CERAMIC TILES AS SUSTAINABLE, FUNCTIONAL AND INSULATING MATERIALS TO MITIGATE FIRE DAMAGE

M.Z. Naser[1], PhD PE, Pushparajah Thavarajah[2], PhD, D. K. Mallawa Arachchi[3]

[1]Glenn Department of Civil Engineering, Clemson University,
[2]Tile Council of North America, SC, USA
[3]Department of Mathematics, Clarkson University, NY, USA.

ABSTRACT

From a fire engineering perspective, this paper tests a hypothesis in which machine learning (ML) can be used to derive generalized material properties for ceramic tiles (CTs) as insulation under fire conditions. As such, this study showcases a thorough comparison between the behavior of commonly available CTs, and insulations in temperatures ranging between 25 to 1000 °C. Findings of this work advocate the use of CTs (or reclaimed CTs) as favorable finishing and interior lining materials to realize improved structural fire performance and fire response management. In addition, our analysis shows that CTs, when selected properly, can behave as thermal shields as opposed to synthetic composite materials often used in linings and flooring which could easily combust under fire conditions. In addition, we note that integrating ML techniques to analyze and develop material models is proving helpful in modernizing the fire assessment of materials and structures. The outcome of this work is expected to be of interest to architects, first responders, building officials, and structural engineers.

INTRODUCTION

In the construction industry, building materials include concrete, timber, and metals [1,2]. With the exception of timber, construction materials do not combust and have been shown to have an adequate performance and stability under elevated temperatures (within 25-500 °C) which is beneficial under fire conditions [3–5]. However, other types of materials can also be used on the outside or inside of buildings such as plastics, and their derivatives. Those materials melt and are easily combustible around 100-300 °C. For example, the 24-storey Grenfell tower (London, UK) underwent a major fire incident in 2017. The aforenoted fire started on 14 June 2017, and then quickly spread to upper floors on one side of the tower. This fire caused 72 deaths and over 70 injuries and significant property damage. Ongoing investigations tied the poor performance of the synthetic polymeric cladding to the rapid spread of fire [6,7].

Proper analysis on materials used in construction requires a thorough evaluation of both thermal and mechanical properties. While ambient testing is possible and with ease, testing materials at high temperatures is complex. This is due to the lack of: expertise, standardized testing methods, and testing equipment [8–10]. As a result, only a few studies on high-temperature properties are available [11–13]. From a fire protection point of view, thermal properties such as density, specific heat capacity, and thermal conductivity are of importance as they describe molecular-level chemical sensitivity to heat and physical integrity to fire. Heat causes chemical degradation via pyrolysis, an irreversible chemical reaction, or via thermal oxidation by both heat and oxygen. When the temperature reaches a critical point, the majority of bonds fail, resulting in disintegration.

It is for the above noted fire incident, and good material properties of traditional materials, that building codes often favor non-combustible or inert construction materials for fire resistance [14] since excessive temperature can permanently change material properties. This paper carries an investigation to examine the hypothesis that CTs, can be comparable to commonly used insulation materials. This paper reviews temperature-dependent thermal properties of CTs and then analyzes such properties using machine learning to develop generalized temperature-dependent models for these materials.

HIGH TEMPERATURE PROPERTIES

Thermal energy and material interaction result in atomic and molecular scale changes. Some of those changes are not reversible because materials may lose volatile compounds with heat, oxidize to form gases, or release fumes from burning materials. Therefore, a significant portion of heat-caused change can be summed by tracing property changes in density, heat capacity, and thermal conductivity. This section reviews these three properties for ceramic tiles.

Figure 1 shows the density changes in CTs with temperature from ambient to 1000°C based on a collection of studies [14–27]. This figure clearly shows two unique trends: (1) the density of CTs is fairly stable up to 1000°C, and (2) density of CTs could potentially slightly increase with rise in temperature. The stable nature of CTs is often attributed to the lack of atomic or molecular changes such as losing volatile compounds and oxidation products [28]. Another reason would be due to the firing-based fabrication of CTs which occurs at high temperatures. During this firing process, a number of processes take place. For example, raw materials lose water at ~100°C, organic matters decompose at ~200°C, they dehydroxylate at ~400°C, silica inverts at ~500 °C, carbonates decompose at ~800 °C, and finally sintering and glass transition occur at ~1000 °C [28]. Thus, once CTs cool down, these materials turn inert wherein all reactions including any other heat-absorbing and emitting reactions, have been completed (i.e. that is, their chemical composition is unlikely to change, thereby maintaining stable densities with heat up to 1000°C).

