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ANALYSIS OF EFFECTIVE THERMAL PROPERTIES OF LOCALLY AVAILABLE JUTE PARTICLE BOARDS

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Abstract

Jute, renowned for its affordability and versatile properties, presents an innovative alternative to foam-based thermal insulators. This study explores the potential of Jute Particle Board (JPB), a locally available and sustainable material, as a building insulation material. The research investigates JPB's thermal conductivity and its impact on indoor temperature through a preliminary numerical simulation. Lee's Disc method is used for measuring the thermal conductivity of poorly conducting materials like jute composites and particle boards. The calculated thermal conductivity of JPB was 0.175559 W/mK which falls within the range of conventional particleboards, offering moderate insulation but not surpassing dedicated insulation materials. However, JPB demonstrates significantly higher thermal resistance compared to commonly used building materials like bricks and concrete blocks. This value suggests JPB's potential as an additional insulating layer to improve building envelope performance. Additionally, numerical modeling is employed to assess the performance of JPB in a typical Bangladeshi household setting utilizing Ansys steady state thermal analysis. The successful implementation of JPB insulation can lead to reduced reliance on imported materials, promotion of local resources and improved energy efficiency in Bangladeshi homes.

Keywords: *Jute, Thermal Insulation, Lee's Disc Method, Ansys Steady State Simulation.*

1. Introduction

Jute has always been a matter of interest to scientists and scholars. Several studies have investigated the thermal insulating properties of jute. Samanta et al. [1] evaluated needle punched jute nonwovens and found them to offer good thermal insulation comparable to mineral wool at specific densities. Debnath et al. [2] explored the potential of jute-based blended fabrics, demonstrating that sandwich-blended jute with materials like polypropylene or acrylic resulted in superior thermal insulation compared to homogeneous blends. These findings suggest that the jute's structure and processing methods significantly affect its thermal performance. They further investigated the relationship between thermal conductivity and air permeability in jute fabrics. Their study revealed that fabrics with higher air content exhibited lower thermal conductivity, highlighting the importance of air trapped within the fiber structure for insulation. Limited research directly addresses the thermal conductivity of raw jute fibers. However, Slater et al. [3] estimated the thermal conductivity of jute fibers based on similar natural fibers like cotton, suggesting a value around 0.046 W/mK. A. Bandyopadhyay et al. [4] investigated the thermal resistance of jute and jute-blend fabrics using the double-plate method of BS4745 and explained the relationship between thermal resistance and thickness to be linear. They also found that fabric conductivity and fabric packing factor follow Lee's equation, from which the thermal conductivity of jute fiber is estimated. Mohanty et al. [5] in found that the thermal conductivity value of jute felt is 0.064 W/mK in the temperature range from $50 - 80\ ^{\circ}C$. There's a growing body of research exploring the use of various recycled and natural fibers in construction. R.A. Braga et al. [6] investigated and compared the mechanical and thermal properties of raw jute and glass fibre-reinforced epoxy hybrid composites. Arnas Majumder et al. [7] in their study prepared jute and wool insulation panels and measured their thermal conductivity and sound insulation index values. They concluded that jute and wool panels can be effectively used as thermo-acoustic building insulation material. Particle boards have been manufactured from different varieties of raw materials in the form of small particles impregnated with resins or other appropriate binders reinforced together with heat and pressure. They can be utilized for housing, industries, and commercial buildings as partition walls, window entryway boards, table tops, board sheets, and so on. A. Sampathranjan et al. [8] studied the mechanical and thermal properties of particle boards made from farm residues. H. Charvátová et al. [9] used computer simulations to compare internal and external thermal insulation in houses, finding internal is better for heating but external reduces condensation risk. Liu et al. [10] employed analytical and numerical models to show that thermal insulation on tunnel walls in deep mines can effectively reduce heat flow from the surrounding rock. I. Omle et al. [11] used advanced computer simulations to find the two best thicknesses and types of insulation for building walls in a cold climate, considering cost and energy savings over time. D. Prakash [12] employed a numerical approach to explore a dual-function roof design that utilizes solar water heating and strategic insulation to achieve energy savings in both winter and summer. While Jute exhibits good thermal

