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Thermal Performance Analysis of Conventionally Available Insulation Materials for Residences in Northern Areas of Pakistan

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ABSTRACT

The problem of energy shortages and changing climatic conditions has received a lot of attention in recent years. The building sector accounts for 60% of global energy consumption, with domestic buildings accounting for 20% to 40%. Most of this energy is used for heating, cooling, and ventilation. To address such energy shortages, the development of extremely energy-efficient buildings is a critical requirement for improving Pakistan's environmental status. Innovative building insulation solutions may be able to assist the country in coping with the crisis. The focus of this study was on the northern areas of Pakistan, intending to evaluate approaches for better thermal performance of buildings in cold climates. Insulation materials that are both innovative and cost-effective have the potential to minimize operational energy requirements and hence make buildings more efficient. In this study two commercially available insulating materials, polyethylene and polystyrene were assessed experimentally for a residential building in Murree, a hill station of Pakistan. The case study building was monitored using extruded polystyrene and polyethylene. Thermal data was recorded on hourly basis using a Testo Saveries System for 14 days in 2019 and for the current study 6 hourly data is used. Comparison of these two market available insulation materials in test room 1 and test room 2 are compared with the control room. The test materials were additionally compared based on their cost and minimum available thickness being applied. Polyethylene (PE) was observed to be five times cost effective than the other insulation material. In addition, the thermal performance of PE was comparatively better than extruded polystyrene (XPS), as in most of the days, the indoor temperature did not drop below 3°C, while Room with XPS had minimum 2°C and the control room showed more fluctuations in temperature from – 2°C to 2.5°C in that duration of the year. Polyethylene was also concluded to be the better material in terms of thickness necessary for optimum thermal performance and is hence suggested for use in buildings in Pakistan's colder regions.

1.0 INTRODUCTION

Internationally buildings contribute almost 40% of total energy use and many countries have a comparable share in it. That is why utilization and supply of energy is an exclusive and vast engineering field. Because of said reason, energy efficiency is a significant topic for buildings since 1970 (Mahdavi et al., 2021). The utilization of energy in buildings is defined by two types of factors, which are physical, and human influenced. The first type of factor is technical and physical, whose origin is concerned with building itself, weather conditions, services system of buildings, and other concerns which cannot be altered during the operational life of buildings (Nord, 2017). Another crucial factor is the social factor which covers a wide range of parameters like local habits of occupants, energy price, major energy sources, and political conditions. By including the human personalized factor into the perspective of building energy utilization, the actual energy use can be defined (Day et al., 2020).

The speed of economic growth highlights the increasing demand for the improved indoor built environment, especially in harsh climates of extremely high or extremely low temperatures. In the building sector, heating, ventilation, and air conditioning (HVAC) consume approximately 65% of energy utilization (Che et al., 2019). A dominant part of overall energy is utilized by buildings in the developing world. This energy consumption may be significantly decreased by incorporating energy-efficient techniques (Cao et al., 2016). A unique building with an energy-efficient design can reduce the operating cost including the size of mechanical systems. The demand for energy for heating and cooling is known as operational energy, while another typology is embodied energy which is the amount of energy essential for producing components and materials of a building including raw material extraction, transportation, and manufacturing (Ajayi et al., 2019). This demand is based on the building envelope details having any sort of insulation or not. Proper insulation selection is a critical process to minimize operational costs. The environmental load can be minimized using cost-effective and efficient techniques. A universal criterion is tough to be established for conventional building materials while doing research. Various assessment tools are developed to assess the performance of different insulation materials (Chen et al., 2015).

The cold climatic region has even severe problems to improve energy efficiency in buildings because of its low temperatures and high demand for space heating to achieve thermal comfort (Krarti, 2020). However, one approach to improving building energy efficiency is to use thick layers of insulation to reduce energy leakage and waste (Yang et al., 2014), but the issue is that, in many renovations and new building design scenarios, space efficiency, along with thermal performance and cost-efficiency, is a particularly important consideration. We need to create acceptable insulation materials with less thickness and comparable thermal performance to achieve space efficiency (Iqbal et al., 2022).

Insulation can be provided in various building construction elements, but the most desirable way is to use insulation provisions on roof slabs and external walls (Nandapala et al., 2020). The people of cold areas use various energy sources to bring comfort to their lives and especially the people who cannot afford the modern or expensive techniques of insulation (Lechner, 2014). Several materials have been used for the insulation purpose to cope with the environmental effect and develop low-cost thermal insulation techniques in our building construction process (Asdrubali et al., 2015).

In Northern Pakistan, conventional homes are constructed with stone masonry whereas new modern buildings, homes, and schools are constructed using uninsulated concrete blocks that have an even lower thermal resistance (ADVIES, 2012). Murree is a city in Pakistan's northern region at an altitude of 2291 m (about 1.42 mi) above sea level and in this very city, more than 1 million family's dwells in temperatures averaging 6.17°C for more than 5 months each year. The relationship between elevation and the number of heating degree days (HDDs) for different cities for a base temperature of 18°C shows linear regression which means that elevation and number of HDDs have a linear positive relationship with p-value < 0.05, t-stat value > 1.96, and $R_2 = 0.78$. It is apparent that HDDs increase with the increase in elevation and are highest for the Parachinar with Murree and HDDs are 838 for 12°C and 2001 at 18°C (Amber et al., 2018)

Residents in these locations of high altitude like Murree have little choice but to consume 3-5 tons of wood in every winter season for space heating, because they are mostly from a lower socio-economic status with limited access to electricity or gas. However, 60-70 percent of heating energy lost via walls and roofs in many buildings in northern Pakistan. Occupants spend one third of their salaries on heating (Khalid et al., 2021). The primary source of energy is non-renewable and damaging to the environment, necessitating the use of alternative methods to ensure thermal comfort. A comprehensive approach to energy-efficient building design can minimize the size of mechanical systems while accounting for the higher cost of energy (Kheiri, 2018). This research examines the efficacy of several types of insulation materials used in different areas of a house to discover the most suitable material for residential structures in Pakistan's colder regions.

Economically effective thermal insulation is needed in many regions of the developing world. Wood, charcoal, or dung is used in a cold climate for space heating which will be threatened in the future. Thermal insulation in buildings would protect resources and would enable improved living conditions (Lehmann, 2014). Insulation may be applied to the roof and walls. The author describes a thermal insulation approach for better thermal condition compared to using firewood to burn to heat up the space in houses and schools constructed from uninsulated stone or concrete. An insulated board made from wheat straw using a simple technique was developed. The board was applied on the inner surface of the wall and roof, finishing with a plaster coat and it presented a better thermal performance. For use of commercially and conventionally available materials, loose-fill insulation is not recommended for building applications because of no cavity walls (Abu-Jdayil et al., 2019).

