

Low-cost Roof Insulation Solutions for Low-rise Residential Buildings and Houses in Pakistan

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Residential, commercial and public buildings consume up to 40% of world's energy production in both developed and developing countries. Recent estimates indicate that by 2040 developing countries may consume up to 65% of the world's energy. The energy conservation movement that started in the developed countries in early 2000s is now finding its ways in the developing countries. Pakistan, the 6th populous country in the world, is facing a huge gap in the supply and demand of electricity due to accelerated economic growth and improvements in the living standards of its middle class. Realizing the importance of energy conservation, the Higher Education Commission of Pakistan with support from USAID funded a three-year research project to develop energy efficient design and construction solutions and products. This paper highlights main findings of three research studies conducted to develop low-cost solutions for roof insulation using locally available materials. Three low-cost materials namely Burnt Clay Pots, Wood shavings, and Hollow Clay Tiles were tested in hot climatic conditions. The reduction in cooling load was between 25%-52% with payback period between 15-43 months. It is hoped that the reported findings would be useful to researchers and practitioners in Pakistan and other developing countries with similar climatic conditions.

Keywords: Energy Conservation, Insulation, Roof, Burnt Clay Pots, Wood Shavings, Hollow Clay Tiles, Passive Cooling

Introduction

Energy efficiency in the built environment is vital to achieving development objectives in emerging economies. There is an increased recognition that the cost of reducing energy consumption is much lower than the cost of generating new energy (Managan et al., 2011). Energy efficient buildings bring many benefits to their users such as lower operating costs due to reduced energy usage and greater comfort through better insulation and lighting. The International Energy Agency (IEA) estimated that residential, commercial and public buildings account for up to 40% of the world's energy consumption. These numbers are even higher for developing countries and recent estimates suggest that developing countries may consume up to 65% of the world's energy by 2040 (IEA, 2017). Pakistan, a developing country in South Asia, is facing a huge gap in the supply and demand of electricity because of accelerated economic growth and improvements in the living standards of its middle class. The shortage of electricity has adversely affected the national economy. According to recent studies, the power shortages have resulted in an annual loss of about 2% of GDP, and total industrial output loss in the range of 12%-37% (Azhar and Salman, 2018). In Pakistan, the residential sector is the largest consumer of electricity, consuming approximately 45.6% of total electricity supply, followed by Industrial (28.4%), Agriculture (11.8%), Commercial buildings (7.4%), Public buildings (6.2%), and Street lights (0.6%). These numbers indicate that buildings and houses together consume approximately 60% of total electricity produced in Pakistan. The total capacity of electric power generation in Pakistan is approximately 19,681 MW/day, whereas the peak demand is approximately 26,520 MW/day. Even a 10% electricity savings in buildings and houses could result in an overall savings of approximately 1,200-1,500 MW/day which is equivalent to daily power generation of 3-4 medium size coal power plants (Azhar and Salman, 2018). Hence, there is an urgent need in Pakistan to design new and retrofit existing buildings and houses to reduce their electricity consumption. In 2016, the Higher Education Commission (HEC) of Pakistan and the United States Agency for International Development (USAID) jointly funded a 3-year project to facilitate design and construction of high-performance, energy-efficient buildings and houses in Pakistan through capacity building of academia and industry in related research, education, and practice. The project team consisted of researchers from USA and Pakistan. More details about this project can be found in the following reference (Azhar and Salman, 2018). This paper highlights main findings of three research studies conducted under this project to develop low-cost solutions for roof insulation using locally available materials. It is hoped that the reported findings would be useful to researchers and practitioners in Pakistan and other developing countries with similar climatic conditions.

