EFFECT OF ROOFING ON THE THERMAL COMFORT IN DOMESTIC BUILDINGS IN SRI LANKA

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ABSTRACT

This study aimed to investigate the indoor thermal performance of different roofing and ceiling alternatives and their configurations used for residential buildings in Sri Lanka. In this regard, a basic residential building was selected as the reference case.

Five roofing and two ceiling materials were used and combinations of roofing/ceiling types were obtained to investigate the relative effect on the indoor temperature fluctuations and energy use. Both 2-pitched and 4-pitched roof designs were selected and the buildings were aligned for two orientations; east-west and north-south. The two-pitched bare roof (no-ceiling) constructed with a commonly used old cement fiber sheet (asbestos) material was selected as the reference case. The computer software tool, DEROB-LTH (version 99.02) was used to model the building and evaluate the cooling energy use and the indoor air temperatures. These parameters were evaluated hourly, daily and monthly basis for three different months of the year 2011.

The simulation results have shown that there is a noticeable difference in cooling energy use and indoor air temperature with the changes in roofing and ceiling materials as well as with different roof configurations. The results suggest a positive conclusion towards the feasibility of using burnt clay calicut tiles with wooden plank flat suspended ceiling, it was further shown that the common roofing material used in the Sri Lankan residential building industry. Asbestos sheet is not feasible in terms of energy cost and indoor thermal performance.

Finally, an economic analysis / cost-benefit analysis was performed in order to investigate the economic viability of applying different roofing/ceiling combinations and the results indicate that most of the designs are feasible in terms of the cooling energy use and additional expenditure incurred. Simple pay back periods were less than 4 years in most cases. The results also elaborated that even though new calicut tile roof design is expensive, it is worth paying for considering the climate of Sri Lanka. It is suggested that through experimental validation and modeling, these results could be further validated to enhance the accuracy of the output obtained from DROB-LTH.

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LIST OF ABBREVIATIONS

CC	-	Conventional Calicut
E-S	-	East-South
NA	-	New Asbestos
NC	-	New Calicut
N-S	-	North-South
OA	-	Old Asbestos
PA	-	Painted asbestos
S-E	-	South-East

CHAPTER 1: INTRODUCTION

1.1 Background

In Sri Lanka, at present, the selection of roof type and roof orientation of residential buildings is primarily based on cost and aesthetic considerations, without much attention to the thermal performance of the roofing materials. However, since Sri Lanka is a tropical country, the roof is exposed to the sun more often than the walls because of the high solar altitude angles. Therefore, in the building envelope of such a building, the roof should be most important element and should receive the highest attention.

Sri Lanka is located between latitudes $5^0 55'$N and $9^0 51'$N. When a building in Sri Lanka is considered, the sun will be directly over the building for two months of the year (i.e. April and September) and the sun will be in North for nearly five months from mid April to early September and in South for another five months from mid October to mid March. Therefore, for five months of the year, the Northern walls will be shielded and for another five months the Southern walls will be shielded from the sun. Throughout the year, in the morning, the Western walls will be shaded and in the evening, the Eastern walls will be shaded. However, the roof will be exposed to the sun throughout the day time round the year.

The undesirable effects of the roof could be mitigated by careful selection of roof cover material, roof orientation, ceiling type and material etc. However, at present, the selection of roof type for especially residential buildings is primarily based on cost and aesthetic considerations, without much regard to its thermal performances. This leads to warm indoors, and occupants of such houses are compelled to use fans to overcome the thermal discomfort indoors. This requires high energy consumption as a whole in the country and is not a healthy development for a country that is threatened with energy scarcity.

Thermo-physical as well as solar radiation properties of roofing material plays a vital role in order to obtain a thermally comfortable indoor climate conditions. Dark colour roofing material promote warm indoor due to its high solar absorptivity (Bansal, Garg, & Kotharil, 1992). Researchers at LBNL have estimated that every 10 percent increase in solar reflectance could decrease surface temperatures by 7^0F (4^0C). Therefore, proper selection of roofing material is needed nowadays.

1.2 Problem statement

In this research study, the indoor thermal climate of a basic residential building equipped with different roofing alternatives is analysed. For that, three (03) different roofing materials are chosen mainly to cover almost all roofing material used in Sri Lankan residential buildings. The cement fibre sheet conventional burnt clay calicut tiles and recently introduced new calicut tiles are selected as roofing materials. Three types of cement fibre sheet roofing namely new un-painted sheet, top surface painted sheet and aged fungi developed sheet were included to cover all categories of cement fibre sheet roofing configuration. The solar radiation properties such as reflectivity, absorptivity and emissivity values were chosen closely as so that to obtain results as much as close to actual results. Two pitched roofing style with two configurations of ceiling; slope and flat suspended types were considered. Both cement fibre sheet and wooden planks were chosen as ceiling materials.

The indoor thermal environment is analysed on hourly basis. The study is carried out by computer simulations with the DEROB-LTH (version 99.02) program. This program has recently been supplemented with an improved angular dependent calculation module for windows.

1.3 Aim and objectives

1.3.1 Aim

The project aims to identify most appropriate roofing and ceiling configuration in terms of indoor thermal comfort for a residential building in Sri Lankan climate. It is intended that the research findings will contribute to the development of a frame work to categorize the roofing types on a more scientific basis than today, so that highly efficient roofing alternative/s are applied in the local building sector.

1.3.2 Objectives

The study also pursues the following objectives:

- To carry out a survey that leads to identify roofing material used in the building sector in Sri Lanka today.
- To study the thermo-physical properties of roofing and ceiling materials.
- To evaluate the hourly, daily and monthly indoor temperature fluctuations with different roofing alternatives.
- To identify which parameters (i.e. roofing type or orientation) primarily influence the indoor thermal climate in a building.