The proper use of thermal insulation in buildings does not only contribute to reducing the required air-conditioning system size in a hot climate but also in reducing the annual energy cost. ("Performance characteristics and practical applications of common ...") Similarly, for cold climate, building insulation along with proper ventilation, not only reduces the quantity of firewood, money, and time for heating, but it ensures thermal comfort of residents and their health. Warmer interiors result in no need to stay all the time in smoke and enable occupants to do productive activities. For improvement of thermal performance at high altitudes, careful selection of insulation material with proper insulation value is necessary (Mazzone, 2020). The application of thermal insulation techniques is a permanent solution indirectly displacing energy resource. Moreover, thermal insulation once installed, keeps functioning for the lifetime of the building (Abu-Jdayil et al., 2019). So, the aim of this study was to identify thermally efficient insulation material based on real-time temperature measurement, for the northern areas of Pakistan, where climatic conditions are cold and harsh. Other considerable aspects of research were cost and space efficiency, as in these areas, no insulations are employed due to lack of awareness, economic issues, and space congestion issues in existing buildings.

Polyethylene (PE) foam is a durable, lightweight, resilient, closed-cell material. ("Medical Grade Foams - Medical Solutions by UFP MedTech") "It is often used for packaging fragile goods due to its excellent vibration dampening and insulation properties." ("PE Foam - Lumbini Industries | Nepal") The researcher describes polyethylene as: "a good insulator, it resists caustic materials, it is almost unbreakable and is environment friendly. Polyethylene is reliable under every circumstance, and it can easily deal with tropical temperatures as well as the frosty cold of the polar weather (Omer, 2008). The utilization of polyethylene is limited in building insulations in hot climate due to its low performance, while in this study, experiment was performed to evaluate thermal performance of PE for cold harsh climatic region. Extruded polystyrene (XPS) boards are used as insulation for roof, cavity wall, floor, and perimeter insulation. XPS boards can also be used as wall cladding insulation & void filling (Li et al., 2020). Extruded polystyrene rigid foam with special skin is manufactured by a continuous extrusion process which imparts a characteristic of the closed-cell structure giving the product its unique physical properties. Extruded polystyrene rigid boards have high resistance to water absorption, good physical, and thermal properties (Lu et al., 2021).

Table 1. Different Parameters for Insulation Materials (Papadopoulos, 2005)

Sr. No	Description	Extruded Polystyrene	Polyethylene
1	Cost	Low	High
2	Thermal performance (experimentation)	Good	Better
3	Thermal Conductivity	0.026 W/(mk) ASTM C -518	0.0298 W/(mk) ASTM C177
4	Thickness	25 mm	12.5 mm
5	Working Hours of application	4 Hr	6 Hr
6	Impact on Environment	5.25 Produced with HCFC 142b which depletes stratospheric O_3 252847*8563.zone to some extent	Non-Toxic
7	Market Availability	Yes	Yes
9	Fire Resistance	Class B1 ASTM D-2863	Class A ASTM E-84
10	Useful life	Long	Long

In most applications of thermal analysis, the Testo Saveris data monitoring system is excellent for temperature monitoring and temperature management, as it does automatic temperature and humidity measurements (Villarino et al., 2017). The measurement data is sent to a Base station via wireless and/or ethernet connections. Several alert alternatives, such as SMS/e-mail alarm or alarm relay, are available if the limiting settings are exceeded. Even if the system is not connected to a working computer, remote alerts can be generated. In addition, the Testo Saveris system can accept transmitters for all measurement parameters with standard current/voltage interfaces (Iqbal et al., 2022). The software stores all the captured data in one place. Simultaneously, the Testo Saveris program allows for a thorough examination and evaluation of the recorded data.

2.0 EXPERIMENTAL SETUP & METHODOLOGY

Murree is a mountain resort town in Pakistan's Rawalpindi District, located in the Galyat section of the Pir Panjal Range. It is located 30 kilometres (19 miles) northeast of Islamabad, on the boundaries of the Islamabad-Rawalpindi metropolitan area. According to the population census of 2017, Murree has a population of 233,017. Murree was chosen for the experiment because of its high-altitude of 2291 meters above sea level. Murree's yearly temperature fluctuates from 3°C to 19°C, according to climatic statistics.

For experimentation and implementation of two test materials, a single-story British period farmhouse (Dar House) with the corrugated roof was chosen near Hamza CNG, sunny Bank, Cart Road, Murree. This house has a single level and four rooms of the same size with one wall exposed to the external. As a result, these requirements were necessary for the selection of test rooms, with a material application area of 250 square feet, including the external wall and corrugated roof.

Figure 1. Exterior View of Test Building

Figure 2. Snow Coverage during Experimentation on Test Building

Two different material assemblies were examined in two identical test rooms, with the results compared. Each chamber had the same size (15'6” x 8'0” x 10'0”), with one wall facing the exterior and the other three walls sandwiched between them. As shown in figure 1 and 2, the building was all covered with snow during the experimentation duration and there was no sunlight, the orientation of Test Room 1 (T.R 1) was north, Test Room 2 (T.R 2) was northeast and control room was northwest. Reference to figure 3, none of test rooms had any window. The 3rd room was monitored as an untreated control room. Insulation material selection was based on established thermal conductivity values, ease of application, market availability, density, economics, and affordability of the target market. During experimentation, the building was not occupied, and no heating device was placed within the building.

