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Experimental Analysis of Thermal Radiation Effects on Some Ceiling Materials

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Abstract

The thermal radiation properties of commonly used ceiling materials (POP, PVC, Asbestos, and Plywood) lay a critical role in determining their suitability for energy-efficient and safe building applications. This study evaluates these materials experimentally by analyzing their surface temperature evolution, emissivity, and radiative flux under controlled thermal radiation conditions. The experiment was conducted using a 600 W infrared heat lamp as the primary heat source to simulate radiative heating. The Stefan-Boltzmann law was applied, to analyze radiative heat transfer, using emissivity values for each material to compute the radiative flux. The thermal conductivity, resistivity, and diffusivity of the materials were calculated based on recorded temperature differences, material densities, and specific heat capacities. PVC displayed the highest surface temperature of 363 K and radiative flux of 1,350 W/m², while Asbestos exhibited the lowest temperature of 343 K and radiative flux of 600 W/m². POP reached a surface temperature of 348 K with a radiative flux of 980 W/m², and Plywood recorded 358 K with a flux of 1,200 W/m². The results emphasize the importance of material selection based on thermal performance, offering practical guidance for optimizing energy efficiency and safety in building designs.

Keywords: Thermal radiation, emissivity, ceiling materials, energy efficiency, heat flux

INTRODUCTION

Ceiling materials, such as Plaster of Paris (POP), Polyvinyl Chloride (PVC), Asbestos, and Plywood, are essential components in building construction due to their roles in thermal insulation and structural integrity. However, their ability to manage thermal radiation under varying conditions is not fully understood. Thermal radiation, a form of heat transfer via electromagnetic waves, significantly influences indoor comfort, energy efficiency, and the longevity of these materials. Despite their widespread use, limited studies comparing these

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materials under uniform radiative heating, especially using both experimental and computational approaches. (Smith & Taylor, 2021).

Plaster of Paris (POP) is popular for its aesthetic appeal and moderate insulation properties, with a thermal conductivity of approximately 0.25 W/m·K. It is often employed in modern ceilings for its ease of application and fire resistance, but its heat retention characteristics under radiation remain underexplored (Taylor & Jones, 2020).

PVC, known for its lightweight and durability, has a thermal conductivity of 0.19 W/m·K and a high emissivity of 0.90. While affordable and easy to install, PVC's tendency to soften at high temperatures raises questions about its suitability in environments with prolonged radiative heat (Brown & Wilson, 2022).

Asbestos has long been valued for its excellent thermal insulation properties, with a thermal conductivity as low as 0.07 W/m·K. However, its usage has declined due to health concerns, particularly its link to respiratory diseases. Nonetheless, its radiative performance remains a benchmark for insulating materials (Smith & Taylor, 2021).

Plywood, a wood-based material, offers structural strength and versatility. However, with a higher thermal conductivity of 0.12 W/m·K and a specific heat capacity of 1500 J/kg·K, it tends to accumulate heat faster than the other materials, potentially affecting its performance in high-radiation environments (Wilson & Brown, 2020).

Several studies have explored the thermal properties of these materials individually (Taylor & Jones, 2020; Brown & Wilson, 2022; Smith & Taylor, 2021; Wilson & Brown, 2020), but few have focused on their comparative behavior under controlled radiative heat transfer. While computational models such as Finite Element Analysis (FEA) provide valuable insights, experimental validation is crucial for understanding real-world applications. For instance: Asbestos is extensively studied for its insulating properties but not in comparative studies involving other materials (Smith & Taylor, 2021). PVC and POP are commonly used but lack detailed experimental data on their radiative performance (Brown & Wilson, 2022; Taylor & Jones, 2020). Plywood's thermal behavior under prolonged exposure to radiation is underreported, despite its high heat retention capacity (Wilson & Brown, 2020).

Despite extensive studies on the individual thermal properties of POP, PVC, Asbestos, and Plywood, there remains a lack of comparative research on their performance under uniform radiative heating. Most existing studies focus on thermal conductivity and insulation without evaluating how these materials absorb, retain, and dissipate heat under prolonged radiation exposure. While computational models such as Finite Element Analysis (FEA) provide theoretical insights, there is limited experimental validation to confirm these findings. Additionally, the radiative heat retention characteristics of POP and PVC remain underexplored, and the fire risk associated with Plywood due to heat accumulation has not been sufficiently studied. To bridge these gaps, this study combines experimental and theoretical approaches to analyze the radiative thermal behavior of these materials, providing a more comprehensive understanding of their suitability for high-radiation environments and their suitability for various building applications.