1.4 Outline of the Thesis

The major body of this research project consists of six chapters. A background for the study, a summary of its contents is given is in chapter one. In chapter two, an overview of the different roofing materials used nowadays in Sri Lanka is presented. Chapter three is a review regarding mainly performance requirements and energy aspects of roofing materials. It is based on earlier reports/books. Chapter four deals with the methodology used in this study. Results of the simulations and a discussion are included in chapter five. Conclusions from this work and recommendations for further research are finally given in chapter 6.

CHAPTER 2: LITERATURE SURVEY

2.1 Introduction

In this section, some historical background of roofing materials used in the residential buildings in Sri Lanka is presented. Different roofing and ceiling materials presently used in the sector and their various configurations is also briefly discussed in this part.

2.2 Development of residential roofing materials

Many new materials have been introduced to the construction market and new building techniques have been developed recent past. Since roof is the most exposed building element to the climatic conditions and it modifies the internal temperature as well therefore the selection of roof covering, insulation and ceiling materials are important. However the selection of roofing materials according to the requirement has been a difficult task for domestic clients because a lack of data of the performance of the roofing materials and it is a common problem now days. But it is important to note that each locality requires a different roofing material for best results. Thermal performance of some of the more common roofing materials used in structures today is investigated here with the available data sources. cadjan roofing system was very common and popular in rural areas in Sri Lanka and still using in villages for small houses and as decorative roofs in cities and cultural centers as well.

Figure 2.1: House with cadjan roof (Source: wikipedia.org/wiki/Cadjan)

2.2.1 Clay tile roofing

This type of roofing is used in homes with European design but commonly use in Asian and tropical regions. There are different brands and makes of clay tile roofing some of which are glazed or coloured. This material is good to use as it's resistant to insects, mould and decay. It is fireproof and would definitely last a long time. Note that this is quite expensive to install and need heavy roofing structure. Some areas of the country is popular for manufacturing clay tiles. Ex: Dankotuwa, Bangadeniya etc. Presently some manufactures specially developed the clay tiles with different shapes, colours and surface finishes etc.

- **Half Round Tile (Traditional Sinhala Tile)**

This is made by using clay and sand mixture and typical local technology is used in the industry. This is curved shape and both ends have different radius to lay out the tile. It is very popular in 1950's and required strong wooden roofing structure due to the weight of the tiles because more number of tiles is used since the greater length of overlapping. The cooling effect of this method is higher because the thickness of the roofing cover is more and there are some ventilation gaps due to less sealing of the tiles. But there are some issues in water seepage and small animals used to live in between the tile gaps. Optimum roofing angle is necessary to get proper flow of the storm water.

Figure 2.2: Conventional clay tile roof (Sinhala Tile)

- **Calicut Tiles**

Calicut tile (CC) is also made by clay and sand mixture and this is much popular than the half round tile and the cost of wooden roofing structure is low compare to the half round tile. The overlapping length is low and the weight per square area is lower than the half round tile. Still the water seepage problem is there and optimum roofing angle is required to flow storm water properly. The traditional handmade half round tile has almost been replaced by the calicut tile. The first interlocking calicut tile was first introduced to Sri Lanka by the British in the 19^{th} century. The calicut tile industry is basically located concentrating the sedimentary clay deposits of Kelani and Ma-Oya. The calicut tile failed to gain popularity probably the strength of the roof structure is higher but lower than the structure for half round tile. Required standard - SLS 2:1975

Figure 2.3: Pitch Calicut tile roof

The two clay types available at Waikkala and Bangadeniya are mixed in a special tank in 3:1 ratio together with water. It is mixed by using pug mill machine applying heavy force. The mixture of clay is separated in to 1 ¼" wide Slices. The measurement of the final clay piece consists 14" x 9" x 1 ¼" stored in a separate area.On the following day, a mixture of Kerosene and Coconut Oil is applied to these clay pieces and the tile shape could be formed using the Press dye. The weight of the clay tile is now 8 ½ g. The raw clay piece is further shaped up on a wooden plate by cutting all unnecessary forms and stored in wooden racks.

These clay tiles are normally dried in those wooden racks up to 3 or 4 days. However this period is decided depending on the climatic atmosphere. Then they are transferred to the oven. The consumption of such a oven is normally 12000 tiles. Then the oven door is sealed with bricks and clay. The clay tiles inside the oven are dried for about 5 days with medium temperature and for about 24 hours with higher temperature. Then the oven is sealed with dampers for one full day and dampers will be removed on the second day. The door is opened on the third day and the clay tiles are taken out on the fourth day. After this complete process, the final weight of the clay tile is about 2 ½ grams. These clay tiles are graded as 1, 2 or 3 by experienced workers.

This type was very popular before but due to various quality issues it becomes to secondary level tile and people compare with price and quality of the product and moves to another products, especially asbestos cement sheets.

According to the industrial investigations the production of calicut tile especially involving the man power with conventional methods. But the factory owners face to short of skill man power problems and results to drop down the industry.

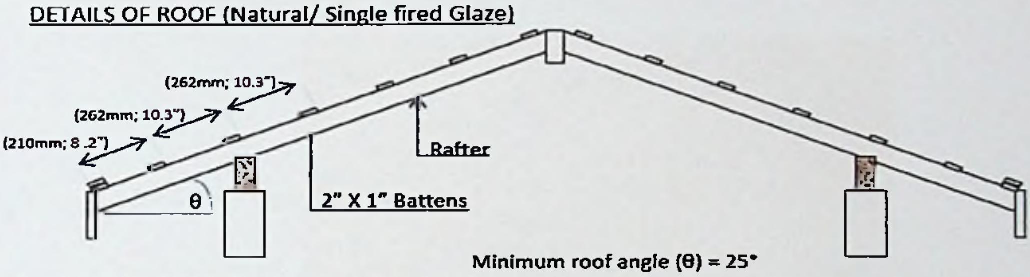
- **New Calicut Tiles**

There are several products developed by the manufactures ex. Samson Rajarata etc. New calicut tile (CC) is also made by clay and sand mixture and developed the shapes and surface texture to flow storm water easily and applying light colours and maintain smooth surface to increase the solar heat reflection and to reduce the heat absorption properties. Refer to the data source of Samson Rajarata Tile (pvt) Ltd, the natural clay converts to high quality roofing tile. The plant is located in Thirappane about 20km from Anuradhapura close to Nachchaduwa wewa and they guaranteed there is no health risk of this clay tile.