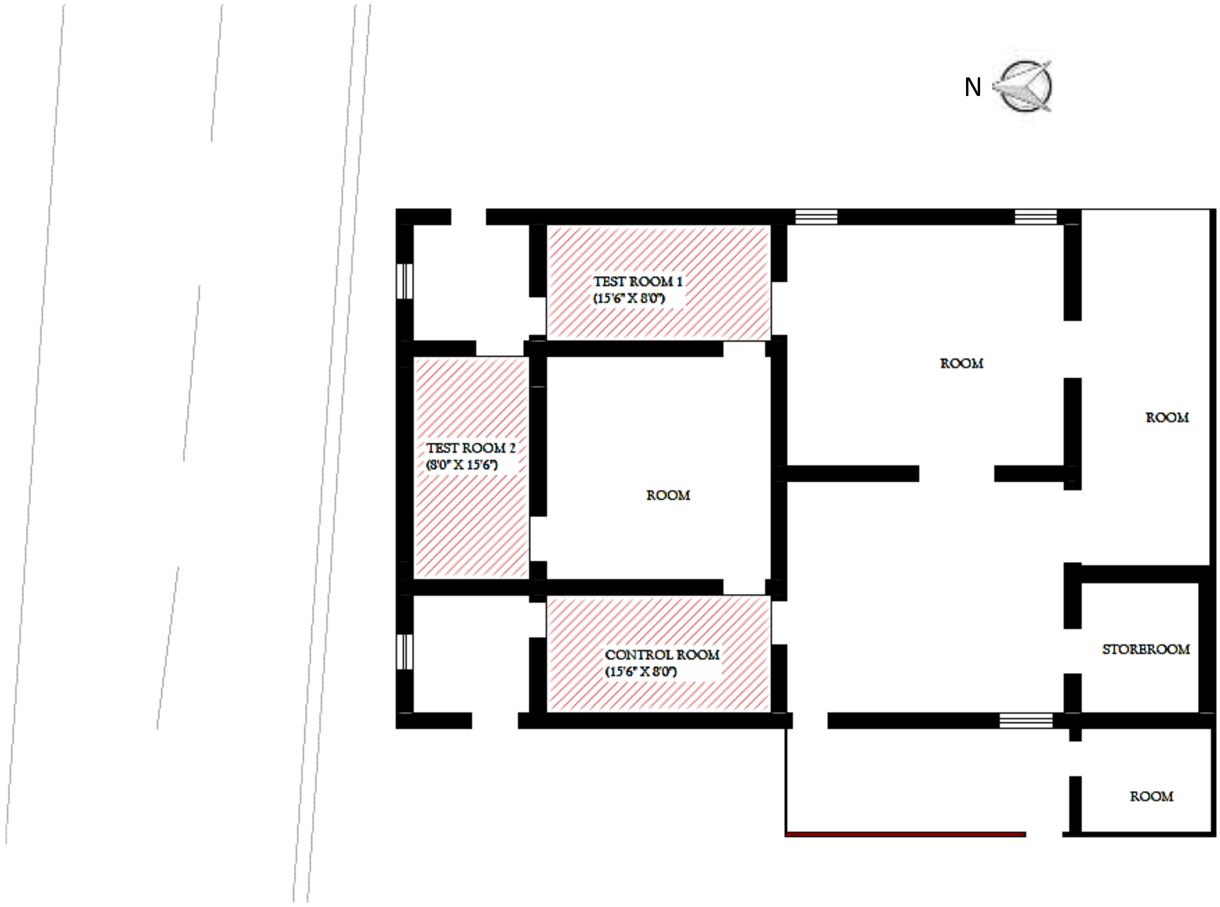

Figure 3. Floor Plan of the Case Study Building

3.0 ATTRIBUTES OF EXPERIMENTED MATERIALS

25 mm expanded polystyrene with a density of 35 kg/m^3 was applied under the corrugated sheet and on one exposed wall in the test room as shown in figure 4 and 5.

Figure 4. Application of XPS in T.R 1

Figure 5. Application of Extruded Polystyrene in T.R 1

3.1. Assembly 2

As shown in figure 6 and 7, under corrugated sheet and on one exposed wall in the test room, 4 ft wide Polyethylene (PE) rolls colour white with aluminium foil (28 kg/m^3 density, 10mm thick, and 100% closed cell) were applied using a bond as adhesive. A regular cutter blade and steel scale were used to cut the material.

Figure 6. Application of PE Roll in T.R 2

Figure 7. Application of PE Roll in T.R 2

The application of each material assembly was monitored for 14 days (about 2 weeks). The average temperature at 12:00 a.m., 6:00 a.m., 12:00 p.m., and 6:00 p.m. were selected for the interpretation of data. A device that was used for monitoring is called "Testo Saveries System" made in Germany. Its temperature ranges from -20°C up to +50°C. It has several wireless temperature probes with display screens and a router. For the subject study, one probe was installed in each test room on the exterior facing wall at 7 ft level to measure indoor temperature. One probe was installed outside the house for measurement of outdoor temperature. s

On the 7th and 14th days of experimentation, data was transferred to the computer system via the router. Through specific testo saveries software, data was collected and stored. Then tables and graphs were developed based on interpretation and comparative analysis of recorded data. Daily outdoor temperature was noted from the online weather report of Murree to compare with indoor temperature.

4.0 COMPARATIVE DATA ANALYSIS & INTERPRETATION

Comparative Data Analysis of Control Room and Two Test Room Temperature Data was done. Comparative analysis of six-hourly data at 12:00 a.m., 06:00 p.m., 12:00 p.m., and 06:00 p.m. was compared among control room, test room 1, 2, and 3 from 22/01/2019 to 04/02/2019.

4.1. THERMAL PERFORMANCE ANALYSIS BASED ON 6 HOURLY DATA

4.1.1. Temperature Analysis On 22-01-2019

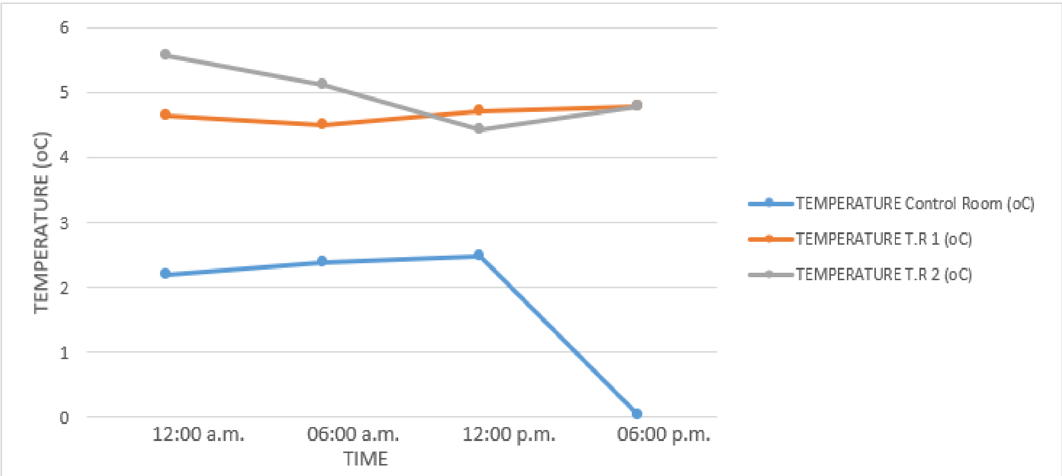

Figure 8. Comparative Analysis on 22/01/2019

The above data shows that during 12:00 a.m. - 6:00 a.m. the temperature of the control room was 2.19°C – 2.37°C, while polyethylene of test room 2 shows better results in comparison to other test rooms. While in the other half of the day test room 1 showed better results. The minimum temperature was at 6:00 p.m. and test rooms had a 5°C temperature difference due to the application of insulation materials. During the 75% duration of a day, the performance of polyethylene insulation in test room 2 was better than in test room 1.

4.1.2. Temperature Analysis On 23-01-2019

The above data shows that on 23/01/2019, the temperature in the control room ranges from 0.21°C to 3.22°C. In test room 1, the temperature varies from 3.48°C to 5.15°C, while in test room 2 it ranges from 4.14°C – 5.16°C. During the maximum duration of a day, the performance of polyethylene insulation in test room 2 was better than in test room 1.