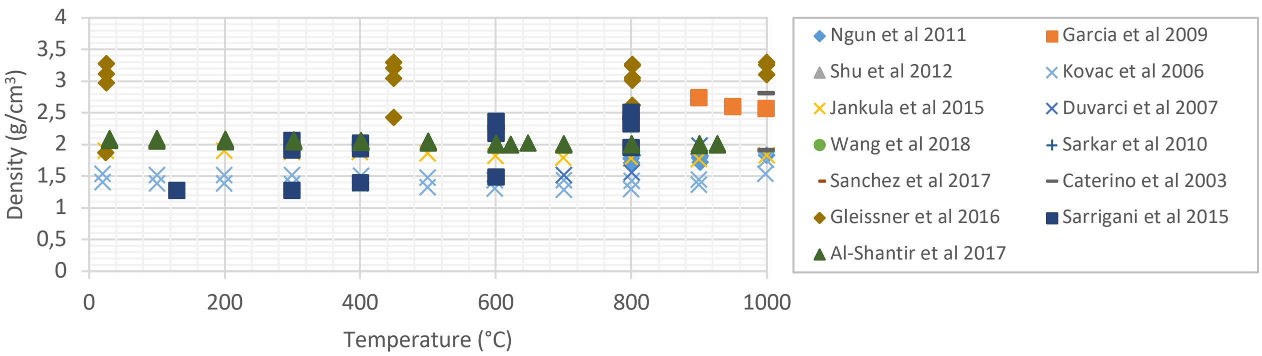
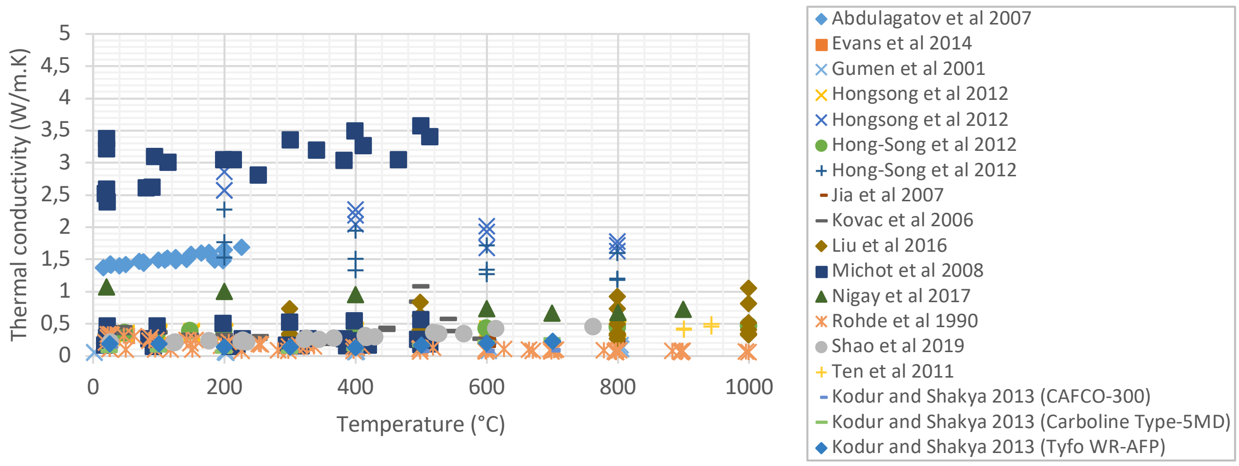
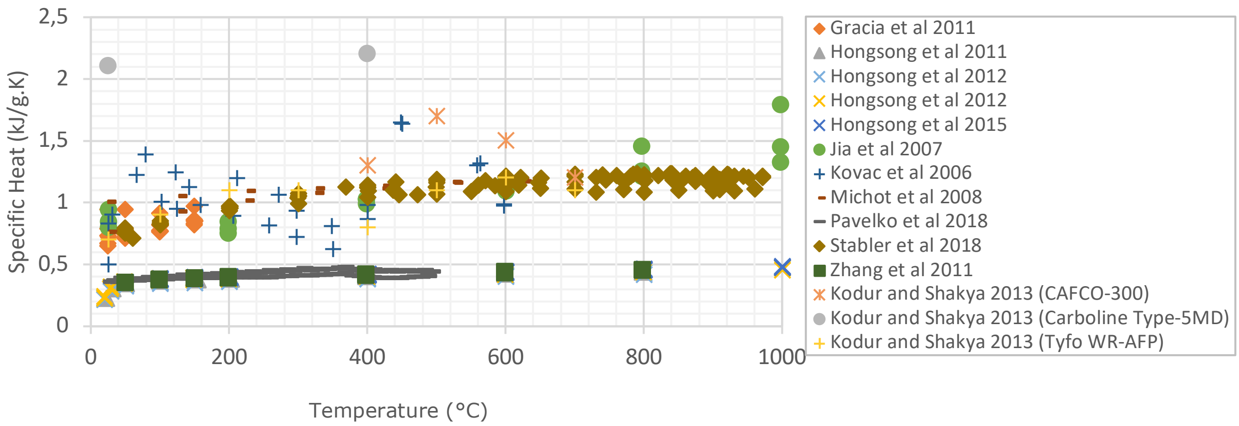


