Simulation of Thermal Performance and Cost Benefits of Cool Roof Options through Building Engineering System Software

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ABSTRACT

The cool roofs in buildings is a promising option to deal with summer Urban Heat Island (UHI) effects. In context to that, studies on different cool roof materials are widely available; however, there is a dearth of studies on insulating material benefits and implication for tropical and sub-tropical climate zones. This work investigates thermal performance, energy savings and cost benefits of cool roof materials. For this study, simulation of various cool roof materials such as Marble, Expanded Polyurethane Spray (EPS), Poly Vinyl Chloride (PVC), Spray Polyurethane Foam (SPF) , Extruded Polystyrene Foam (XPS), Thermocol sheet, Asphalt tile, Gypsum tile and Jumbolon-board have been carried out using Energy Plus software package. The results of zone air temperature show that maximum zone air temperature occurs in the month of May. The maximum zone air temperature obtained for conventional roof is 32.1ºC, whereas that for Thermocol sheet, SPF, XPS, Jumbolon-board, EPS, marble, PVC, Asphalt tile and Gypsum tile is 28.8, 28.9, 28.8, 29, 29.1, 31.9, 30.5, 30.2 and 30.7ºC respectively. Conventional roof surface outside and inside temperature difference is 2.9^0C, whereas, roof surface outside and inside temperature difference for Thermocol sheet, XPS, Jumbolon-board, SPF, EPS, marble, PVC, asphalt tile and gypsum tile is 9.2, 9.3, 8.7, 7.5, 8.1, 3, 3.1, 3.3 and 2.2^0C, respectively. Notably, XPS, Thermocol sheet, SPF, Jumbolon-board, EPS, Marble, PVC, Asphalt tile and Gypsum tile cool roof materials can save around 5.47, 5.38, 5.35, 5.15, 4.93, 1.09, 2.62, 2.31 and 2.18 MWh annually, respectively for the selected building. The payback period for marble, PVC, gypsum tile and asphalt tile is above 1 year, whereas the effective payback period obtained for XPS, Thermocol sheet, SPF, EPS and Jumbolon-board varies from 3 to 6 months. It is concluded that the cool roof materials may be used effectively to save energy and cost.

Keywords: Energy Modeling, Simulation, Cool Roof, Thermal Performance, Parametric Study.

1. INTRODUCTION

The rapidly growing building energy use has raised concerns globally. The total energy consumption of buildings in residential and commercial sectors has steadily increased and reached as high as 40% in developed countries. Similar trends are reported in Pakistan where energy demand for building is continuously increasing [9]. The heating and cooling demand of a building depends on many factors such as thermal characteristics of building envelope, occupancy schedule, utilization etc. [1, 3]. However, the heat gain through roof is the most significant part of heat transfer through building envelope especially single-story buildings like elementary schools and residential houses. It is proved

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that the radiative thermal properties of building roof has a great effect on annual energy consumption of a building. The solar reflectance of roofs' surface affects indoor air temperature, thus, heating and cooling energy demand increases significantly, when little or no insulation is present at roof [4, 5]. The energy balance at roof surface is determined from incident solar radiation, roof surface reflection and absorption, heat transfer, internal and external thermal index and its structure [7]. In order to reduce heating and cooling demand of building, different reflective materials are used to decrease indoor air temperature. Insulating building roof offers various thermal benefits such as surface cooling, dampen temperature oscillations, increased service life of materials, reduced energy consumption, improved environmental quality etc. [6, 11, 12, 15, 20]. Various studies have found potential benefits, which may vary depending on the type of material, building and roof design, local climate and insulation efficacy. Moreover, cool roof contributes to reduce urban air temperature [8, 10, 11]. The most promising of all are huge energy and cost savings associated with using cooling roof materials [2, 13, 14, 16-19]. There is a dearth of relevant studies on the benefits and implication of insulating material for tropical and sub-tropical climate zones of Pakistan although there are other studies related with building environment [20-22]. Therefore, this study investigates the thermal benefits and implications of cool roof materials through simulation.