Review of Literature

The majority of residential buildings and houses in Pakistan are constructed using masonry walls and a reinforced concrete or reinforced brick-concrete roof. In most cases, no thermal insulation is used in walls and roof by builders to keep the construction cost at a minimum. Interviews with the buildings' owners, architects, and builders revealed that at present no energy efficiency measures are being implemented in the design and construction of most urban and rural houses (Azhar and Salman, 2018). A significant amount of energy is wasted due to the heat gain/loss through non-insulated walls and roofs (Khan *et al.*, 2017). Building envelope has a major role in controlling indoor thermal environment. Its components include roof, walls, floors, and windows. Studies showed that after climate, building envelope is the most important factor for better thermal performance of a building as it is the barrier against external environment (Sattar, 2018). The research conducted in hot climates indicated that cooling energy can be saved up to 34.1% annually and 36.8% on peak by improving building envelope using insulation, thermal mass, light color paint of external walls, and shading (Dimoudi *et al.*, 2016). Roofs absorb maximum solar radiation in terms of area in most low-rise residential buildings and houses. Heat entering through roof is a major factor in increased cooling loads especially for reinforced concrete or reinforced brick-concrete roofs (Charde and Gupta, 2013). Researchers have investigated various traditional and non-traditional materials for roof insulation such as waste olive seeds, ground PVC, woodchips, straw-clay mud, palm leaves, etc. A review of literature by Aslam (2018) showed following interesting work throughout the world, "Abu-Jdayil made a composite material using unsaturated polyester and date-pits or date palm wood as filler to serve as insulation. Labat used straws and clay mixed with a large quantity of water to make roof and walls insulation material. Wei developed a similar thermal insulation material by mixing rice straw with clay and water. Benmansour created an insulating material using natural cement, sand and date palm fibers for use in the tropical climate." Some of the ideas reported in the published literature are adapted in this research.

Research Aim and Methodology

The aim of this research is to develop low-cost roof insulation solutions using "best of the old" techniques that do not require special manufacturing and/or construction skills. A list of "best of the old" techniques was developed based on an in-depth literature review and published case studies. After that, a brainstorming session with local design and construction experts was conducted to evaluate suitability of each technique for hot climates. Three techniques namely inverted Burnt Clay Pots (BCPs), Wood shavings, and Hollow Clay Tiles (HCTs) were selected due to their low-cost and ease of implementation in Pakistan. An experimental research approach was adopted for the remainder of this study. Test roofs were constructed and the thermal performance of each material was tested. Energy simulations were conducted for validation of experimental research results and/or complementing experimental findings. All testing was conducted in the Materials Testing Laboratory of the Department of Architectural Engineering and Design, University of Engineering and Technology, Lahore, Pakistan. In the following sections, brief test results of the three selected low-cost roof insulation solutions are presented. Readers interested in more details are advised to read the following reports: (Aslam, 2018; Shafique, 2018; Sattar, 2018).

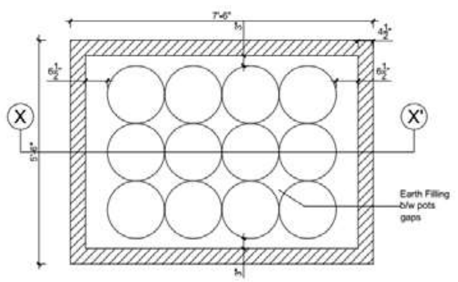
Solution 1: Use of Inverted Burnt Clay Pots (BCPs) for Roof Insulation

Background and Aim

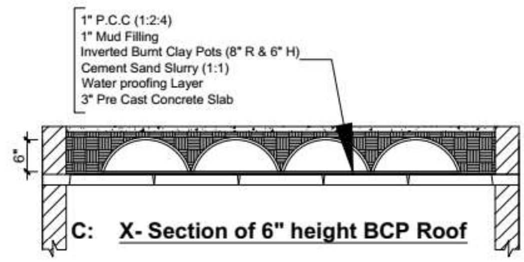
Burnt Clay Pots (BCPs) are typically used for making yogurt in rural and suburban areas of Pakistan. They are cheap and easily available throughout Pakistan and other neighboring countries. These clay pots can be placed in an inverted position on a roof and covered with a layer of mud and cement to fill-up the voids and create a smooth top surface. The air trapped inside the pots act as an insulator and resist the heat flux entering into the living space through the roof. The BCPs have been used as an insulation material in the past in some historic buildings in Pakistan, India, and Bangladesh (Yadav, 2016) but no formal research has been conducted to determine their optimum size to ensure maximum insulation. An experimental investigation is conducted on BCPs with heights varying between 4 to 12 inches to determine the best height for minimizing the heat transfer. Full details of this research study can be found in the following references (Shafique, 2018 and Shafique *et. al.*, 2018).