insulation properties in non-woven and blended fabric forms, limited research directly addresses its thermal conductivity in particleboard form. Further research is necessary to fully understand the thermal performance of JPBs. This study is conducted based on this gap in contemporary research and aims to explore the thermal conductivity of locally available JPBs. In this study, numerical investigation on the thermal performance of JPBs is assessed as well. By utilizing Lee's Disc method, an apparatus is developed to experimentally determine the thermal conductivity of JPBs, providing a solid basis for comparison with commonly used materials and dedicated insulators. Additionally, the research employs Ansys Steady State Thermal simulation software to numerically model the effectiveness of JPBs in insulating a typical Bangladeshi household, predicting their potential impact on indoor thermal comfort. The study is significant as it explores a sustainable, affordable alternative to expensive or imported insulation materials, promoting the use of locally available, renewable resources.

2. Methodology

Materials and Sample Preparation

The JPB sample was shaped as a disc with the same diameter of the discs in the Lee's Disc apparatus. The disc-shaped board was ground for better handling. The diameter of the sample specimen was measured by a calipers and the surface area was calculated to be $A = \frac{\pi d^2}{4}$. The thickness of the specimen was measured by a screw gauge. Observations were taken at five different spots and the mean value was used for further calculations.

Experimental Methodology

The Lee's Disc Method is a simple and effective way to measure the heat conductivity of a poorly conducting material like jute composites, particle boards, etc [13]. It provides a better understanding of how to calculate thermal conductivity [14]. The schematic diagram of Lee's Disc Apparatus is shown in Fig. 1. It consists of two parts. The lower part C was a circular metal disc usually made of brass. In order to obtain accurate readings, the brass discs were wrapped in a thermal insulator such as cotton, felt or plastic. The experimental specimen P, here it was a circular-shaped JPB, was placed on it. The lower part of the steam chamber, B was made of a thick metal plate of the same diameter as of C and P. Calibrated thermometers were inserted in the upper side and lower side of the specimen, i.e. in the upper and lower discs. Once the steam generator started producing steam, boiler outlet was connected to the inlet of the steam chamber by a rubber tube which introduced heat to the system with discs and particle board sample. The entire setup was allowed to reach a steady-state condition, characterized by minimal temperature fluctuations (not exceeding $0.5°C$) for at least 10 minutes. The temperatures T_1 (Temperature of the upper disc) and T_2 (Temperature of the lower disc) were recorded and the specimen was removed from the setup. As a result, the steam chamber started directly heating the lower brass disc C until its temperature was raised $10°C$ from the previously recorded steady state temperature. Finally, the steam chamber was removed and the lower disc was allowed to cool down by natural convection. The variation of its temperature during the cooling phase was recorded at regular intervals (every 30 seconds).

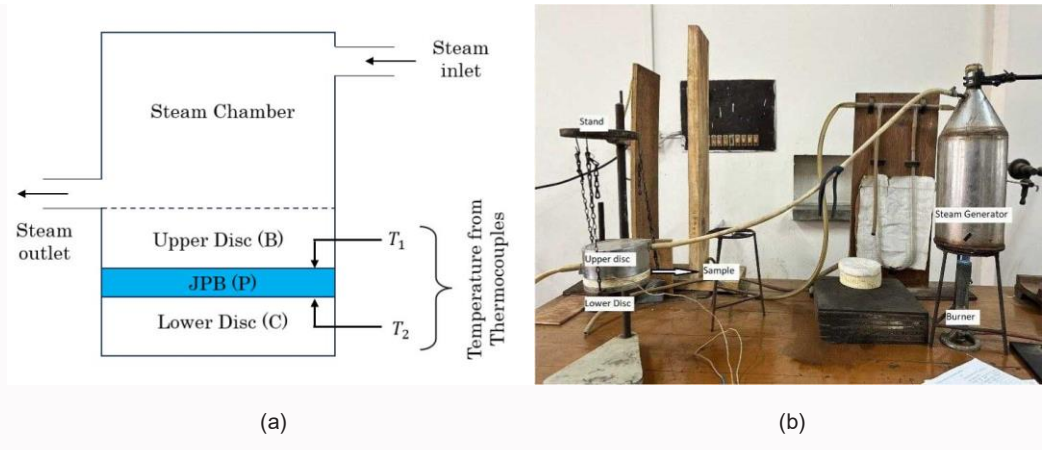


Fig 1: Setup of Lee's Disc apparatus for thermal conductivity measurement

From the graph showing this variation of temperature with time, the slope at the point where temperature was equal to T_2 was calculated utilizing the 'Second Order Central Difference Method' as follows-