Figure 2.4: Developed calicut tile

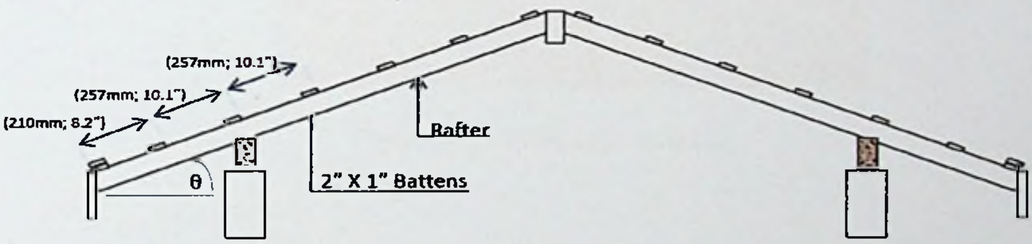
Samson Rajarata Tiles (Pvt.) Ltd.	Title:	Prepared By:	Thusitha	
	LAYING INSTRUCTIONS S1 - TILES	Approved By:		
		Dept./Area:	Sales & Marketing	
		Document No:	SRT-MK-SP001	
		Date of Issue:	04-04-2014	
SPECIFICATIONS	Rev. No:		Page No:	1 of 1

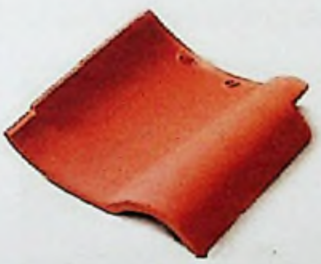
DETAILS OF ROOF (Natural/ Single fired Glaze)



Minimum roof angle (θ) = 25°

DETAILS OF ROOF (Double fired Glaze)





Length (mm)	310 ± 3
Width (mm)	307 ± 3
Effective Length-Natural and Single fired Glaze (mm)	262 ± 2
Effective Length -Double fired Glaze (mm)	258 ± 2
Effective width (mm)	250 ± 3
Unit weight (Kg)	3.1 ± 0.05
Water absorption (%)	< 10
Transverse Breaking Load (N)	> 1000
Coverage (No. tiles per 100 sq.ft)	142

Figure 2.5: DSI Normal curved calicut tile and data sheet

Source: (Samson Rajarata Tiles (Pvt) Ltd)

2.2.2 Cement Tiles

The shapes are similar to the developed Calicut tiles and made by cement and sand mixture. The cost of the wooden roofing structure is lower than the above since the thickness of the tile is low compare to the above. Improved products with the smooth surface finish and light coloured for high reflectivity and low absorption properties are available in the market.

Figure 2.6: Concrete roof tile

2.2.3 Asbestos roofing sheets

Figure 2.7: New asbestos sheet roof

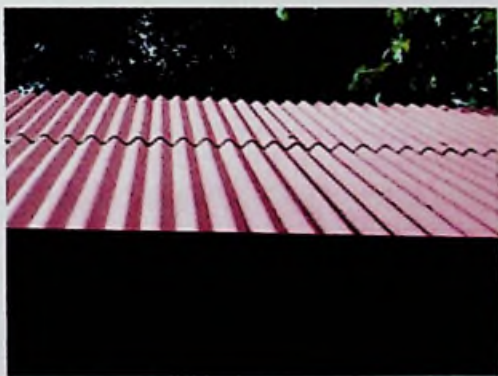


Figure 2.8: Painted asbestos sheet roof

Asbestos cement roofing sheets are high strength, low cost roofing solution for industrial building sector and domestic residential buildings in Sri Lanka. The main advantage is the cost per square meter is less compare to the other roofing materials and the roof structural cost is of wooden is also less compare to the conventional calicut and developed calicut tile roofs. There are two main companies manufacture cement fibre sheets in Sri Lanka using imported asbestos fibre. A mixture of Portland cement and asbestos fibre is wetted and pressed in to a flat or corrugated sheet. The commonly available asbestos sheet technical data are given bellow tables.

Figure 2.9: Old fungi developed asbestos sheet root

The specifications of cement fibre asbestos roofing sheet is standardized by SLS 9:1988

a. Breaking load	$5kN/m^3$
b. Density	$1200kg/m^3$
c. Water absorption	28% of dry mass
d. Water tightness	No formation of drops
e. Resistance to acidified water	$1.15kg/m^3$

Table 2.1: Table of roof angle data

Roof Angle Chart			
Angle (A)	**Base (L) cm**	**Height (H) cm**	**Remarks**
10°	30.4	5.4	Not Suitable
11°	30.4	5.9	
12°	30.4	6.5	
13°	30.4	7.0	
14°	30.4	7.6	
15°	30.4	8.1	Not Recommended
16°	30.4	8.7	
17°	30.4	9.3	
18°	30.4	9.9	Most Suitable For Sri Lankan Climate
19°	30.4	10.5	
20°	30.4	11.1	
21°	30.4	11.7	
22°	30.4	12.3	
23°	30.4	12.9	
24°	30.4	13.5	
25°	30.4	1.2	

Source: Technical broachers of RHINO roofing products

Most popular and established asbestos roofing sheet manufactures in Sri Lanka are Rhino roofing company and Elephant roofing Product Company. According to their market surveys the users of their roofing sheets are happy with the affordable prices but the most common complaint is less thermal comfort inside the houses.

According to the literature sources and technical broachers of RHINO sheets can be laid with a minimum pitch of 18^0. The conditions, to which the roof will be exposed due to geographical position and in case of large rafter lengths, should be taken into consideration. Rhino sheets should always be laid with mitred corners. The outer corrugation of one side is lower than the other corrugations. This low corrugation could face forward in the laying direction.