Experimental Design

All experimentation was carried out on test roofs of 5.5 ft x 7.5 ft rooms constructed for this study at the campus of University of Engineering and Technology, Lahore, Pakistan. The roof slab was 3 inch precast concrete with no insulation on the top. Each test roof was prepared as follows: (1) the roof was cleaned and a water proofing coat was applied; (2) one inch thick cement sand slurry in 1:1 ratio was evenly spread on the surface for fixing of BCPs; (3) the BCPs were laid on the roof. The voids were filled with mud and in addition one inch thick mud layer was evenly spread on top of the BCPs; and (4) one inch thick plain cement concrete (in 1:2:4 ratio) layer was applied above the mud layer to stop rain water penetration. Figure 1 shows the test roof configuration and experimental setup.



(a) Typical roof plan of a test room.



(b) Typical roof cross-section of a test room.

(c) Placement of BCPs on the test roof.

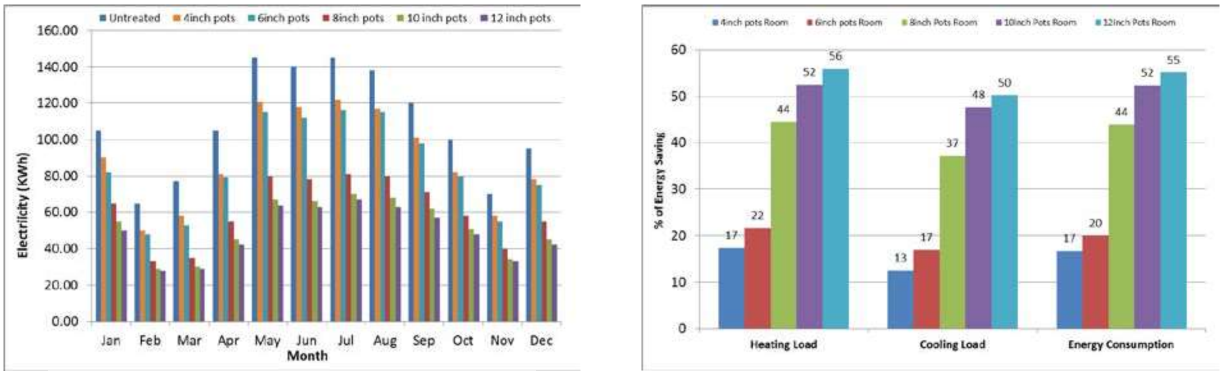
(d) A finished roof with a 1-inch thick PCC layer.

Figure 1: The experimental details of using BCPs on test roofs.

Temperature sensors were placed both outside and inside the rooms to measure the ambient and inside temperature readings. These sensors were connected to a data logger and hourly temperature data were recorded for 5 months from December 2017 to May 2018. The collected data were validated and fed into an energy simulation software (Autodesk Green Building Studio) to run the energy analysis for a complete year cycle.

Results/Main Findings

The final results shown in Figure 2 indicate that a BCP of a larger height provides better thermal insulation in both winter and summer seasons. The energy performance of a BCP is significantly improved when its height was 8 inches or more. The roofs made with BCPs of 8 inch, 10 inch and 12 inch height resulted in 44%, 52%, and 56% energy savings as compared to the untreated roofs. Although the best performance is shown by BCPs of 12 inch height but the energy savings difference between 10 inch and 12 inch heights is not significant. The total cost (materials, equipment, and labor) is approximately PKR 68 (49 cents) per sq. ft. The life cycle cost analysis indicated that the BCPs of 10 inch height are more economical than the 12 inch height and their pay back period is approximately 21 months. This short payback period makes BCPs an ideal product for low-cost roof insulation especially in developing countries with hot climate. This study confirmed that with a BCP roof system, the cooling and heating loads of a building/house can be significantly reduced. It is an eco-friendly solution that requires no special materials and skills and can be easily taught to people in rural/suburban areas. This study recommends use of 10 inch high inverted BCPs for both new construction and retrofitting of low-rise residential buildings and houses.