$$\frac{dT}{dt} \approx \frac{T(t_0 + h) - T(t_0 - h)}{2h} \quad (1)$$

The amount of heat flowing through the specimen P per second, Q was calculated by Fourier's law:

$$\boldsymbol{Q = kA\frac{T_1 - T_2}{d}} \quad (2)$$

Where the steady state temperature of B is T_1 , temperature of C is T_2 , surface area of P is A, thermal conductivity of P is k and thickness of P is d. When the apparatus is in steady state (temperatures T_1 and T_2 are constant), the

rate of heat conduction into the brass disc C is equal to the rate of heat loss from C during the cooling period. If the mass and specific heat of the lower disc are m and c, respectively and the rate of cooling at T_2 is $\frac{dT}{dt}$, then the amount of heat conducted per second is

$$\boldsymbol{Q = mc\frac{dT}{dt}} \tag{3}$$

Equating (2) and (3), k was determined as

$$\boldsymbol{k = \frac{mc\frac{dT}{dt}}{A(T_1 - T_2)}} \tag{3}$$

Numerical Methodology

The simulation assumed a constant heat flux from the inside toward the outside. To balance the energy flow rate, a constant convection boundary condition was applied to the outside of the wall, with the ambient temperature set to 40℃. The simulation was run twice: first with concrete for the wall only, and then replacing a thin layer of concrete with jute particle board as an insulator.

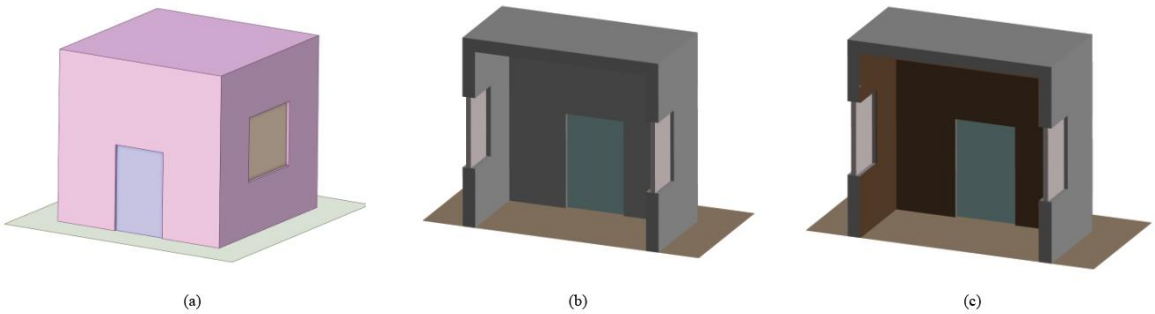


Fig 2:Initial model of the house (a) exterior (b) model without insulation (c) model with JPB insulation

The house model used for this was a single-room house with two windows and a door which is illustrated in Fig. 2(a). The walls and the roof of the house were made of concrete. The windows were considered to be made of glass. It had a plywood door and a marble floor. In the first case, the house had no inner insulation as in Fig. 2(b). In the second case the house had an insulation layer of jute particle board as depicted in Fig. 2(c). The properties of these materials are described in Table 1.

Table 1: Material Properties

Material	Thermal Conductivity (W m^{-1} k^{-1})
Jute Stick Particle Board	0.1755
Plywood	0.2
Glass	1.4
Concrete	2.25
Marble	1.28

The contacts were defined properly corresponding to the heat transfer and the mesh was generated with linear node connections of elements. The maximum element size was defined as 0.05 m. We can analyze the acceptability of a mesh using different mesh matrix. For the generated mesh some matrices are given in Table 2. Mesh quality metrics such as element quality, orthogonal quality, and skewness are essential for evaluating and ensuring the precision and stability of simulations. Element quality typically ranges from 0 to 1, with values closer to 1 indicating better-quality elements; a value above 0.7 is generally considered good. Orthogonal quality also ranges from 0 to 1, with higher values indicating better alignment; values above 0.7 are desirable. Skewness, which measures the deviation of element angles from their ideal values, ranges from 0 to 1, with lower values being better; a skewness value below 0.5 is generally preferred. A high-quality mesh with optimal values in these metrics is critical for achieving reliable and accurate results in computational analyses. Based on the above discussion the mesh quality is acceptable for the study.