2.2.4 Metal roofing sheets

Metal roofing is also used in the domestic roofing especially in rural areas and upcountry state dwellings. Galvanized sheets are commonly use and especially the properties like low thermal capacity, high reflectivity are useful in some roofing applications. But the occupants suffer due high rate of heat transmittance to the indoor environment. But the life span of the metal roofs are high and the roofing structural cost is also less compare to the other roofing materials. This type of material comes in different forms and makes. There is the corrugated galvanized iron that comes in 8, 10 and 12 feet in length. There is also the pre-painted long span that is called ribbed roofing. It used to be the zinc and copper were the more popular metal sheeting used but they are now quite expensive that galvanized or steel roofing are now used. Of all the roofing materials in the market today, this is the cheapest.

2.2.5 Other roofing materials

Asphalt composition roofing shingles are the perennial favorite, and this is due to many factors: attractive cost, wear ability, and fire retarding properties. Asphalt shingles typically a durable material and in practice using longer than 30 years in most of European countries. Roofing shingle manufacturers no longer produce only the usual flat 3 tab asphalt shingle. Now, asphalt composition shingles have become thicker and more textured, and even look like other materials such as wood or slate. This thicker - and naturally more expensive - roofing shingle is called an architectural shingle. Asphalt shingles are easier to install and faster to put up than other types of roofing materials.

Wood shake roofing material is selected by many homeowners in european countries, and for good reason. Wood shake looks super. When wood shake shingles weather, they do so in a mottled, variegated way that is pleasing to the eye. Also, wood shake, despite being an organic material, can last from 30 to 50 years if properly maintained.

2.3 Developments of roofing configurations of the domestic buildings in Sri Lanka

2.3.1 Types of building roofs

The designs of the tropical region roofs are dependent on its usage and the region or country in which to build it. A roof may be designed primarily as protection against rain, sunlight and wind. Other roofs may be designed to keep out the rain but admits sunlight.

Several factors come in play when choosing the right roofing design for your structure. A residential building in the tropics is designed with steep roof pitch and wide eaves to keep out the rain. In the dessert, flat cement roofing is ideal because of the hot sun. However, with the different roofing materials available in the market today, you can just about adapt to any roof style and pick any material that would suit your location's climate. The roof is the defining feature of a house so its design is very important. You can differentiate the types of roofing according to style and material and pitch.

2.3.2 Types of roofing configurations

There are several types and subtypes of roofing. Here are some of the most common styles of roofing used in structures. Simply put it's the triangular shaped roof put squarely and without much fuss on top of a square or rectangular building. A gabled roof has two equal surfaces that has the same size and pitched at the same angle back to back to form a ridge at the top. This design is simple and cheap to construct. Variants are:

- Four pitch roof design
- Two pitch roof design
- Side gable roof - very economical as there's only one side

- Front gable roof - used in house facade
- Cross gable roof -two gabled roofs put at right angles
- Dutch gable roof - a hybrid type of gable and hip roof
- **A-frame** -it is a roof with no perpendicular walls to support the roof. This roof is commonly used in vacation cottages.
- **Shed** - This is a basically a half gable used mostly for porches. This streamlined design is often used for modern homes.

Figure 2.10: Four Pitch painted asbestos roof

Figure 2.11: Four Pitch calicut tile roof

CHAPTER 3: ROOFING HEAT TRANSFER THEORY

3.1 Introduction

This section discusses the roofing heat transfer mechanisms in brief. Effect thermo-physical properties and solar-optical properties on the indoor thermal climatic conditions are briefly discussed.

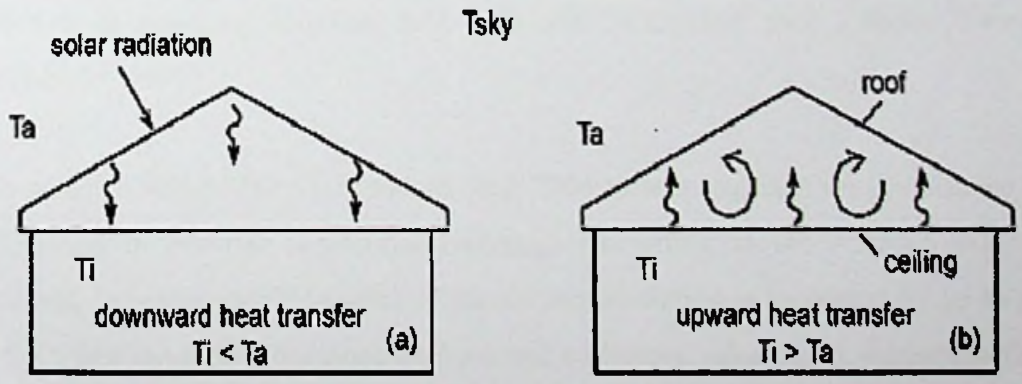
3.2 Effect of solar optical parameters on roof heat transfer

Roofing is the building component that contributes most to the indoor thermal environment and to the corresponding thermal comport conditions of the inhabitants. The roof heat transfer occurs mainly due to two processes. The outdoor indoor air temperature difference causes conductive/convective heat transfer through roofing/ceiling material. The magnitude of heat transfer dependent on the thermal conductivity, thickness of the roofing material and influenced by outdoor/indoor wind velocity and independent of roof orientation, roof angle etc. A detailed description of the roofing heat transfer mechanisms is presented later in this chapter.