(a) A comparative analysis of monthly energy consumption for cooling/heating loads for test rooms made with BCPs of varying heights.

(b) A comparative analysis of the performance of roofs made with BCPs versus conventional roof for energy savings.

Figure 2: A comparison of the performance of test roofs made with BCPs with traditional non-insulated roofs.

Solution 2: Use of Wood Shavings Layer for Roof Insulation

Background and Aim

Huge quantities of wood shavings are produced in the woodworking industries across Pakistan. At present, this waste material is mainly used as a fuel. The idea to use wood shavings as an insulating material goes back a long way (Hans and Bernhard, 2000). Attempts to use wood shavings for thermal insulation in the western world from 1920-1980 failed due to high risk of fire. In Pakistan, most low-rise residential buildings and houses are made from masonry and reinforced concrete, which makes the risk of fire damage very low. Hence this idea is worthwhile to try especially in the rural and suburban settings where wood shavings are available at no or very negligible cost. In this experimental study, the performance of wood shavings layer on a reinforced concrete roof assembly is tested for thermal insulation. Full details of this research study can be found in the following references (Aslam, 2018 and Aslam *et. al.*, 2018).

Experimental Design

Two test rooms of 5.5’x7.5’ in size were constructed using 9-inch thick brick masonry. The roof consisted of a 3 inch thick prefabricated reinforced concrete slab with 1.30 degree slope. Each test room had a glass panned window of 4’x5’ facing west. A galvanized iron door of 5’x2.5’ was provided to access each room. The roof of the first room was left uninsulated (hereinafter called as the traditional room). For second room (hereinafter called as the treated room), a polyethene sheet was placed on the roof top for water proofing followed by 1.5 inch layer of sand and a thin layer of cotton fibers. Then a layer of wood glue was spread on the cotton fibers by trowel. After that, the first layer of wood shavings was placed at 2.5 lbs/ft^2 rate and gently compacted. It was followed by a second layer of wood shavings at the same rate. A layer of wood glue was placed between the two wood shavings layers. In that way, a 3-inch thick compacted wood shavings layer was prepared. On the top of the wood shavings layer, a thin layer of wood glue was applied and left to cure for one day. This procedure converted the wood shavings layers into a rigid foam like mass. On the top of wood shavings layer, another water-proofing layer (polythene sheet and sand) was placed followed by roof tiles of 1.5 inch thickness to ensure no water penetration into the wood shavings mass. The roof configuration and a photograph of the completed test roof are shown in Figure 3. Temperature sensors were placed both outside and inside the rooms to measure the ambient and inside temperature readings. These sensors were connected to a data logger and hourly temperature data were recorded for 38 days.