Table 2: Matrices for the generated mesh

Quality Matrix	Minimum Value	Maximum Value	Average Value	Standard Deviation
Element Quality	0.065	0.9998	0.83897	0.0983
Orthogonal Quality	0.03398	1	0.77419	0.12652
Skewness	0.13057	0.96602	0.22464	0.12793

In this study, two types of boundary conditions were applied to model the thermal behavior of the room. Firstly, a convection boundary condition was assigned to the outer surfaces, including the walls, door, and windows with a convection coefficient of 10 W/m²/°C [15]. Secondly, an internal heat flux boundary condition was applied to simulate the heat generated due to solar radiation. The specified heat flux was 900 W/m² (during March in Bangladesh) [16]. Using ANSYS Fluent, a temperature distribution contour plot was generated and a computational path was created through the thickness of the inner wall. This path allowed for detailed analysis and plotting of the temperature variations from one side of the wall to the other. Next, the inner layer material was replaced with jute particle board. A simulation with the same parameters was performed and the same observations of inner wall temperature, temperature distribution contour, and temperature distribution across the wall were plotted. Analyzing these observations, a comparison between the insulated and uninsulated conditions was observed.

Validation of the Numerical method

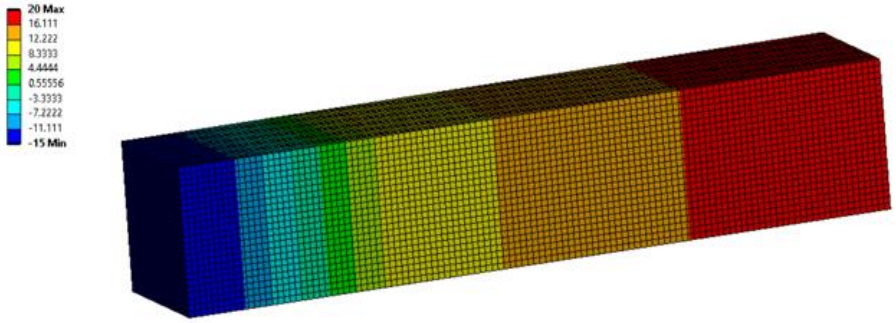


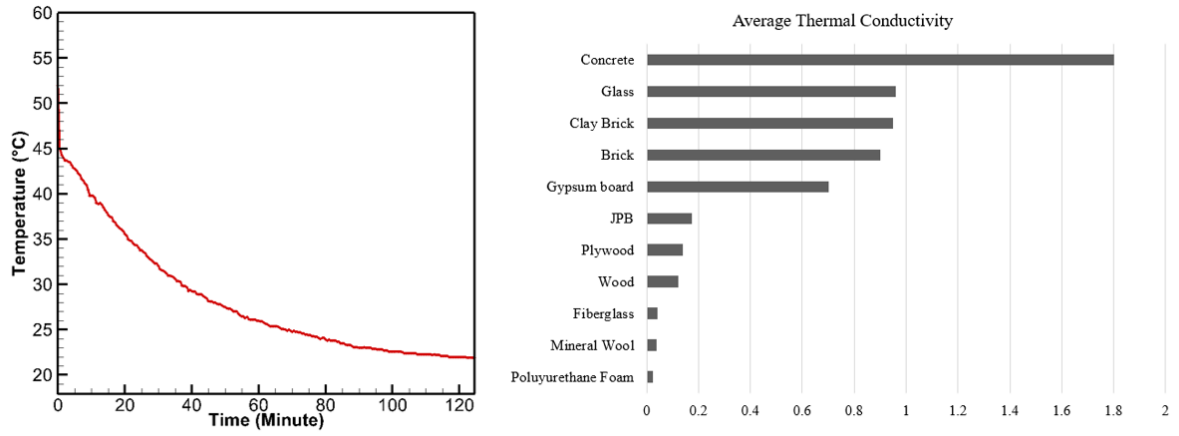
Fig 3: Simulation of temperature variations in the multilayer wall, from outside to inside, showing a temperature range congruent with the reference study