However, the solar driven heat transfer through roofing material is a complex process and mainly dependent on the solar absorptivity/reflectivity of the roof exterior surface. The thermal performance of a building is significantly affected by the solar absorptance of the roof (Givoni B. , 1994). Due to the exposure to the direct sun light during the daytime, the roof becomes the hottest element of the building envelope, which should be paid more attention to minimise the heat gain (Mohammed & Ahmad, 2012) The building surface partly absorbs and reflects solar radiation. The absorbed part of solar radiation has an effect on surface temperature and indoor temperature of the building (Givoni B. , 1998) reported that about 1kW/m^2 of solar radiation falling on a roof surface during clear sky conditions and from 20%-90% of this solar radiation is absorbed (Suehrcke, Peterson, & Selby, 2008). The absorbed solar radiation causes the surface temperature increase and thereby downward heat transfer to the indoor volume.

However, the effect of roof heat transfer to the indoor volume is dependent on various other parameters such as building orientation, wind speed etc as well (Chen, 2009).

The roof colour that is apparent from the reflected visible part of the solar radiation usually gives an indication of the value of solar absorptance (Suehrcke, Peterson, & Selby, 2008) (e.g. a black surface with low visible reflectance suggests a high solar absorptance). Building heat gain from a roof has been investigated a warm/hot climate. In locations close to the equator (tropical areas with latitude angle 23.58 or less) ambient temperatures and solar radiation levels are sufficiently high that even during winter buildings do not require active heating. Daytime heat flow from a sun-exposed roof surface is essentially only in downward direction and the downward heat flow generally is undesired, as it tends to overheat the building or put extra load on an air-conditioning system. Figure 3.1 illustrates the difference between downward and upward heat flow through a roof space. For downward heat flow, schematically depicted in Figure 3.1(a), the heat transfer between the roof and the ceiling is predominately due to thermal radiation. For upward heat flow (Figure 3.1b), on the other hand, where the air in the roof space is heated from below, heat is transferred by both convection and radiation.



Figure

Figure 3.1: Downward and upward heat transfer through a roof space: (a) upward heat transfer; (b) downward heat transfer

Source: (Suehrcke, Peterson, & Selby, 2008)

The downward heat flow from the roof can be reduced through the use of a light roof colour, reflective foil and/or insulation. While the installation of roof insulation and reflective foil has now become mandatory in many countries.

3.3 Effect of exterior surface colour on roofing heat transfer

Many researchers have attempted to characterize the roofing heat transfer. The roof solar absorptance is primarily dependent of roof colour and surface (Givoni B. , 1994). According to him, light colour roofing material absorbed less solar energy compared to dark or grey coloured surfaces of the same material. The benefits of light roof colour have been noted many times, particularly in locations where the sun is almost directly overhead and for single story buildings. It was reported that the space cooling requirements, after application of reflective roof coatings on nine Florida homes, decreased by 19% and the staff of a Florida school found that interior comfort noticeably improved after the grey bitumen roof surface was painted white (Parker, 2004) . And on the other hand, using a numerical simulation of a building, suggested that the peak values of heat flow from a roof could reduced by as much as 60% when a white surface replaces a corroded galvanised one (Suehrcke, Peterson, & Selby, 2008). It was found from measurements of ¼ scale models in Arizona, that ceiling insulation is more effective in reducing daytime heat gain than increased roof albedo (Simpson & McPherson, 1997).

The recent ANSI/ASHRAE Standard 90.2-2004 now recognises the importance of roof reflectance in low-rise residential buildings According to the ANSI/ASHRAE 90.2 standard, the resistance (U-value) of the ceiling insulation is increased by up to a factor of 1.5 when the roof reflectance and thermal emittance values have minimum values of 0.65 and 0.75, respectively. In other words, a reflective roof surface increases the effective thickness of the insulation by 50% (e.g. in parts of Florida), but no increase is provided for a climate zone such as Wisconsin in USA.

3.3.1 Effect of weathering/aging of roofing material on downward heat transfer

The cooling benefit of a roof surface with high solar reflectance decreases with time as the surface accumulates dust and deposits. With time or in other words aging, the unpainted roofing material, especially in tropical climates where high levels of humidity and air temperature prevails throughout the year, becomes discoloured due to the development of fungi. The accumulated dust deposits aggravate this situation and as a result, the roof exterior surface solar absorptivity get increased (Givoni B. , 1994).

The reduction in solar reflection of white roofs is in the order of 10–30% with most of the reduction occurring in the first year (presumably the degradation usually slows as rain and wind start removing some of the deposits). His research paper mentions a study from Sacramento, California that indicates a 20% reduction of the first year energy savings for all subsequent years (2–10 years) (Eilert, 2000).

A detailed recent study on the aging and weathering of cool roofing membranes (Akbari, et al., 2005), which included 13 white roof material samples that had been exposed for 5–8 years in eight different locations, found that their solar reflectivity had dropped from 0.8 to nearly 0.5. However, in the study it was also found that washing the samples could almost completely restore the original reflectivity.

It was suggested that a reflective (e.g. white) roof surface in place of a dark one can be of great benefit in hot and sunny climates (increase human comfort and/or reduce the cooling load). However, the benefits are variable and are not easily accounted for (unlike the thermal resistance of solid material and bulk insulation) (Levinson, Akbari, Konopacki, & Bretz, 2005).

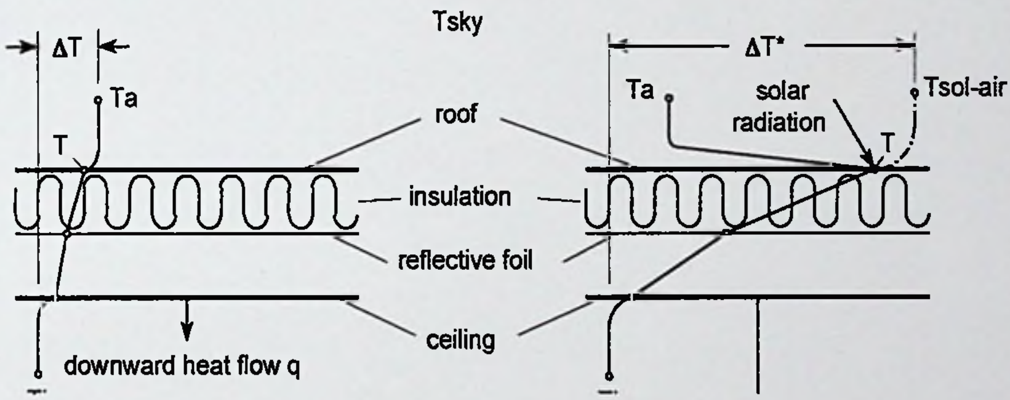
3.4 Temperature profile in roof space for downward heat flow

Downward heat flow from the roof may be caused by,

i. A temperature difference between the outside and inside temperature and,

ii. Solar radiation that is being absorbed on the roof surface.