2. METHODOLOGY

This study is conducted to find the benefits and implications of using cool roof materials in Hyderabad, Sindh region, which is a tropical city of Pakistan. The simulations are performed in EnergyPlus software for naturally ventilated and air conditioned building to assess thermal performance and cost benefits of various cool roof materials. The cool roof materials considered for this study, are those commonly available in the local market i.e., Marble, EPS, PVC, XPS, Thermocol sheet, Asphalt/ asbestos tile, Gypsum tile and Jumbolon-board. The major output variables are surface outside and inside temperature difference, zone air temperature and cooling energy requirement. The outside and inside roof temperatures are obtained from hourly weather data for Hyderabad. An average of 24 hours surface

temperature of roof used to find daily inside and outside roof surface temperature. The hourly cooling energy required to overcome the heat flux and maintain required room air temperature is calculated from EnergyPlus software. Annual cooling energy requirement is determined from the sum of hourly cooling energy requirement over the year. Since the building is a single room, the room air-temperature is considered as the zone air-temperature. The analysis is based on the comparative study of conventional roof and roof insulated with various cool roof materials. The main factors taken into account are; cost of material, total installation cost, cooling energy demand, electricity cost saved, and payback period.

The size of building, in this research work, is the average size of office room at MUET, Jamshoro, Pakistan. The geographical parameters of the city used in energy plus software package for simulation are shown in Table 1.

Table 1: Geographical Parameters of Hyderabad, Pakistan	
	Object Value
Latitude	25.38(°)
Longitude	68.42(°)
Time Zone	+5.0 (hour)
Elevation	30 (m)

The building is single zone and modeled with the help of EnergyPlus software as shown in Fig.1. It is considered as naturally ventilated as well as air-conditioned in order to get thermal and energy performance of various cool roof materials. In fenestration, the door is in the south wall, and is made-up of wood. The detailed spatial and architectural dimensions and the coordinates of building are given in Fig. 1 and Table 2.
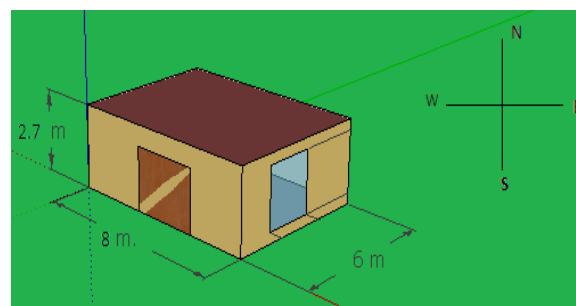

Fig.1: A Single Zone Modelled Building (Length = 8m, Width = 6m, Height = 2.7m, Floor Area = 48m^2)

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In order to assess thermal performance and cost benefits of various cool roof materials, the basic physical properties of cool roof materials and the heat transfer equations solved for evaluating thermal performance, cost and payback period are given in Tables 3-4, respectively.

Table 2: Boundary Conditions for Selected Building					
	Roof	North	East	South	West	Floor
Surface Type	Roof	Wall	Wall	Wall	Wall	Floor
Outside Boundary Condition	Outdoors	Outdoors	Outdoors	Outdoors	Outdoors	Indoors
Sun Exposure	Yes	Yes	Yes	Yes	Yes	No
Wind Exposure	Yes	Yes	Yes	Yes	yes	No
View Factor	0	0.5	0.5	0.5	0.5	0

Table 3: Physical Properties of Cool Roof Materials							
Name	Roughness	Thickness (m)	Conductivity (W/mk)	Density Kg/m^3	Specific Heat (J/Kg-K)	Thermal Absorptance	Solar Absorptance
*Conventional Roof	Medium Rough	0.1	1.7	2400	960	0.8	0.7
Marble	Medium Smooth	0.025	2.08	2710	880	0.903	0.44
EPS	Medium Smooth	0.025	0.035	30	1215	0.9	0.4
SPF	Medium Smooth	0.025	0.025	35	1120	0.9	0.3
PVC	Smooth	0.002	0.17	1350	950	0.9	0.3
ThermocolSheet	Medium Smooth	0.05	0.035	16	1215	0.9	0.4
XPS	Medium Rough	0.05	0.03	32	1190	0.9	0.4
Asphalt Tile	Rough	0.003	0.5	1700	837	0.8	0.3
Gypsum Tile	Medium Rough	0.0075	0.16	850	1900	0.9	0.4
Paint	Medium Smooth	0.000021	1.38	1250	3060	0.8	0.2
JumbolonBoard	Medium Smooth	0.025	0.026	38	1090	0.9	0.4
*Conventional roof is made up of single concrete layer							