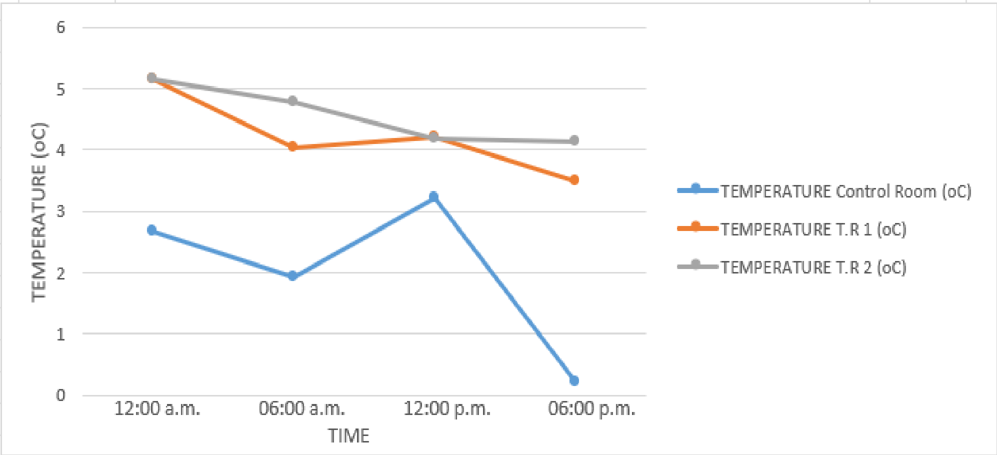

Figure 9. Comparative Analysis on 23/01/2019

4.1.3. Temperature Analysis On 24-01-2019

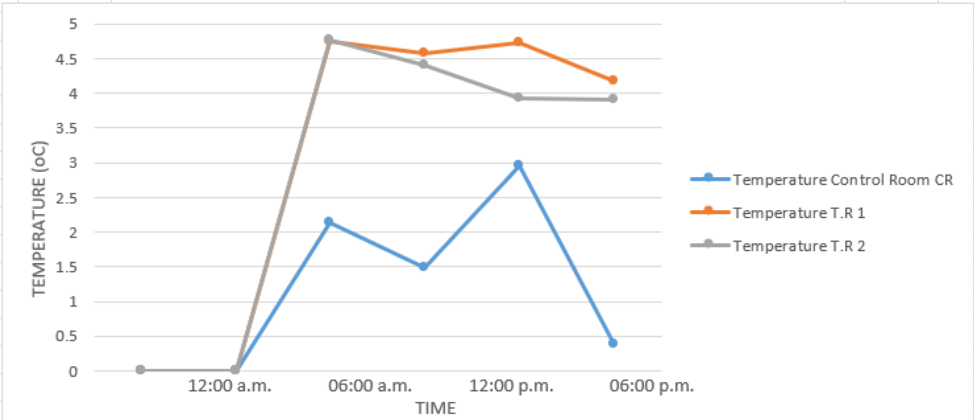

Figure 10. Comparative Analysis on 24/01/2019

The above analysis shows that temperature in test rooms vary from a minimum of 3.78°C to a maximum of 4.76°C, causing 2°C – 4°C improvement in comparison to control room temperature, while the temperature ranges in test room 1 was 4.17°C to 4.75°C and in the last test room 2, the temperature ranges from 3.91°C to 4.76°C. During the maximum duration of a day, the performance of polyethylene insulation in test room 2 was better than in test room 1.

4.1.4. Temperature Analysis On 25-01-2019

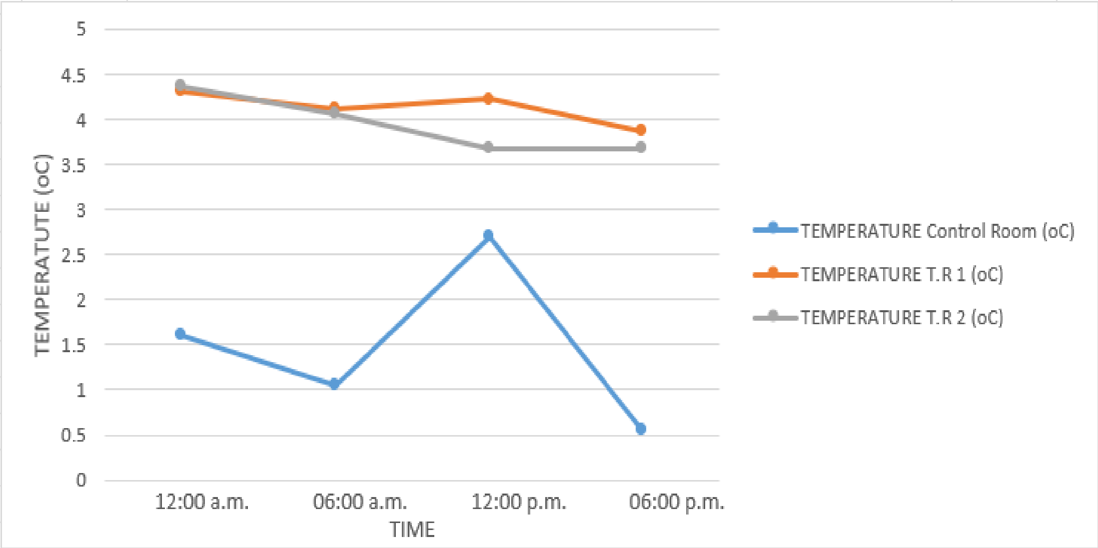

Figure 11. Comparative Analysis on 25/01/2019

On 25th Jan 2019, the control room temperature ranges from 0.55°C to 2.7°C. In test room 1 temperature ranges from 3.86-4.31°C. In test room 2, the temperature range is 3.67°C to 4.36°C. The above analysis shows that during a 100% duration of a day, the performance of polyethylene insulation in test room 2 was better than test room 1.

4.1.5. Temperature Analysis On 26-01-2019

The data shows that on 23/01/2019, the temperature in the control room ranges from 1.1°C to 3.2°C. In test room 1, the temperature ranges from 3.33°C – 4.11°C. The above analysis shows that the performance of extruded polystyrene is better than the other during the 25% duration of the day.