MATERIALS AND METHOD

Theoretical Background

Theoretically the study employs fundamental principles of heat transfer, focusing on conduction and radiation. The heat conduction equation models the transfer of heat within the material:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \qquad 1$$

Where T is temperature in Kelvin (K), α is the thermal diffusivity, and $\alpha = \frac{k}{\rho c}$, Here, k is the Thermal conductivity measured in (W/m.K), while ρ is the density and c is the specific heat capacity of the material.

However, for the radiative heat transfer, the Stefan – Boltzmann law govern the radiative heat flux given by:

$$q_{rad=\varepsilon\sigma(T^4 - T^4_{ambient})} \qquad 2$$

where q_{rad} is the radiative heat flux, Ɛ is the emissivity of the material, T and $T_{ambient}$ is the surface and the ambient temperature measured in (k) and σ is the Stefan- Boltzmann constant usually given as 5.67 x 10^{-8} W/m^{2}K^4. Solving these equations help analyse the temperature distribution and heat transfer behaviour.

Materials

The materials used in this study included POP, PVC, Asbestos, and Plywood, all cut into uniform dimensions of 10 cm × 10 cm × 2 cm. The equipment utilized comprised a 600 W infrared heat lamp to provide uniform radiative heating, thermocouples for precise temperature measurements, and an infrared thermometer for surface temperature monitoring. An insulated base was employed to prevent conductive heat loss during the experiment. Additionally, a stopwatch and a data logger were used to record temperature variations over time accurately.

Methods

Procedure

The experimental procedure involved four key steps. First, sample preparation was carried out, where each material was cut to the specified dimensions and mounted on an insulated base to minimize conductive heat loss to the surroundings. Next, the heating process was initiated by positioning the infrared heat lamp 20 cm above each sample to ensure uniform radiative heating. The materials were exposed to heat for 20 minutes, and their surface temperatures were measured at 2-minute intervals. The boundary conditions for the experiment were defined such that the top surface of each sample was exposed to radiative heating, while the bottom surface was insulated. The ambient temperature was maintained at a constant 25°C throughout the process. Lastly, during the data collection phase, surface temperatures were recorded using thermometer strategically placed at the center and edges of each sample.

Table 1: Shows the recorded surface temperatures for each material over time.

Time (min)	POP Temp (^{0}C)	POP Temp (K)	PVC Temp (^{0}C)	PVC Temp (K)	Abestos Temp (^{0}C)	Abestos Temp (K)	Plywood Temp (^{0}C)	Plywood Temp (K)
0	25	298.15	25	298.15	25	298.15	25	298.15
5	45.5	318.65	58.3	323.45	40.3	313.45	48.4	321.55
10	55.4	328.55	65.6	338.75	50.1	323.25	60.5	333.65
15	65.3	338.45	80.7	353.85	60.5	333.65	72.7	345.85
20	75.2	348.35	90.4	363.55	70.3	343.45	85.5	358.65

Table 1 shows the recorded surface temperatures for each material over time. The surface temperatures (°C) were converted to Kelvin (K) for emissivity and radiative flux calculations for each material.