Table 4: Parameteric equations for thermal performance evaluation and payback computations	
Parameter	Equation
Heat Transfer through Roof	$q_{roof} = \varepsilon\sigma\left(T4_{roof} - T4_{sky}\right)\left(\dfrac{(1+\cos\beta)}{2}\right) + \varepsilon\sigma\left(T4_{roof} - T4_{gnd}\right)\left(\dfrac{(1-\cos\beta)}{2}\right)$
Zone air Temperature	$qconv = \displaystyle\sum_{i=1}^{n\,surfaces} hc, i\, Ai\, (Ta - Ts, i)$
Thermal Conductivity	$k = \dfrac{Qdx}{Adt}$
Specific Heat Capacity	$Q = C_p \times m \times \Delta T$
Over all Heat Transfer Coefficient	$U = \dfrac{1}{AR_{total}}$
Payback Period	$PB_{cr} = \dfrac{C_{Total}}{CE_{annum}} \times N$
Cost Saving	$C_s = E_s \times CE_{kWh}$
Net Cooling Energy Requirement	$E_{net} = E_{Conv} + E_R$
Installation Cost of Cool Roof Material	$C_{RM} = C_M \times R_A$
Total Cost	$C_{Total} = C_{RM} + C_{labor}$
Life Span of Cool Roof Material	N
No. of Installations/Year	N = 1 / n

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3. RESULTS AND DISCUSSIONS

Simulations have been carried on Energyplus software package for naturally ventilated and air-conditioned buildings. This gives results for thermal performance of cool roof materials, roof outside and inside surface temperature, cooling energy requirement, and energy saving potential of each cool roof material.

3.1 Thermal Performance of Naturally Ventilated Building

The cool roof materials such as; Marble, EPS, SPF,

PVC, Thermocol sheet, XPS, Gypsum tile, Asphalt tile, Diamond Jumbolon-board have been used to evaluate thermal performance of naturally ventilated building. The building is considered naturally ventilated, as air-conditioning is not used to control indoor thermal environment.The hourly weather data for Hyderabad is used to obtain outside and inside roof surface temperature using EnergyPlus. An average of 24 hours temperature is used to find daily outside and inside roof surface temperature. The comparison of results for cool roof's surface outside and inside temperature, for the selected materials, for the month of July, is shown Figs.2-3, respectively.
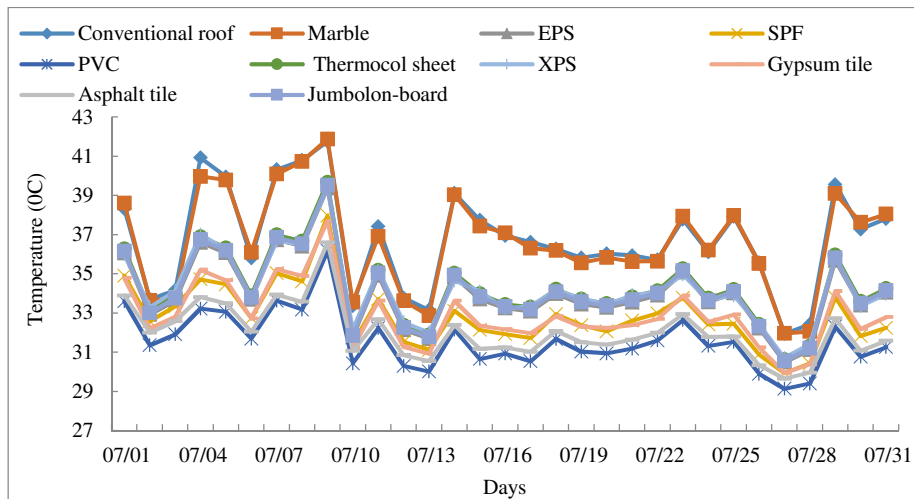