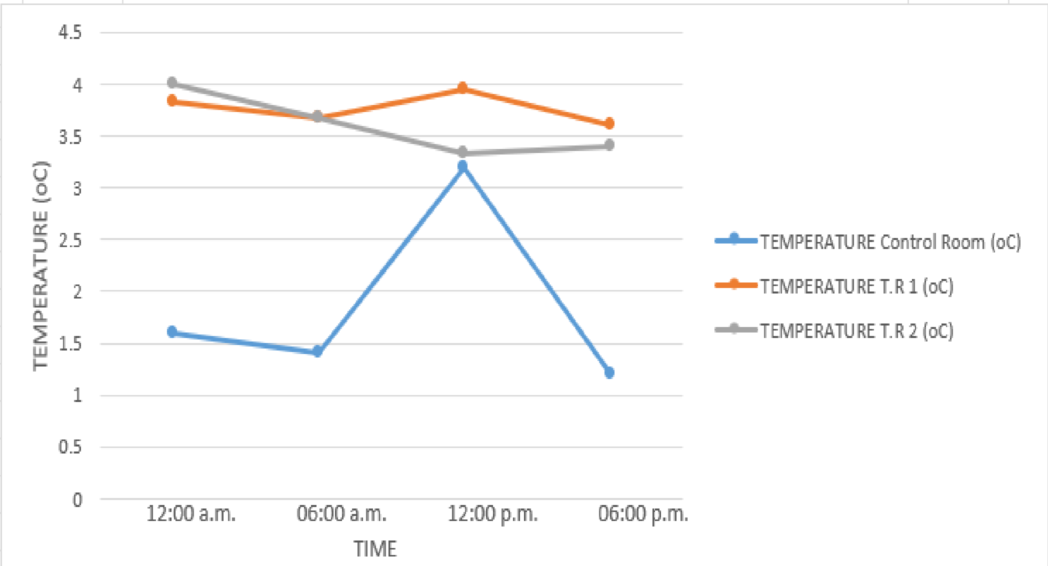

Figure 12. Comparative Analysis on 26/01/2019

4.1.6. Temperature Analysis On 27-01-2019

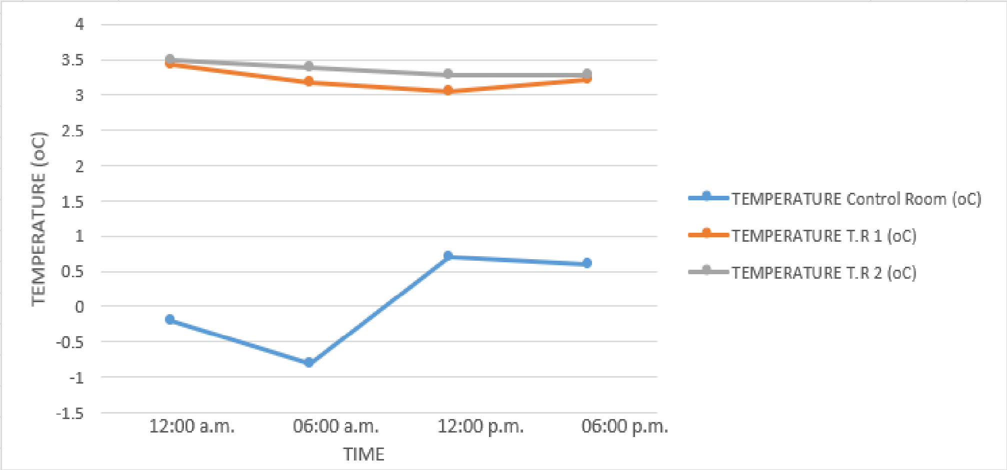

Figure 13. Comparative Analysis on 27/01/2019

The above data shows that during 12:00 a.m. - 6:00 a.m. the temperature of the control room was -0.8°C to – 0.2°C, while polyethylene of test room 2 shows better results in comparison to other test rooms. While in the other half of the day test room 1 showed better results. The minimum temperature was at 6:00 p.m. and test rooms had a 3°C temperature difference due to the application of insulation materials. On 27/01/2019, the above analysis shows that the performance of the two insulation materials is comparable but precisely performance of polyethylene insulation is better than the other.

4.1.7. Temperature Analysis On 28-01-2019

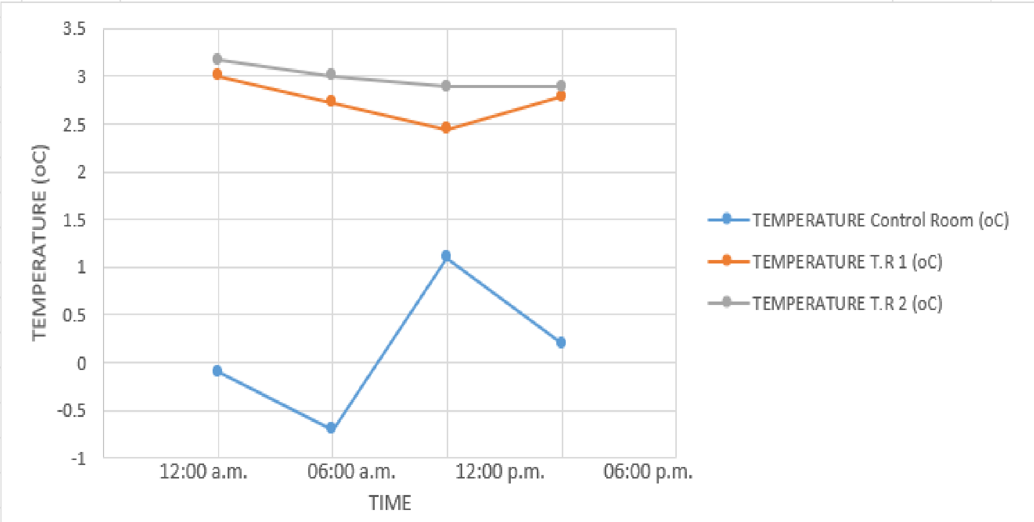

Figure 14. Comparative Analysis on 28/01/2019

On 28/01/2019, the above analysis shows that temperature in test rooms vary from a minimum of 2.44°C to a maximum of 3.17°C, causing 2°C – 3°C improvement in comparison to control room temperature, while the temperature ranges in test room 1 was from 2.44°C to 3.0°C and in test room 2, the temperature ranges from 2.89°C to 3.17°C. The above analysis shows that the performance of both insulation materials is comparable but precisely performance of polyethylene insulation is better than the other material.

4.1.8. Temperature Analysis On 29-01-2019

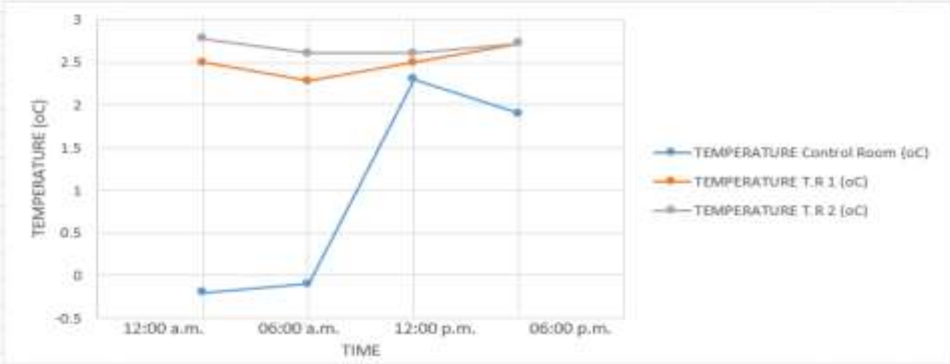

Figure 15. Comparative Analysis on 29/01/2019

The above analysis shows that during a 100% duration of a day, the performance of polyethylene insulation in test room 2 was better than in test room 1. The control room temperature ranges from -0.2°C to 2.3°C. In test room 1 temperature varies from 2.28°C - 2.72°C, while in test room 2, the temperature range is 2.61°C to 2.78°C.

4.1.9. Temperature Analysis On 30-01-2019

The above analysis shows that during a 100% duration of a day, the performance of polyethylene and XPS is comparable. During 12:00 a.m. - 6:00 a.m., the temperature of the control room was 1.5°C to 1.6°C, while in the other half of the day test room showed better results. The minimum temperature was at 6:00 p.m. and test rooms had a 1.5°C temperature difference due to the application of insulation materials.