Fig. 1 *Variation of density in CTs as a function of temperature*

Thermal conductivity measures the ability of a material to transfer one unit of heat. Dehydration, Dehydroxylation and decarbonation reactions reduce thermal conductivity of CTs [29], as well as unevenly distributed high porosity which also reduce thermal conductivities [15,29–39](see Fig. 3). On the other hand, the specific heat describes the amount of heat required to raise a unit mass of material a unit temperature. Fig. 2 also shows that CTs have relatively constant heat capacities from ambient to 1000°C. Generally, water, organic compounds, and hydroxyl group absorb heat for molecular vibrations; the molecule motions results in kinetic energy transfer to neighboring particles. Lack of these compounds as free molecules to interact with heat could keep CT heat capacity low and nonfluctuating with temperature.



(a) *Variation of thermal conductivity*



(b) *Variation of specific heat*

Fig. 3 *Sample of properties of CTs under fire*

MACHINE LEARNING MODEL

The rationale behind using ML to arrive at a holistic understanding of CTs' behavior under high temperatures arises from the unique capability of ML to identify patterns hidden within observations. From this view, artificial neural networks (ANN) will be used. ANNs encompass a set of layers that are to be arranged in an optimized topology. Each of these layers contains a number of neurons. A typical illustration of an ANN is shown in Fig. 4. This figure shows three different layers. The first layer, called the input layer, contains the temperature-dependent material properties. The first layer is also connected to middle or hidden layer(s). The hidden layer(s) has the ability to establish linear and/or non-linear relations through transformative operations. On the other side, the hidden layer(s) is also connected to the output layer. In this work, a multilayer perception ANN that has "feed-forward back-propagation and supervised learning", as inspired by topology of the human brain, is used to develop the ANN [40], and seen in [41].

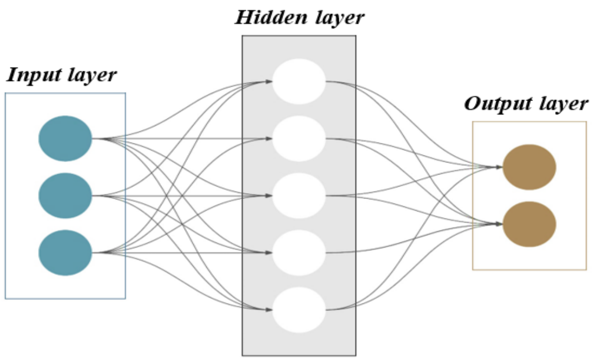


Fig. 4 *Layout of an ANN*

Once the above topology of the ANN is defined, the newly developed ANN is then used in the training stage. In this stage, the ANN is primed to understand how do CTs property patterns change under elevated temperatures. The goal is to realize a holistic interpretation that exemplifies the thermal properties of common CTs. An ANN can be built through the deep learning tool in MATLAB [42]. Before the ANN analysis starts, the compiled data, as obtained from a literature review and that was plotted earlier, is first randomly arranged to minimize and limit bias of a specific study, CT type, or testing procedure [43]. Then, this data is split into two sets. The first set (made of 70% of all data points) is used to train the ANN and the remaining set of data were used to test the performance of ANN. This split percentage was arrived at from suggestions of similar works [44,45].