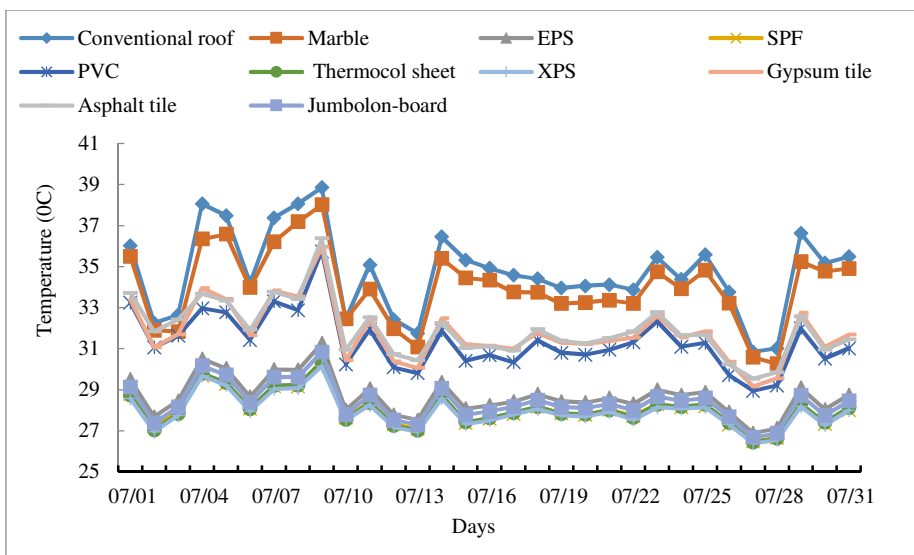Fig. 2: Daily trends of roof outside surface temperature

Fig. 3: Daily trends of roof inside surface temperature

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The outside and inside roof surface temperature difference is 2.9℃ for conventional roof whereas, XPS, Thermocol sheet, jumbolon-board, EPS and SPF are efficient and reduces the roof surface temperature difference by 9.3, 9.2, 8.7, 8.1 and 7.5℃, respectively. The comparatively less efficient cool roof materials such as marble, PVC, asphalt tile and gypsum tile reduces temperature by 3, 3.1, 3.3 and 2.2℃ respectively as shown in Table 5.
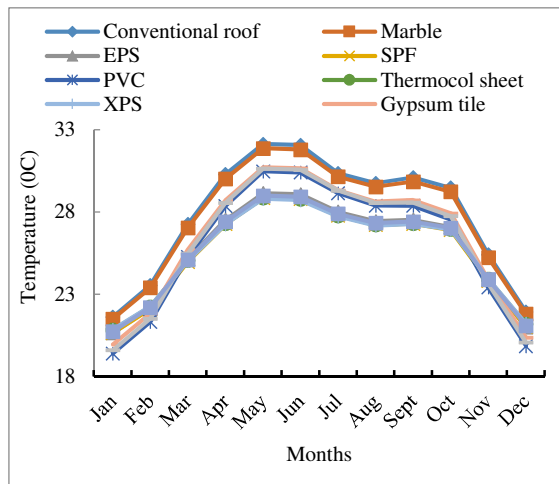

Fig. 4: Monthly Trends of Zone Air Temperature

Table 5: Roof's Outside and Inside Surface Temperature Difference			
Cool Roof Material	Roof Surface Outside Temperature (℃) (maximum)	Roof Surface Inside Temperature (℃) (maximum)	ΔT (℃)
Conventional Roof	41.8	39	2.9
Marble	41.8	38.8	3
EPS	39.3	31.2	8.1
SPF	37.9	30.4	7.5
PVC	38.1	35	3.1
XPS	39.4	30.1	9.3
Thermocol Sheet	39.6	30.4	9.2
Asphalt Tile	36.6	33.3	3.3
Gypsum Tile	37.8	35.6	2.2
Jumbolon-Board	39.5	30.9	8.7

where ΔT = Temperature Difference

Zone air temperature is the indoor temperature of air volume present in a building. A comparison of zone air temperature of different materials with conventional roof and with each other has been made on the basis of thermal performance as shown in Fig. 4. This depicts that maximum zone air temperature is observed with conventional roof in building. While PVC, EPS and Jumbolon-board cool roof materials have lower zone air temperature when applied to building's roof.