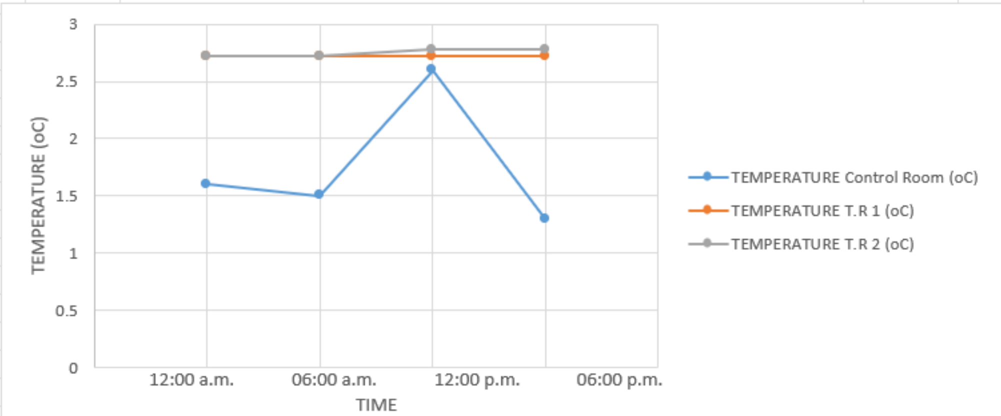

Figure 16. Comparative Analysis on 30/01/2019

4.1.10. Temperature Analysis On 31-01-2019

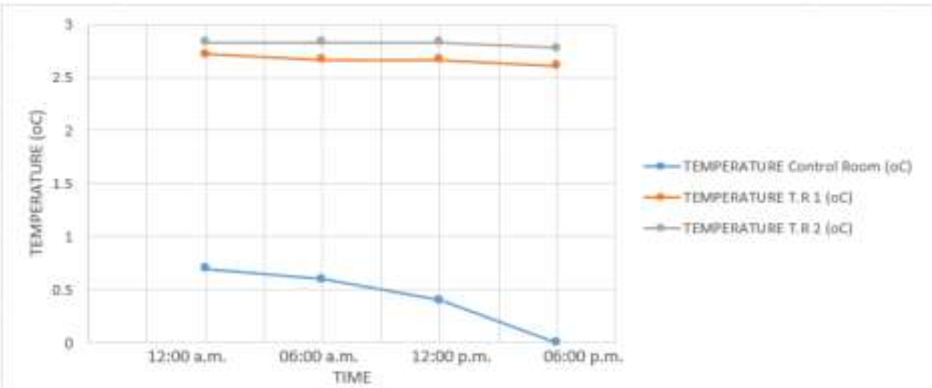

Figure 17. Comparative Analysis on 31/01/2019

The above analysis shows that during a 100% duration of a day, the performance of polyethylene insulation in test room 2 was better than in test room 1. The above data shows that on 31/01/2019, the temperature in the control room ranges from 0.0°C to 0.7°C. In test room 1, the temperature ranges from 2.67°C – 2.72°C, while in test room 2 it ranges from 2.78°C – 2.83°C.

4.1.11. Temperature Analysis On 01-02-2019

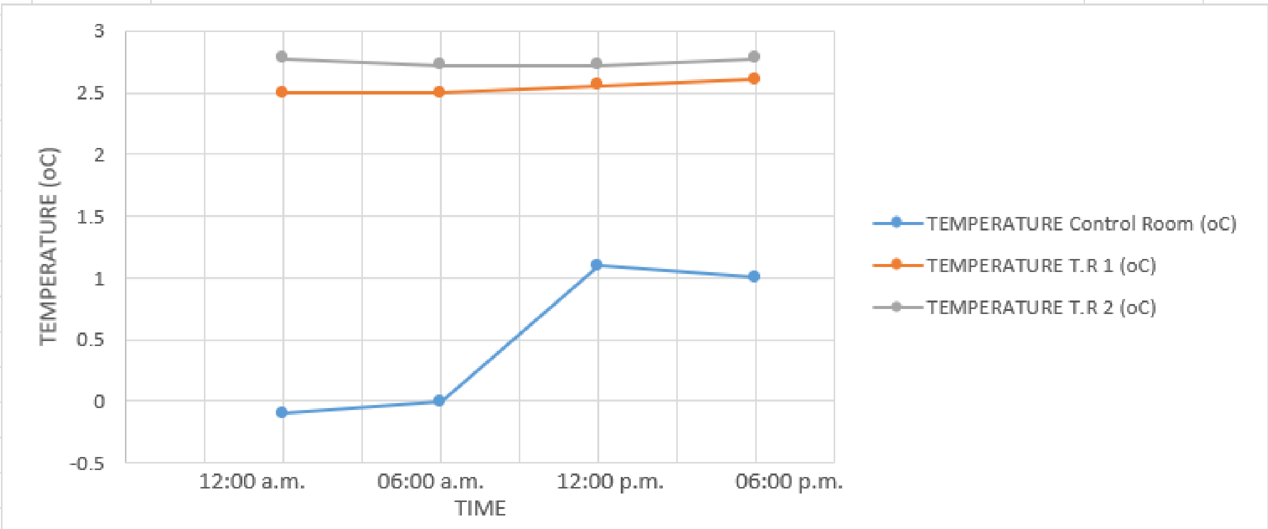

Figure 18. Comparative Analysis on 01/02/2019

On 1st Feb 2019, the control room temperature ranges from – 0.1°C to 1.1°C. In test rooms, the temperature varies from 2.50°C to 2.78°C while polyethylene showed better results than other. The above analysis shows that during a 100% duration of a day, the performance of polyethylene insulation in test room 2 was better than in test room 1.

4.1.12. Temperature Analysis On 02-02-2019

The temperature ranges in the control room were observed from 0.4°C to 2.5°C. The 2nd test room had a maximum temperature of 4.56°C at 06:00 am while throughout the day its performance is better than the other material. The below analysis shows that during a 100% duration of a day, the performance of polyethylene insulation in test room 2 was better than in test room 1.