The numerical simulation conducted in this study was validated by reproducing the results presented by Stan-Ivan Felicia-Elena, Dinu Radu-Cristian, and Duinea Adelaida-Mihaela [17]. Using the same simulation parameters, including thermal conductivity, boundary conditions, and geometry, the results obtained showed satisfactory agreement with the reference study as shown in Fig. 3. The variation of temperature across the interfaces ranges from $20°C$ to $-15°C$, congruent with the results of the mentioned study. This successful replication confirms the repeatability of the adopted methodology and its reliability for predicting thermal behavior. Such validation ensures that the numerical approach applied in analyzing the thermal performance of JPBs is both accurate and credible, further reinforcing the findings of this research.

3. Results and Discussion

Experimental Result

The cooling curve of brass disc is depicted in Fig. 3. Applying second order central difference method, rate of cooling at the temperature equal to $T2 = 40.5°C$ (t = 540 s) is calculated to be $-0.02\ °C/s$. The cooling rate of the lower disc C is assumed to be indifferent to the rate of heating of the disc while receiving heat from the sample. Using the Equation (3), thermal conductivity of the jute particle board specimen is obtained as 0.175559 $W/m\ K$.



(a) (b)

Fig 4:(a) Variation of temperature against time during cooling phase of lower brass disc, C; (b) Comparison of average thermal conductivity of JPB with that of building materials and dedicated insulators

The result suggests that locally available JPBs do not exhibit exceptional thermal insulation properties compared to dedicated insulation materials, yet they offer comparable insulation to standard particleboard as shown in Fig. 4. The calculated thermal conductivity is much less than the threshold value of conductivity for a material to be considered as standard thermal insulator. Furthermore, the particle board has lower thermal conductivity, thus greater resistance to heat flow than conventional building materials such as clay brick, concrete blocks and masonry cavity wall. The JPBs provide around five times greater thermal resistance than the conventional brick walls and ten times greater than that of concrete blocks. This paves the way for using JPBs as an additional insulating layer on the walls in residential or commercial building.

Numerical Result

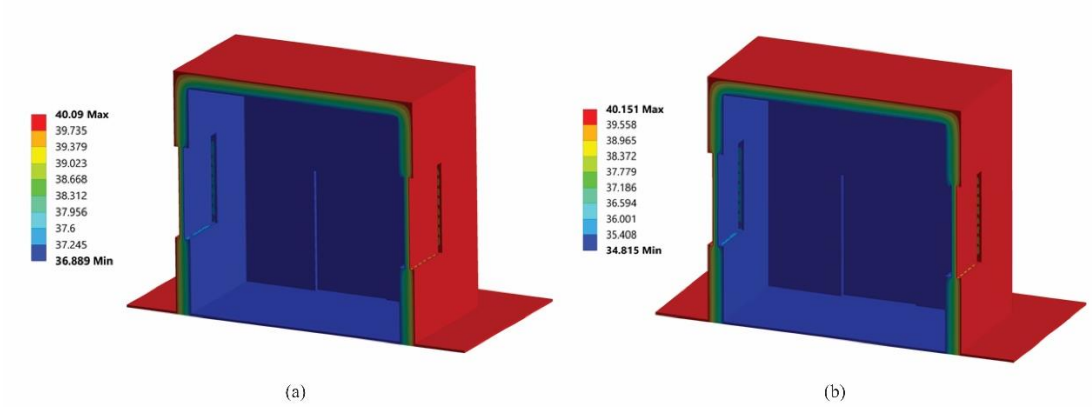


Fig 5: Temperature contour($°C$) of the simulation of house (a) without insulation (b) with insulation

In Fig. 5(a) and Fig. 5(b), the temperature contour plot is shown where the outside temperature is high and colored red. The inner side of the house is blue and across the wall, the temperature can be viewed changing from red to blue. As the outside temperature is the same for all parts, the materials with lower thermal conductivity can conduct less heat and thus the inner temperature is lower. In Fig. 6, the temperature distribution across the wall from point 1 to point 2 reveals important details about the thermal performance of the wall materials. The outside temperature is approximately 40 °C, and without an insulation layer, the inner wall temperature is observed to be around 36.837 °C. This indicates that the concrete wall, with its thermal conductivity of 2.1 W/m K, allows some heat to pass through, resulting in a moderate temperature difference between the outside and inside surfaces. The graph describing the variation of temperature across the wall in Fig. 6(a), shows a nearly constant slope and suggests that the thermal conductivity of the concrete is consistent throughout the wall. This constant slope indicates a steady rate of heat transfer through the concrete, with no significant changes in material properties affecting the thermal resistance. Thus, the concrete wall, while providing some insulation, allows for a predictable and uniform heat transfer from the exterior to the interior, maintaining an inner temperature of about 36.837 °C in the absence of additional insulation.