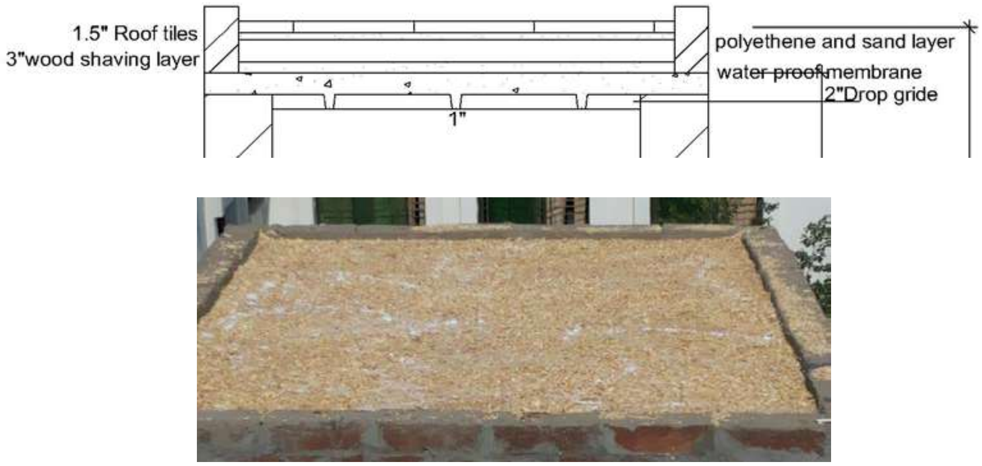


Figure 3: Cross-section (above) and photograph (below) of a treated roof with wood shavings.

Results/Main Findings

Figures 4 and 5 show the temperature profiles (outside temperature, inside temperature, and temperature difference) of traditional and treated rooms during the 38-days test period from April 24 to May 30, 2018. Though the temperature data was collected for full 24 hours' time span but here only data recorded at 4:00 PM is shown because the outside temperature was maximum at this time on most days. As can be noted from Figures 4 and 5, in the treated room a maximum temperature drop of 13.3°C (23.9°F) was recorded whereas in the traditional (or untreated) room the maximum temperature drop was 4.2°C (7.6°F). This comparison shows that the use of wood shavings as an insulation material helped to further reduce the inside temperature of the room by 9.1°C (16.4°F) i.e. a 31% reduction in the cooling load. This temperature drop is significant because it creates a comfortable indoor environment and in turn reduces the cooling (or heating) load for an air conditioning system (if used). The total cost (materials, equipment, and labor) is approximately PKR 28 (20 cents) per sq. ft. A life cycle cost analysis indicated a payback period of 15 months. This research is in progress to determine wood shavings durability and resilience.

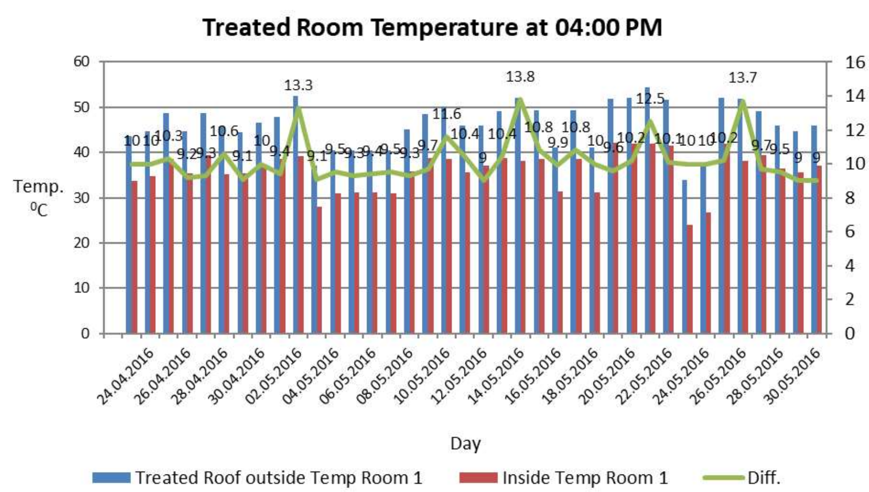


Figure 4: Comparison of treated room's inside and outside temperatures at 04:00 PM.