The exposure of the roof surface to solar radiation increases the roof surface temperature and sets up a heat flow in parallel to the one set-up by temperature difference. As demonstrated in the Figure 3.2 below the temperature profile of a roof with and without solar radiation exposure, suggesting the effect of solar radiation absorption usually is the most important factor for the daytime downward heat flow from a roof surface in a hot climate. In tropical regions the daytime heat flow due to the outside–inside air temperature difference is typically in the order of 5 K, while the heat flow due to solar radiation absorption on the roof surface is of the order of 20 K.



(a) (b)

Figure 3.2: Daytime roof temperature profile: (a) without solar radiation; (b) with solar radiation

Source: (Suehrcke, Peterson, & Selby, 2008)

It should be noted that the solar absorptance of the roof surface is not the only variable influencing the roof temperature. The thermal emittance from the roof surface, which determines the radiative heat exchange with the sky, also plays an important role (particularly in low wind conditions). Measurements suggest that roofs in tropical climates cool 1-6K below ambient temperature during night time and that the temperature depression may be limited by the formation of dew (Khedari, Mansirisub, Chaima, Pratingthong, & Hirunlabh, 2000).

Typically the sky temperature depression below ambient is 2–20 K and strongly depends on the level of cloudiness (Cooper ,2002). For non-metallic surfaces (e.g. painted steel and roof tiles) the thermal radiation emittance to the sky is typically about 0.9 while for bare metal surfaces it varies (for zinc/aluminium and galvanised steel the thermal emittance is approximately 0.3 (Cooper,2001).

CHAPTER 4: METHODOLOGY

4.1 Introduction

This thesis investigates the effects of different roofing/ceiling configurations on the indoor thermal performance of a basic residential building in Sri Lanka. Three different roofing materials; cement fibre sheet (asbestos), conventional burnt clay calicut tile (manufactured in Wennappuwa area) and improved burnt clay calicut tile (new calicut tile typed introduced during the recent past) were compared. Three types of cement fibre sheet roofing; new asbestos sheet, top surface painted sheet and fungi developed old sheet roofing were included to cover almost all configurations of cement fibre sheet material. To investigate the effect of ceiling material and shape, both sloping and suspended ceiling types were included. For that cement fibre sheet (asbestos) as well as wooden plank ceiling types were selected as ceiling material. The indoor thermal environment in terms of indoor temperature and cooling energy use was studied using computer simulations. For this, the DEROB-LTH software was used.

4.2 The simulation software

In order to determine the effect of the roofing/ceiling configurations on the indoor thermal environment of a basic domestic building was investigated by computer simulation. For this, the Dynamic Energy Response of Buildings (DEROB-LTH version 99.02) program was used. It has been originally developed at the Numerical Simulation Laboratory, School of Architecture, University of Texas, USA. Later, it was further enhanced at the Department of Building Science, Lund Institute of Technology (LTH), Sweden.

DEROB-LTH is a versatile simulation tool that facilitates the creation of models of actual buildings with relatively high accuracy. It handles energy transmission across the building envelope by taking account of thermal properties of building materials. In addition to the thermal loads from direct and diffused solar radiation, it considers solar radiation reflected from the ground and shading devices. This software takes account of infiltration and forced ventilation. It can also take account of static pressure driven air exchanges between volumes that take place across openings at different levels (advection connection). It can also calculate the air-conditioning loads and required plant capacities. With DEROB-LTH, it is possible to study the full interaction between the window, the space, the ventilation and internal loads generated by the occupants of the space. Especially the effects on indoor temperatures, thermal comfort, and peak loads can be studied during any climatic condition.

4.3 The simulated residential building

In this study, a basic residential building in Sri Lanka was constructed using the simulation software. A detailed description of the building geometry, material of construction and their thermo-physical properties, solar optical properties are presented in the following sub sections.

4.3.1 Geometry of the simulated building

The building is a standard 6m length, 5m wide, and 3m wall height (interior dimensions). The total usable floor area of the building is 30m². The north wall consists a door of size 2.5m x1.5m and the east wall consists a window of size 2m x 1m. The modelled house selected for simulations is given Figure 4.1 (as drawn by DEROB-LTH software). It is compatible to the Building Regulations in Sri Lanka (Building Regulations, 1985). The openings provided were properly oriented (i.e. facing north or south) and shaded with roof overhangs at all sides of the building. Initially, the roof orientation of the modelled building with the DEROB-LTH software was at east-west direction and subsequently, it was rotated by 90° so that the ridge is aligned with the north-south orientation as this study focus on the orientation effect of building on the indoor thermal performances. The roof material was interchanged with five different types selected for this study.

These roofs were combined with two ceiling material types commonly used in Sri Lanka. They are cement fibre sheet (asbestos) and wooden plank ceilings and two ceiling designs; sloping and suspended were used. However, for a particular roofing material, it was able to make five ceiling configurations. They were roofing with no-ceiling, sloping asbestos, sloping wood, and suspended asbestos and suspended wood ceilings. The number of air changes was maintained as 1ach/hour for all cases representing the conditions of closed windows. However, the space between the roof and the ceiling (attic space) was considered as sealed in all cases.