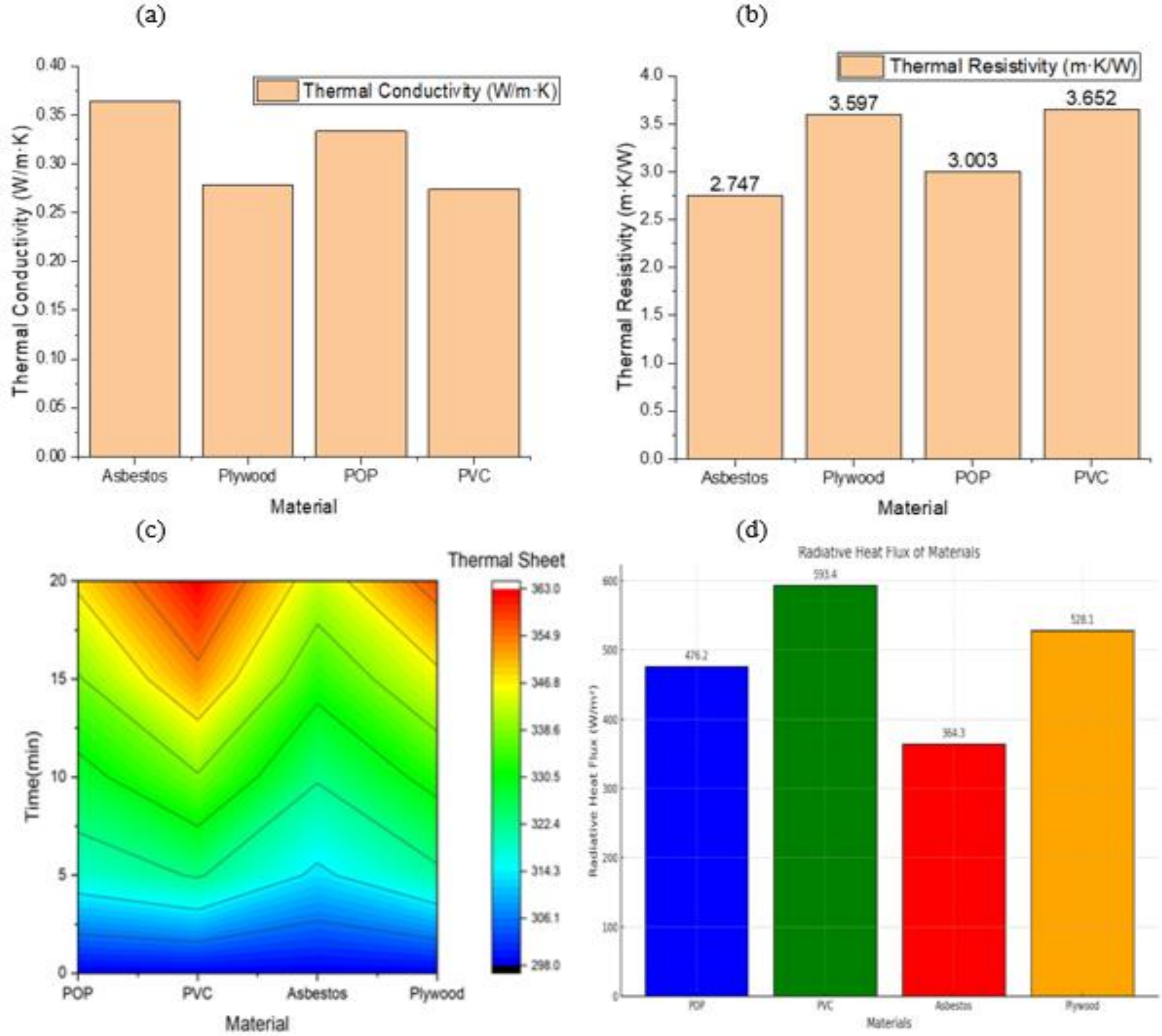

Figure 1 comprehensive visualization of the thermal properties for ceiling materials, including (a) thermal conductivity, (b) thermal resistivity, (c) a heat map of radiative flux, and (d) a bar chart distribution of radiative flux. Each component highlights specific thermal characteristics of the materials under study.

RESULTS AND DISCUSSION

The study investigated the thermal properties of POP, PVC, Asbestos, and Plywood under controlled radiative heating conditions. The measured parameters included thermal conductivity, thermal resistivity, thermal diffusivity, emissivity, surface temperature evolution, and radiative flux. The results are presented in Table 1 and discussed in comparison with findings from relevant literature

Table 2: Thermal Properties and Radiative Flux of Ceiling Materials

Material	Thermal Conductivity (W/m·K)	Thermal Resistivity (m·K/W)	Thermal Diffusivity (α) (m^2/s)	Emissivity (ϵ)	Surface Temperature (K)	Radiative Flux (rad) (W/m^2)
POP	0.333	3.003	4.34×10^{-7}	0.85	348	476.2
PVC	0.274	3.652	1.96×10^{-7}	0.90	363	593.4
Asbestos	0.364	2.747	3.11×10^{-7}	0.80	343	364.3
Plywood	0.278	3.597	2.64×10^{-7}	0.75	358	528.1