The training stage of this ANN starts by analyzing temperature-dependent thermal properties (say, values of specific heat at target temperatures; 100, 200, 300… and 800°C, as reported by various researchers, and so on for other properties). This analysis applies random weightages in a series of transformative operations and transfer function (i.e. tangent etc.) [46].

Transformed outputs from this analysis are then totaled to generate predictions (i.e. ANN-predicted values for specific heat, thermal conductivity and density at particular temperatures, i.e. 25, 100, 200 ... 800°C).

The suitability of the ANN training is examined by two indicators (correlation coefficient (R) and mean absolute error (MAE)) (see Eqs. 1 and 2) [47]. It is due to this good agreement that it can be inferred that the developed AI model was able to capture the temperature-dependent behavior of common CTs.

Correlation coefficient (R):

$$R = \frac{\sum_{i=1}^{n}(A_i - \overline{A}_i)(P_i - \overline{P}_i)}{\sum_{i=1}^{n}(A_i - \overline{A}_i)^2 \sum_{i=1}^{n}(P_i - \overline{P}_i)^2} \quad \text{Eq. 1}$$

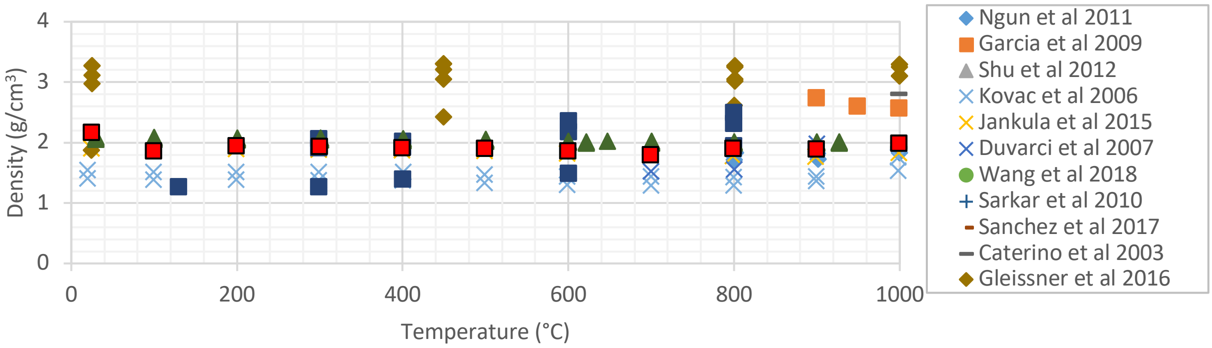
where P_i and A_i are predicted and actual values, respectively.

Mean average error (MAE):

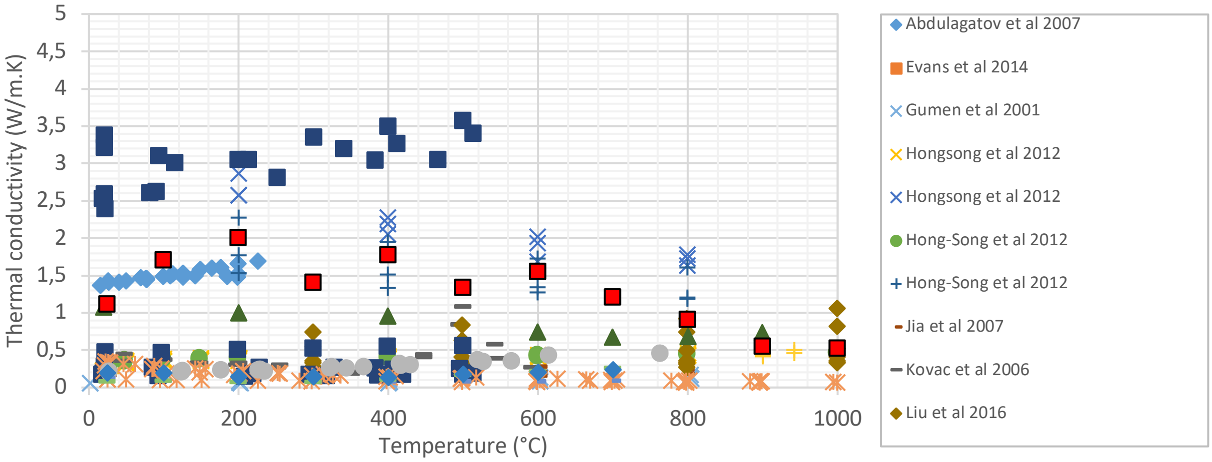
$$MAE = \frac{\sum_{i=1}^{n}|E_i|}{n} \quad \text{Eq. 2}$$