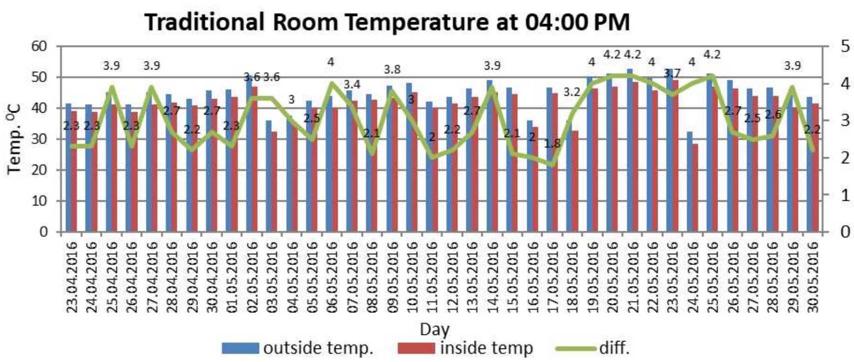


Figure 5: Comparison of traditional room's inside and outside temperatures at 04:00 PM.

This study confirms that wood shavings are a good insulation material for low-rise residential buildings and houses due to their less thermal conductivity and higher thermal resistance. In addition, wood shavings are a ecological, sustainable, and inexpensive insulating material and no special logistics are needed for their application. The local work force can be easily trained to use this material in the new construction or retrofitting of existing houses in the rural and suburban areas of most developing countries.

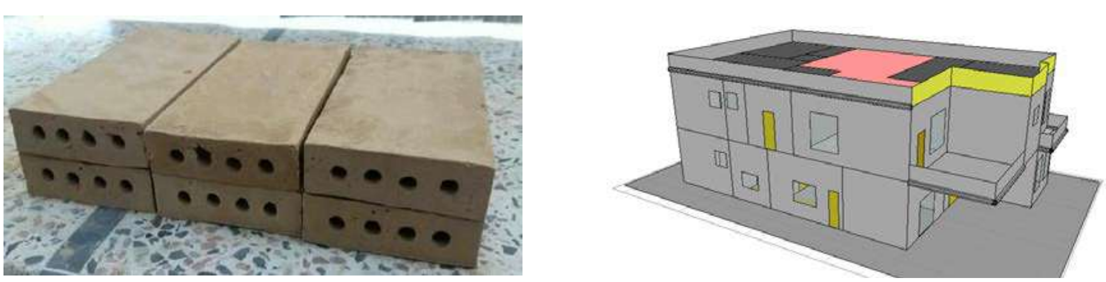
Solution 3: Use of Hollow Clay Tiles (HCTs) for Roof Insulation

Background and Aim

For thousands of years clays have been widely used in building construction. A high percentage of late nineteenth and early twentieth century buildings in the United States and Europe used Hollow Clay Tiles (HCTs) as a structural, fire proofing, and insulation material. Since the 1950s, HCTs have nearly vanished from the construction arena throughout the world due to easy and cheap availability of concrete products (Wells, 2007). In this experimental investigation, the performance of HCTs for thermal conductivity is investigated and a comparison is made with conventional solid brick and clay tiles. Full details of this research study can be found in the following references (Satar, 2018 and Satar *et. al.*, 2018).

Experimental Design

Since the HCTs are not readily available in the market, several prototypes were designed and tested for weight, water absorption, thermal conductivity, and compressive strength and a final design is selected that provided the highest thermal conductivity with lowest weight. All test tiles were first air dried for 15 days and then baked in a kiln with highest temperature around 1,600˚C (2900 ˚F). The final prototype tile dimensions were 5″ x 10″ x 1.5″ with four cavities of 0.5 inch diameter along the longer axis as shown in Figure 6a.



(a) Final prototype of the hollow clay tiles *(b) 3D model of the test house*

Figure 6: Final prototype of the HCTs and 3D model of the test house

The weight of each tile was 5.1 lbs (2.1 kg), water absorption roughly 13.7%, and average compressive strength around 1,327 psi (9.1 MPa). The thermal conductivity coefficient K was 0.34 BTU/hr·ft·°F (or 0.59 W/mK). In order to investigate the thermal performance of the prototype tiles, a double story 6,000 ft^2 test house was selected (Figure 6b). Its energy model was developed in Autodesk Ecotect 2011 to investigate the thermal performance of the test roofs in a simulated environment. Three test cases were modeled and simulated as follows: (A) Case 1: 9 inch brick walls with 3/8 inch plaster (inside & outside) and RCC roof with solid brick tiles finish; (B) Case 2: 9 inch brick walls with 3/8 inch plaster (inside & outside) and RCC Roof with solid clay tiles finish; and (C) Case 3: 9 inch brick walls with 3/8 inch plaster (inside & outside) and RCC Roof with prototype hollow clay tiles finish.