The average monthly zone air temperature of conventional roof and cool roof materials like marble, EPS, SPF, PVC, XPS, Thermocol sheet, Gypsum tile, Asphalt tile and Jumbolon-board foam have been simulated and presented in Fig. 4. The month of May found to be the hottest where the maximum zone air temperature reaches to 32.1℃ with conventional roof whereas maximum zone air temperatures obtained for Thermocol sheet, SPF, XPS and Jumbolon-board is 28.8, 28.9, 28.8 and 29℃ respectively. Furthermore, comparatively less efficient materials i.e., marble, gypsum tile and EPS observed zone air temperature of 31.9, 30.5 and 30℃, respectively.

3.2 Thermal Performance of Air-Conditioned Building

The thermal performance of conventional roof is compared with various cool roof materials in an air-conditioned space. The thermostat set temperature is set at 25℃ as upper and 17℃ as lower limit for attaining comfortable indoor thermal environment whereas applied cooling load is in the form of lighting and occupancy. Cooling energy requirement is one of the major output variables to simulate in Energyplus software package. It shows cooling energy required to overcome the heat transfer and maintain the set point temperature.

The energy required to overcome the heat is obtained from simulation as shown in Fig. 5. Results show that highest annual cooling energy is required when the building has a conventional roof i.e., 34566 MJ. Furthermore, total annual cooling energy requirement with other selected cool roof materials is given in Table 6.

The net cooling energy saved is calculated by subtracting the cooling energy required by a building with cooling roof surface from that required by a building with conventional roofing. A comparison of net cooling energy saving with different cool roof materials is shown in MJ and in kWh in Table 7.

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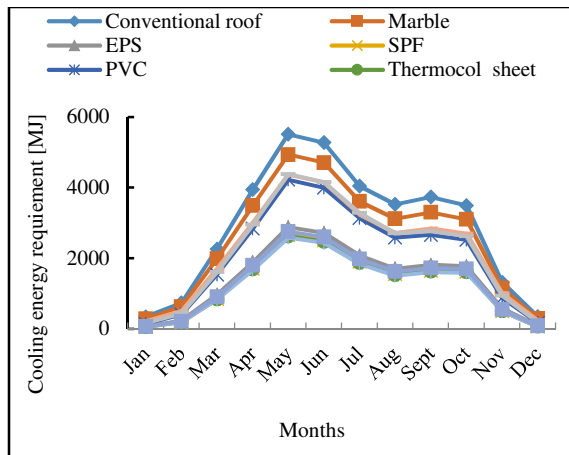
Fig. 5: Monthly Trends of Colling Energy Required

Table 6: Total Cooling Energy Required Per Year

Cool Roof Materials	Total Cooling Energy Required/Annum (MJ)
Conventional	34566
Marble	30638
EPS	16807
SPF	15279
PVC	25133
Thermocol Sheet	15181
XPS	14874
Gypsum Tile	26714
Asphalt Tile	26220
Jumbolon-Board	16015

Table 7: Net Cooling Energy Savings per Annum

Cool Roof Materials	Net Cooling Energy Saved/Year (MJ)	Annual Energy Saved/Year (kWh)
Marble	3928	1091.1
EPS	17759	4933
SPF	19287	5357
PVC	9433	2620
Thermocol Sheet	19385	5384
XPS	19692	5470
Gypsum Tile	7852	2181
Asphalt Tile	8346	2318
Jumbolon-Board	18551	5153

The results show that the efficient cool roof materials such as XPS, thermocol sheet, SPF and jumbolon board foam were able to save 5470, 5384, 5357and 5153 kWh of energy per annum, respectively.

Whereas, EPS is competitive and shows better results to save annual cooling energy of about 4933 kWh. However, PVC, Asphalt tile and Gypsum tile showed comparatively low cooling energy saving potential.