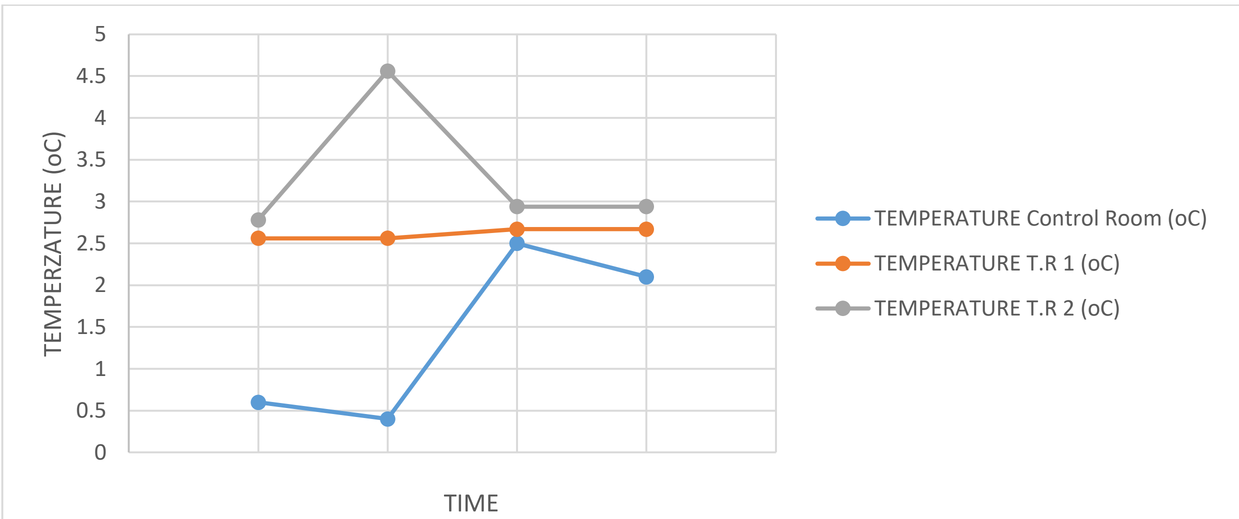

Figure 19. Comparative Analysis on 02/02/2019

4.1.13. Temperature Analysis On 03-02-2019

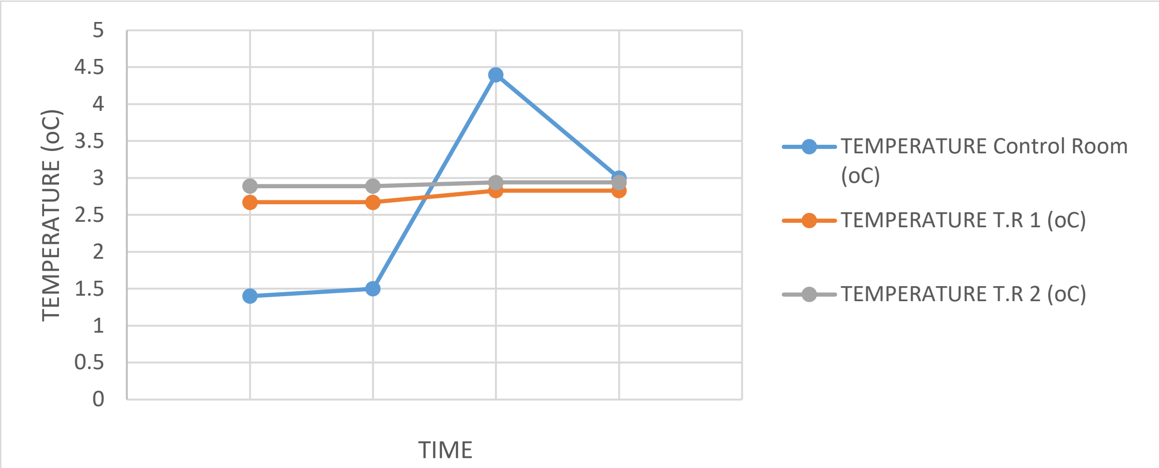

Figure 20. Comparative Analysis on 03/02/2019

On 3rd Feb 2019, the temperature in the control room ranges from 1.4ºC to 4.4ºC. In test room 1, the temperature was from 2.67°C – 2.83°C, while in test room 2 it ranges from 2.89°C – 2.98ºC. During the 100% duration of the day, the performance of polyethylene in test room 2 was better than in the other test rooms. Indoor temperature was maintained in ranges of 2.5°C to 3.0ºC.

4.1.14. Temperature Analysis On 04-02-2019

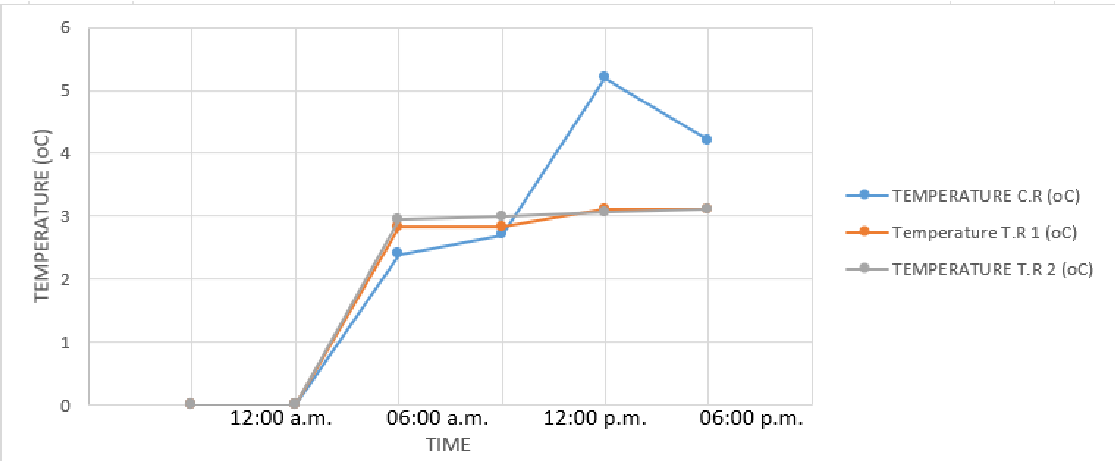

Figure 21. Comparative Analysis on 04/02/2019

The above data shows that during 12:00 a.m. - 6:00 a.m. the temperature of the control room was 2.19°C – 2.37ºC, while polyethylene of test room 2 shows better results in comparison to other test rooms. The minimum temperature was at 12:00 a.m. and test rooms had a 2°C temperature difference due to the application of insulation materials. During the 75% duration of a day, the performance of polyethylene insulation in test room 2 was better than in test room 1.

4.2. Thermal Performance Analysis Based on Daily Basis in Relation with Outdoor Temperature

Daily temperature indoor and outdoor data was also calculated through probes installed in each test room along with one probe installed outside for external temperature measurement. The figure 22 reflects the abrupt fluctuations in outdoor temperature ranging from -3.5°C to maximum 1°C in experimental duration. Further details are illustrated depicting minimum, maximum and average temperature in the control and both test rooms respectively for the period of the almost two weeks in 2019.

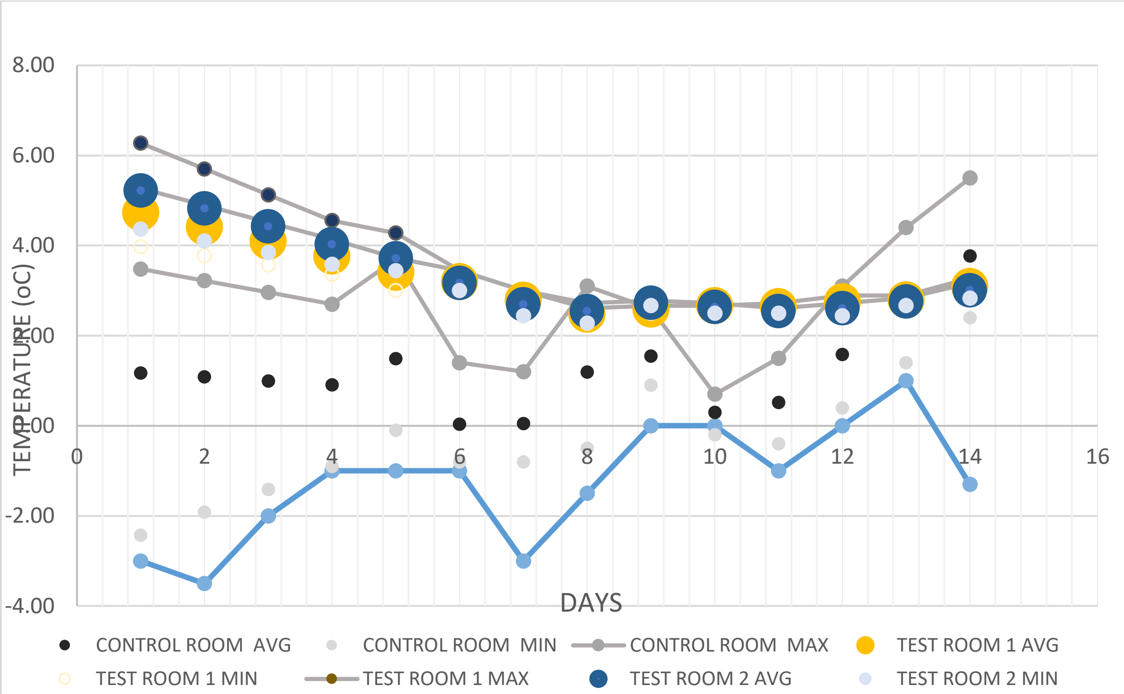

Figure 22. Daily Temperature Comparison of indoor and outdoor

However, in control room, minimum temperature recorded 0°C and temperature in insulated rooms showed steady temperature ranges. Both insulation materials performed comparable to each other, while test room 2 with polyethylene had 7% more thermally effective in comparison to the other material.

