oven structure, in order to retain the generated heat for a longer period of time during the cooking process. Its lower thermal conductivity also helps prevent the escape of energy from the outer layers of the tandoor oven. It was shown that adding iron powder to the clay is an appropriate approach to enhance the bending modulus of the resulting composite material system. However, it was observed that the additives reduce the material's toughness and consequently, they lessen the cumulative energy required for material fracture. Since the tandoor ovens are mainly used in mobile food trucks, they may be prone to be affected by impulse loads during the transport. Therefore, further analysis (i.e., multi-objective optimization) needs to be performed in order to derive the optimal tradeoff between the resistance of the material to failure (modulus) and the required energy to crack the material (toughness).

In the next phase of this research, additional clay samples with different additive amounts can be made and their thermal, physical and mechanical properties be evaluated. Moreover, a finite element simulation of the tandoor oven can be established in order to better understand and characterize the behavior of the composite oven and its layers under different baking (heating) conditions in-service. Finally, multi-objective optimization approaches can be utilized to find the optimal additive materials amount and layer thicknesses for obtaining the desired performance of the tandoor oven regarding both thermal and mechanical properties.

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