3.3 Cost Saving of Cool Roof Materials

The cost savings can easily be computed as 1 kWh of electricity costs approximately PAKRS. 10/-. Fig. 6 shows percentage cost savings by comparing the electricity cost required to cool a building with conventional roofing and that with cool roof materials. The results show lower cost savings with marble as its installation cost is higher. On the other hand, the optimum cool roof options include XPS, Thermocol sheet, SPF and Jumbolon-board that offers cost savings from 15-16% annually. EPS, on other hand, seems to be a moderate option with cost savings per annum of up to 14%. The other cool roof materials i.e. gypsum tile, asphalt tile and PVC offers less than 10% cost saving annually.
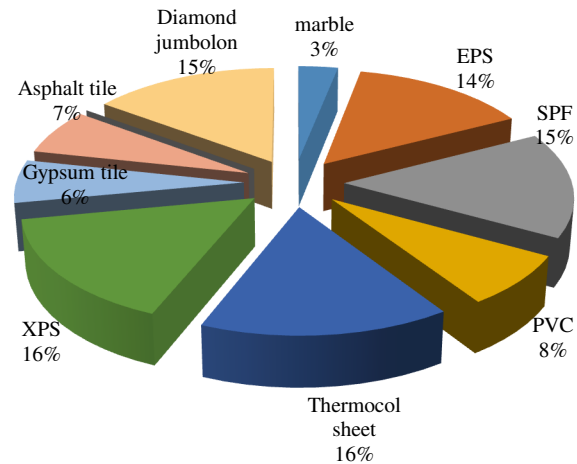

Fig. 6: Cost Saving of Cool Roof Materials

3.4 Payback Period of Cool Roof Materials

The cost comparison of various cool roof materials is carried out along with their payback period and the most effective cool roof option has been appraised. Some of the assumptions have been made like 2 labors and one day is required for installation of each option, labor cost per day is PAKRS. 1000/- and cost of electricity is PAKRS. 10/- per unit kWh.

The cost per square meter of each cool roof material has been obtained from local market as shown in Table

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8. The installation cost and payback periods are calculated using relevant equations given in Table 4. The values of installation cost and annual cooling energy savings are used to obtain payback period.

Table 8: Cost of Cool Roof Materials	
Cool Roof Material	Cost/sq.m
Marble	646
EPS	151
SPF	106
PVC	1076
ThermocolSheet	250
XPS	280
Gypsum Tile	860
Asphalt Tile	753
Jumbolon-Board	387

The type of expected life of material has the biggest impact on payback period although other factors such as exposure to the sun, slope of the roof, type of maintenance etc. do play important role. The average life span of material is used to calculate installations per year of different cool roof materials, as shown in Table 9, and use this data to calculate payback period.

Table 9: Life Span of Cool Roof Materials			
Cool Roof Materials	Life Span (years)	Average Life Span	Installations/Year (N)
Marble	20-30	25	0.04
EPS	10-15	12.5	0.08
SPF	15-20	17.5	0.06
PVC	15-30	22.5	0.04
Thermocol Sheet	5-10	7.5	0.13
Asphalt Shingle	15-18	16.5	0.06
XPS	10-15	12.5	0.08
Gypsum Tile	5-10	7.5	0.13
Diamond Jumbolon-Board	10-15	12.5	0.08

The payback period is obtained using the total installation cost, cost saving from electricity and installations per annum as shown in Tables10-11, respectively in relevant equation.

The payback period of each cool roof material is) calculated with two methods. In one method life span of cool roof material has not been considered (Fig. 7(a)) and in the other case life span material is considered (Fig. 7(b)). In the case of without considering life span the cool roof materials, Thermocol sheet and XPS needs payback period of approximately 3 months whereas SPF and Jumbolon board has payback period of about 4 months. The EPS

has a bit higher payback period of 6 months. However, all these options seems energy efficient and cost effective. On the other hand, the cool roof materials Asphalt tile, PVC, Gypsum tile and marble seems less efficient with payback period varying from 1.5 to 3 years.