4.3. Comparative Cost Analysis of Three Experimented Material Assemblies

Cost analysis of the experimented insulation materials including extruded polystyrene, and polyethylene roll was conducted based on a market survey. The results showed that material assembly II, polyethylene roll with aluminium foil was the more cost-effective material in comparison to the other material as the market rate of polyethylene is only 21 Rs/SFT and that of extruded polystyrene is 98 Rs/SFT.

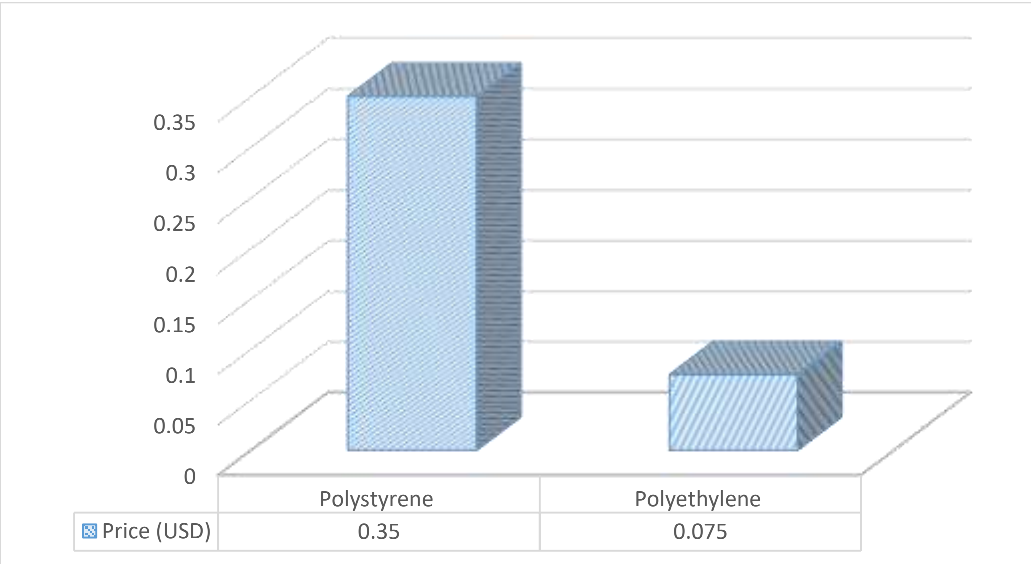

Figure 23. Cost/sft Comparison of Test Materials

The analysis shows that polyethylene roll is the more economical material to be used to achieve better thermal performance in Northern areas of Pakistan.

4.4. Comparative Space Efficiency Analysis of Three Experimented Material Assemblies

In buildings, space efficiency is no doubt a major concern while developing building envelop. While experimenting on the improvement of the building envelope, the thickness and density of experimented materials were significant factors. So, the two materials were compared in terms of their thickness being employed during experimentation. The thickness of extruded polystyrene sheet was 25 mm, while the thickness of the polyethylene roll used was 12.5 mm, half of the thickness of other materials. So, polyethylene was proved to be a preferable option in this concern too.

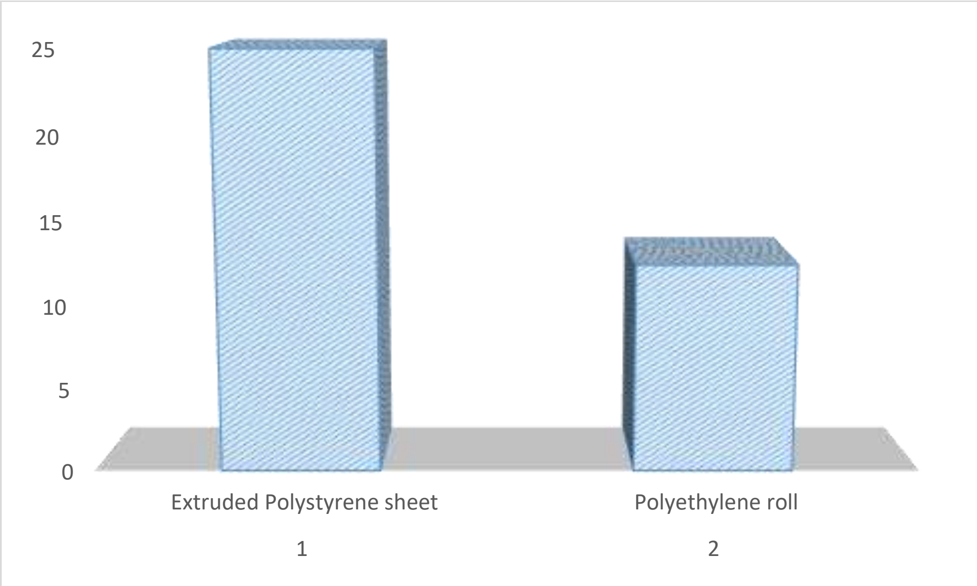

Figure 24. Thickness Comparison of Test Materials

The analysis shows that polyethylene roll is the most space-efficient material having a minimum thickness to be used to achieve better thermal performance in Northern areas of Pakistan.

5.0 CONCLUSIONS

The study aimed to experimentally test the performance of three insulation material assemblies selected based on established thermal conductivity values, ease of application, market availability, density, economics, and affordability of the target market. Based on comparative analysis of 14 days of experimentation data recorded from Testo Saveries System, cost and thickness comparison, the following conclusions can be derived

As per experimentation and results recorded by Testo Saveries System, polyethylene performed better than extruded polystyrene in terms of thermal efficiency. Polyethylene (PE) was proved to be the more cost-effective material in comparison to extruded polystyrene (XPS) as its cost is only 21 Rs. /SFT. Space efficiency was an important concern of occupants due to their compact space planning. In terms of this parameter, the thickness of polyethylene assembly was 1/3rd in comparison to XPS.

6.0 RECOMMENDATIONS

Focusing on the construction and retrofit of existing British period houses is not only a good contribution to knowledge but also a way to ensure energy efficiency, climate resilience, and the continuation of our rich architectural heritage. Existing construction techniques are currently focused, but further research will be focused on combining heritage preservation with energy-efficient practices, we can create sustainable and resilient built environments. A report commissioned by organizations like the National Trust and Historic England suggests that retrofitting the UK’s historic buildings could reduce carbon emissions by 5% annually and generate £35 billion in economic output, focusing on the construction and retrofit of existing British period houses aligns with conservation goals and can serve as a valuable model for other countries, including Pakistan. By combining heritage preservation with energy-efficient practices, we can create sustainable and resilient built environments. By retrofitting heritage houses within conservative principles, we can contribute to knowledge, sustainability, and the preservation of our cultural heritage.

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Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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