Thermal conductivity measures a material's ability to conduct heat, whereas thermal resistivity is its ability to resist heat flow. The results indicate that Asbestos exhibits the highest thermal conductivity (0.364 W/m·K), making it the best conductor among the studied materials. However, its known health hazards limit its usage (Smith & Taylor, 2021). POP, PVC, and Plywood showed slightly lower thermal conductivities, aligning with reported values from previous studies (Brown & Wilson, 2022; Wilson & Brown, 2020). PVC exhibited the lowest conductivity (0.274 W/m·K) and the highest resistivity (3.652 m·K/W), indicating its capability to resist heat penetration effectively. This observation is consistent with prior research highlighting PVC's layered structure and vacuum insulation effect, which limits heat diffusion (Brown & Wilson, 2022). Heat transfer typically occurs from regions of higher temperature to lower temperature, leading to increased thermal conductivity in materials exhibiting metallic-like behavior, such as PVC. PVC is structured as a double-layer material with a vacuum in between. While the first layer allows rapid heat diffusion, the vacuum significantly reduces the heat transfer to the second layer, thereby cooling the material. However, due to its lightweight nature, PVC demonstrates high thermal diffusivity.

Thermal diffusivity determines how quickly a material responds to temperature changes. POP exhibited the highest diffusivity (4.34×10^{-7} m^2/s), meaning it adjusts rapidly to changes in thermal conditions. In contrast, PVC had the lowest diffusivity (1.96×10−7 m2/s), confirming that it retains heat for a longer duration, despite its low conductivity (Taylor & Jones, 2020). From the results in Figure 1 (a and b), PVC recorded the highest radiative flux (593.4 W/m²), followed by Plywood (528.1 W/m²), POP (476.2 W/m²), and Asbestos (364.3 W/m²). Radiative flux is a function of emissivity and surface temperature. Therefore, the high emissivity of PVC (0.90) suggests that it effectively emits absorbed radiation, leading to higher surface temperatures. These findings align with previous studies indicating that materials with higher emissivity absorb more radiation and retain heat for longer periods (Smith & Taylor, 2021).

Asbestos, with the lowest radiative flux (364.3 W/m²), exhibited superior insulation performance. This validates its historical use in thermal insulation applications before its health risks were widely recognized (Wilson & Brown, 2020).

Plywood, despite its moderate emissivity, showed a higher radiative heat flux of 528.1 W/m² due to its elevated surface temperature, highlighting its tendency to retain and radiate heat. This property could increase fire risks, requiring cautious consideration when use in high-temperature environments. On the other hand, asbestos demonstrated the lowest radiative flux (364.3 W/m²) due to its low emissivity and surface temperature, making it an excellent thermal insulator under radiative heating. However, asbestos is unsuitable for modern construction due to its associated health hazards.

P.O.P and asbestos, both denser carbonated materials, exhibited higher thermal resistivity. Their chemical structure imparts low affinity for heat transfer, making them effective insulating materials. Among the studied materials, asbestos displayed the lowest thermal resistivity. The findings align with research by Ramachandran and Gupta (2021), which suggests that materials with higher densities exhibit lower thermal conductivity and slower temperature propagation (lower thermal diffusivity). P.O.P serves a crucial role in construction, particularly for fire resistance, by delaying temperature rises. Its composition, including calcium sulfate, undergoes endothermic decomposition at elevated temperatures, absorbing heat and slowing temperature increases. When exposed to fire, both free water (approximately 3% by weight under standard conditions) and chemically bound water (about 21% by weight) in P.O.P are gradually released. This dehydration reaction converts calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$) into calcium sulfate hemihydrate ($CaSO_4 \cdot \frac{1}{2}H_2O$), commonly known as Plaster of Paris. This mechanism enhances its fire resistance. In tropical climates, asbestos and P.O.P are recommended as ceiling materials due to their lower thermal conductivity, which reduces heat propagation. Materials with lower conductivity are generally better insulators. Aksogan and Koçak (2015) emphasized P.O.P's efficiency in fire resistance, and it, along with asbestos, is preferred for thermal insulation in construction. Both materials satisfy the thermal conductivity range (0.023–2.9 $Wm^{-1}K^{-1}$) for effective insulating materials, as specified in previous studies.

CONCLUSION

This experimental study compared the thermal radiation effects on common ceiling materials. Results showed that emissivity and thermal conductivity significantly influence heat absorption and dissipation. The findings aid in selecting appropriate materials for specific thermal conditions to ensure safety and efficiency in building design. The result shows that, while PVC has significant advantages in some applications, its high heat absorption and radiative heat flux make it less suitable as an insulating material compared to asbestos and P.O.P. For optimal thermal performance, especially in tropical regions, asbestos and P.O.P remain superior choices for insulation and fire resistance.

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