where E is the error between predicted and actual values for a particular temperature, n is the total number of observations.

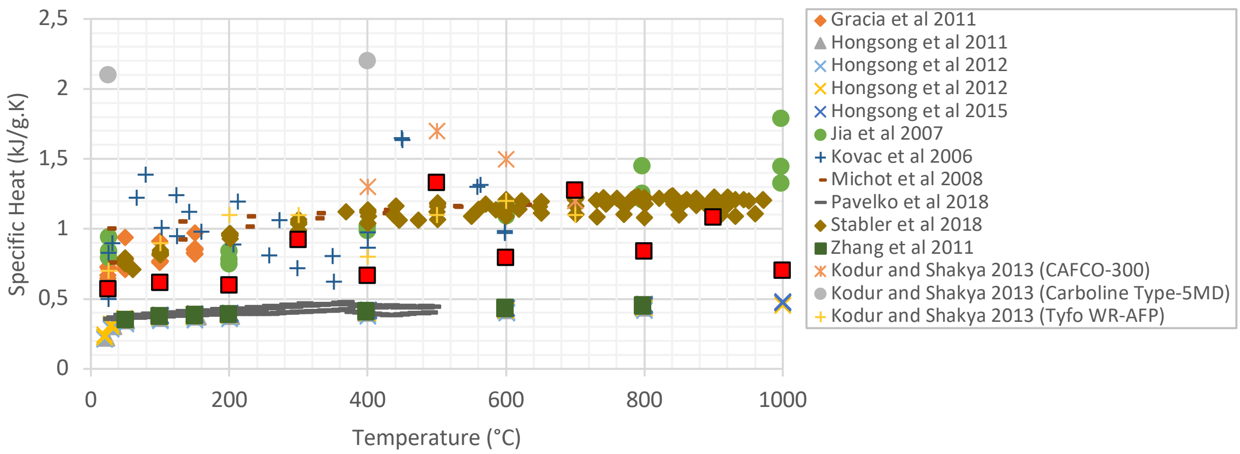
In general, the presented analysis shows that CTs have superior thermal properties that are similar to those found with concrete (from fire resistance point of view) and hence are favorable for use in construction as finishing or lining materials. Ceramic tiles also share main characteristics of other insulation materials such as spray-applied fire resistive materials (SFRM) and since CTs do not decompose, or undergo significant degradation under fire conditions, like SFRMs, the use of CTs could be much more feasible and economical as these materials may not require being replaced post a fire incident. Figure 5 shows the ANN-predicted properties of CT.



(a) Density (R = 97.2%, MAE = 13.3 kg/m³)



(a) (b) Thermal conductivity (R = 97.1%, MAE = 0.07 W/m.K)



(b) Specific heat (R = 99.8%, MAE = 0.59 J/kg.k)

Fig. 5 *Comparison between predicted and measured thermal properties*

CONCLUSIONS

This paper presents a comparison between premature-dependent thermal material models for ceramic tiles as well as used ML to predict general thermal properties for CT under elevated temperatures. This derivation was carried out by applying a coupled sequence of Artificial Neural Networks (ANNs). Other conclusions from the results of this investigation are also listed herein:

- Ceramic tiles are effective thermal insulating materials due to their inert nature.
- There seems to be a lack of general guidance on conducting and developing material tests for building materials including ceramic tiles at elevated temperatures.
- ML techniques can analyze and develop material models (such as ceramic tiles) and will be helpful in modernizing fire assessment of materials and structures.

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