Results/Main Findings

Figure 7 shows the total energy, cooling and heating loads for three cases. In case 1 (solid brick tiles finish), the total energy load is 25,750.6 kwh including 24902.2 kWh of cooling and 848.3 kWh of heating load. In Case 2 (solid clay tiles finish), the total energy load is 21516.2 kWh including 20,656.9 kWh as cooling and 859.3 KWh as heating loads. In Case 3 (hollow clay tiles finish), the total energy load is 19,272.5 kWh with 18,435 kWh as cooling load and 837.29kWh as heating load. The comparative analysis of the three cases reveals that the lowest cooling and heating loads are produced by the HCTs. The second lowest cooling and heating loads are given by conventional solid clay tiles. A comparison of HCTs with conventional clay tiles showed an average saving of approximately 10.75% (2,221.9 kWh) of energy. The comparison of HCTs with conventional brick tiles revealed a 25.1% reduction in energy loads. These results clearly indicate that the HCTs can be safely used as a replacement for conventional brick and clay tiles. The total cost (materials, equipment, and labor) is approximately PKR 96 (69 cents) per sq. ft. A life cycle cost analysis shows a payback period of approximately 43 months. The thermal performance of HCTs can be further improved by applying suitable reflective coatings.

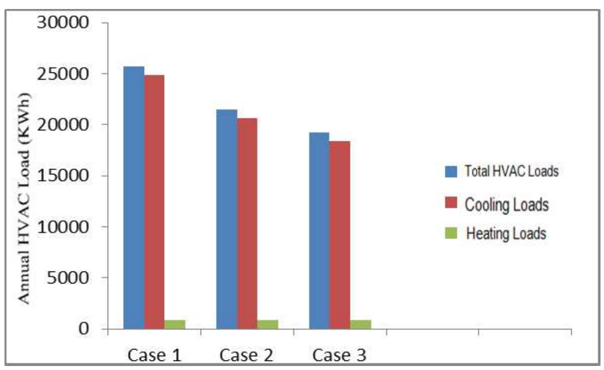


Figure 7: A comparison of thermal performance of the three test roofs

Conclusions and Recommendations

Three low-cost roof insulation solutions namely Burnt Clay Pots (BCPs), Wood shavings, and Hollow Clay Tiles (HCTs) are tested in this study and following important findings are revealed: (1) Use of 10 inch diameter inverted BCPs reduced the inside temperature (or cooling load) of the room by 52% as compared to the uninsulated reinforced concrete roof. The payback period of this technique is 21 months; (2) Use of 3 inch wood shavings layer resulted in 31% inside the room temperature reduction when compared to the conventional untreated roof. The payback period is 15 months; and (3) Use of HCTs resulted in 25.1% reduction in cooling loads as compared to the conventional roof with a payback period of 43 months. These results indicate that in terms of thermal performance, the inverted BCPs performed the best following by wood shavings and HCTs. However, the payback period of the wood shavings techniques is shortest as compared to the other two methods. In terms of total cost per sq. ft. (materials, equipment, and labor), the wood shavings is the cheapest option (PKR 28/20 cents) followed by BCPs (PKR 68/49 cents) and HCTs (PKR 96/69 cents). The total cost of 2" polyurethane sheet, which is a commercially available product in Pakistan, is approximately PKR 346 (US$2.48). A quick cost comparison indicates that the proposed solutions' costs are 8%, 20% and 28% respectively of the commercially available product cost. This research study would recommend all three solutions and owners/designers can choose a solution most suitable for their project based on local climatic conditions, design parameters, and availability of relevant materials.

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