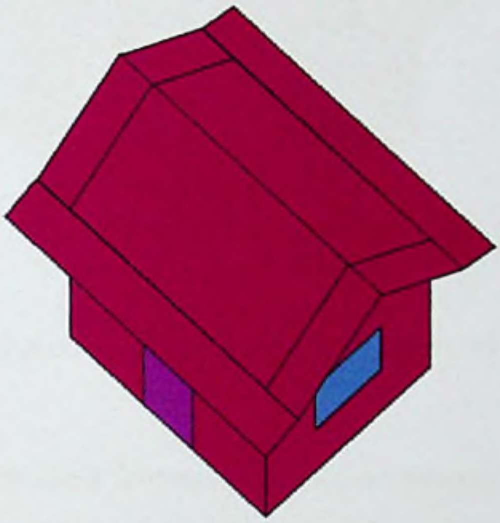


Figure 4.1: Simulated 2-pitched residential building as drawn by DEROB-LTH software

4.3.2 Description of building elements

In the modeling, building elements were carefully selected as close as to the actual construction materials used in the residential buildings in Sri Lanka. The walls were constructed with ordinary bricks and cement plastered both exterior and interior sides. The floor was constructed with compact earth filling, plain concrete floor, and cement plaster and finally finished with floor tiles. The door and the window frame were made by hard wood and the window glass was selected with ordinary clear glass.

Initially, the roofing design was a basic 2-pitched one and simulations were performed changing the corresponding roofing/ceiling configurations. Subsequently, it was remodeled as a 4-pitched one by necessary variations of building elements and similar series of simulations were performed and simulations is given Figure 4.2

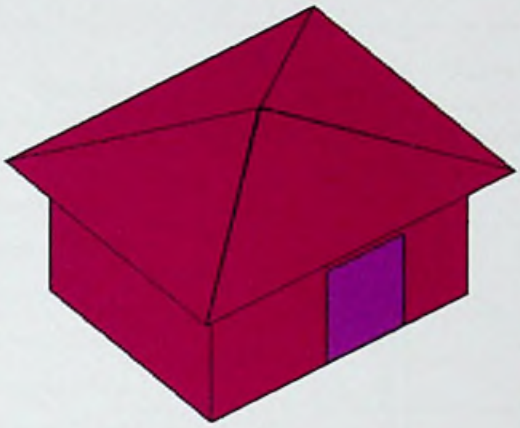


Figure 4.2: Simulated 4-pitched residential building as drawn by DEROB-LTH software

In this study, cement fiber sheet (commonly called as asbestos in Sri Lanka) and two types of burnt clay calicut tiles (conventional calicut tile and new calicut tile) were used as roofing material. Nowadays, the most Sri Lankan residential buildings are constructed with cement fiber sheet as roofing material. Therefore, in this study, all types of cement fiber sheet roofing types were included; new (un-painted) sheet, top surface painted sheet (with light colour) and old (fungi developed) sheet.

Ordinary burnt clay calicut tile manufactured in Wennappuwa area was used in this study. Further, a new calicut tile introduced recently to the local building sector was also included. The cement fiber sheet (bottom surface painted with low emissivity paint) and wooden planks were selected as ceiling material and both slope and suspended configurations were used for simulations.

Since the attention is on the indoor thermal performance of the roofing and ceiling material used in the Sri Lankan residential buildings, the material used for wall, floor, door and window of the building were kept constant for all simulations.

A description of the construction elements of the building and their thermo-physical properties entered in *DEROB-LTH* is presented in Table 4.1 below.

Table 4.1: Description of the building elements used in DEROB-LTH program

S/n	Building element	Material type (from outside to inside)	Thickness (mm)	Thermal conductivity (W/mK)	Specific heat (Wh/kgK)	Density (kg/m³)
1	Exterior wall	Cement plaster	15	0.72	0.24	1800
		Burnt clay brick	200	0.82	0.24	1850
		Cement plaster	15	0.72	0.24	1800
2	Ceiling	Cement fiber sheet	6	0.22	0.25	1600
		Wooden plank	8	0.12	0.38	510
3	Roofing material	Cement fiber sheet	6	0.22	0.25	1600
		Conventional calicut tile	16	1	22	2000
		New calicut tile	14	0.22	0.23	900
4	Wooden door	Hard wood	25	0.16	0.35	720
5	Window frame	Hard wood	25	0.16	0.35	720
6	Floor	Earth filling	500	1.4	0.22	1300
		Plain concrete	50	1.7	0.25	2300
		Cement plaster	20	0.72	0.24	1800
		Floor tile	6	0.8	0.24	1600

Source: Cengel (2007), Incropera & Dewitt (2009), Nayak et al (1999), Samson Rajarata tile Co (2009)

4.3.3 Surface properties

The goal of this study is to assess the impact of roofing configurations on indoor thermal climate. In this regard, thermo-physical properties as well as solar-optical properties of roofing and ceiling materials have to be properly selected to obtain more realistic results. Therefore, surface properties of all the building elements were selected as much as close to the actual values. Solar-optical properties such as emissivity and absorptivity values for the interior and exterior surfaces of the building elements entered in the DEROB-LTH model were as described in Table 4.2 below.

Table 4.2: Surface properties of building elements of the modeled domestic building

S/no	Material type	Building element	Surface type	Surface colour/material	Absorptance (%)	Emittance (%)
1	Roofing material	New asbestos (un-painted)	Top surface	Light grey	60	95
			Bottom surface	Light grey	60	95
		Painted asbestos (top surface)	Top surface	Off-white	35	90
			Bottom surface	Light grey	60	95
		Old asbestos	Top surface	Old surface (blackish grey)	75	95
			Bottom surface	Light gray	60	95
		Conventional calicut tile	Top surface	Red colour	30	95
			Bottom surface	Red colour	30	95
		New calicut tile	Top surface	Red colour	30	95
			Bottom surface	Red colour	35	90
2	Wall	Walls	Exterior	Off white	35	90
			Interior	Off white	35	90
3	Ceiling material	cement fiber sheet	Top surface	Light grey	60	95
			Bottom surface	Off-white	35	90
		wooden plank	Top surface	Normal wood finish	45	95
			Bottom surface	Normal wood finish	45	95

Source: Cengel (2007), Incropera & Dewitt (2009), Nayak et al (1999), Samson Rajarata tile Co (2009).