Table 10: Cost Saving of Cool Roof Materials	
Cool Roof Materials	Cost Saving/Year (Rs)
Marble	10911
EPS	49330
SPF	53570
PVC	26200
Thermocol Sheet	53840
XPS	54700
Gypsum Tile	21810
Asphalt Tile	23180
Jumbolon-Board	51530

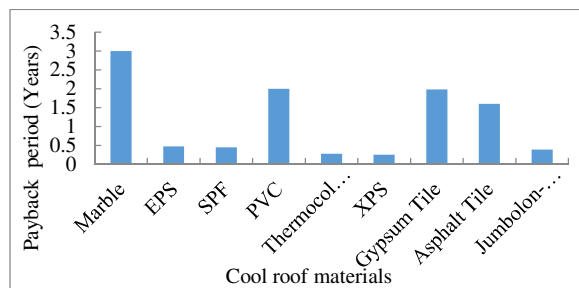| Table 11: Total Installation Cost	
Cool Roof Materials	Total Installation Cost for Roof Material (Rs)
Marble	33008
EPS	9248
SPF	7088
PVC	53648
Thermocol Sheet	15440
Asphalt Tile	38144
XPS	14000
Gypsum Tile	43280
Diamond Jumbolon-Board	20576

Fig. 7(a): Payback Period of Cool Roof Materials without considering Material Life Span
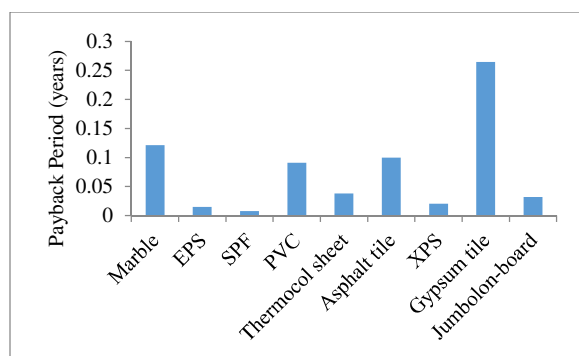

Fig. 7(b): Payback Period of Cool Roof Materials with and without considering Material Life Span

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4. CONCLUSION

This work discusses thermal performance, energy saving, cost saving and payback period of using cool roof materials. This work has been carried out by simulating a building in the hot and dry weather of Hyderabad, Pakistan where cooling energy demand is normally very high with high electricity-bills. The comparative analysis of a building with conventional roof and the roof installed with different cool roof materials. The Conventional roof's surface outside and inside temperature difference is 2.9°C. Thermocol sheet, XPS and Jumbolon-board foam can be considered efficient which reduces surface inside temperature by 9.2, 9.3 and 8.7°C respectively. The energy saving potential of EPS, XPS, Thermocol sheet, SPF and Jumbolon-board was 4.9, 5.4, 5.4, 5.3 and 5.1 MWh, respectively. The cost savings for XPS, Thermocol sheet, SPF, Jumbolon-board and EPS are 54,700, 53,840, 53,570, 51,530 and 49,330 rupees. The effective payback period obtained for XPS, Thermocol sheet, SPF and Jumbolon-board is 3-5 months.

5. NOMENCLATURE

$I_{t\theta}$	Incident solar radiations
$\tau E_{t\theta}$	Direct solar radiations
$(U/h \times \alpha Et\theta)$	Effective heat transfer from absorbed radiations
$U(T_o\text{-}T_i)$	Effective heat transfer due to temperature difference
$Fsky = (1+\cos\beta)/2$	View factor of roof to sky
$F_{gnd} = (1-\cos\beta)/2$	View factor of roof to ground
K	Thermal conductivity of a material in W/m-k
Q	Heat transfer in Joules
A	Area of material in m^2
Dx	Thickness of material in meters
Cp	Specific heat capacity of material in (j/Kg-k)
M	Mass of material in (kg)
ΔT	Temperature difference (°C)
U	Overall heat transfer in W/m^2k
A	Area in m^2
R	Thermal resistance °C/W
C_{RM}	Installation cost of cool roof material
C_M	Cost of material/sq. m
R_A	Area of roof
C_{Total}	Total cost

ACKNOWLEDGEMENT

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