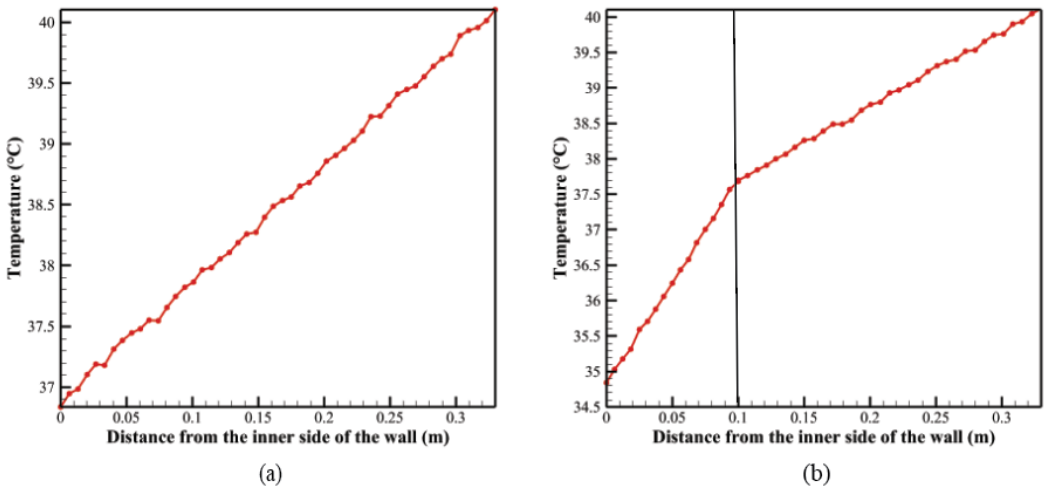


Fig 6: Variation of temperature across the wall (a) without insulation (b) with insulation

The temperate distribution plot across the wall with an insulating layer is shown in Fig. 6(b). From x=0 to x=0.1 m, variation of temperature across the JPB layer has been shown. At x > 0.1 m, the graph shows the temperature distribution across the concrete wall, which is exactly the same as the slope without an insulating layer. Across

the JPB layer, the temperature distribution demonstrates a steeper slope. Consequently, the temperature at the inner surface of the wall (x=0) is 34.844 °C, which is almost $2°C$ less than that in Fig. 6(a). Hence, A 10 cm layer of JPB significantly reduces the rate of heat transfer from outside, helping to maintain a lower and more stable indoor temperature. Therefore, even when the exterior temperature is higher, the inner walls of a house with a JPB layer will retain less heat, leading to a cooler interior environment compared to walls without insulation.
This can be clearly observed from the inner wall temperature with the insulator and without the insulator. With the insulator, the temperature is 34.844°C but without the insulator it is 36.837°C. Therefore using the jute particle board the temperature can be decreased up to 2 °C during summer at a lower cost than any other alternative for a 10 cm thick insulation.

4. Conclusion

This study evaluates the potential of locally available JPB as a building insulation material by analyzing its thermal conductivity and assessing its impact on indoor temperature through preliminary numerical simulations. The thermal conductivity of JPB was calculated to be 0.175559 W/mK with an accuracy of about 97%. This value falls within the range typically observed for conventional particleboards (0.067 W/ m K to 0.275 W/ m K) [18]. JPB exhibits higher thermal resistance than commonly used building materials, enhancing thermal insulation for building envelopes. However, its performance is not as satisfactory as dedicated insulators. The thermal conductivity is influenced by the properties of jute fibers, wood particles, and binders. A 2°C reduction in inner wall temperature indicates potential energy savings for cooling, making JPB a cost-effective option for energy-efficient buildings.

5. Acknowledgement

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