4.4 Internal loads

In this study, the effect of roofing/ceiling configurations on the indoor thermal climate was evaluated selecting a basic residential building. It was assumed that only two (02) occupants are living in the house. It was also assumed that, during the day time (0800hrs-1700hrs), no occupant is present in the house and all are present during the entire night time. It was also assumed that there are two numbers of energy efficient CFL bulbs in the house and they are kept switched on during the night for a particular period (i.e. 1800hrs- 2200hrs) and again early in the morning (0500hrs-0700hrs). For the occupants, ASHRAE (2004) suggests that about $108\,W/person$ should be assumed for persons seated at rest and $125\,W/person$ for those standing relaxed. It was suggested around $117\,W/person$ for sedentary work (Olgyay, 1963). As most of the time in a residential building, occupants are generally involved with light work or seated relaxed, hence, in this study, the heat gain from an occupant is taken as $100\,W/person$. This value corresponds to around 92% of the value given by ASHRAE (2004). ASHRAE (1996) suggests the use of 20-50W/m² for lighting in a residential building. Thus, the most dominant source of internal heat gains consists of the heat from occupants. The total internal heat gains were thus as described in Table 4.3 below.

Table 4.3: Total internal heat gain (W)

Time (hour)	Occupant heat gain (W)	Lighting heat gain (W)	Total heat gain (W)
01.00-04.00	200	0	200
05.00-07.00	200	40	240
08.00-17.00	0	0	0
18.00-22.00	200	40	240
23.00-24.00	200	0	200

4.5 Thermal comfort range for Sri Lankan residential buildings

One of the primary objectives of a building design is to ensure that the building is thermally comfortable to its occupants, possibly throughout the day and round the year. Thermal comfort could be achieved for several combinations of environmental and personal parameters. These combinations of parameters form a basis of a comfort zone on the psychrometric chart given in the following Figure 4.2.

The choice of indoor air temperature can be based on the comfort zone recommended for a particular country/region. In this context, Sri Lankan researchers (Jayasinghe & Attalage, 1999) have conducted continuous research to establish a thermally comfortable zone acceptable for the indoor climate in Sri Lankan residential building. According to these two authors, and as demonstrated in the following psychrometric chart, the general comfort zone recommended for sedentary activities and for different internal air velocities lies somewhere between 23-32^{0}C.

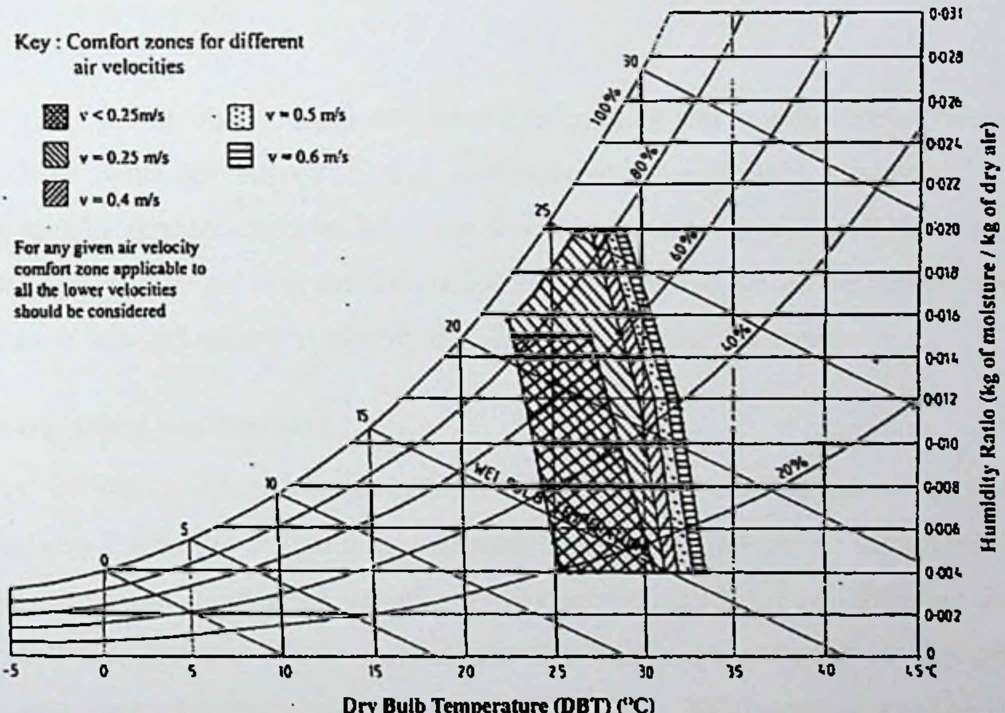


Figure 4.3: Psychrometric chart giving modified comfort zones Source: (Jayasinghe & Attalage, 1999)

CHAPTER 5: RESULTS & DISCUSSION

5.1 Introduction

In this section, the results of the simulations are presented and briefly discussed. The main focus of this study was to compare different roofing & ceiling materials as well as roof configurations commonly used in the Sri Lankan residential building sector. For that five roofing alternatives selected are incorporated with two ceiling material types. A bare roof (no ceiling), flat sloping ceiling (finished ceiling as referred in Sri Lanka) and suspended ceiling configurations were investigated. The indoor thermal performance of the residential building was investigated with two types of roofing configurations; two-pitched and four-pitched and for two different orientations; ridge tile aligned to the east-west and the north-south.

In all cases, cooling energy use is evaluated hourly, daily and monthly basis. The indoor temperature with no air-conditioned environment is evaluated similarly. As the simulations become too complex and more time consuming if done for all the months of the year, the simulations were carried out for March, June and December (when different extremes of sun path occur) to identify the effects throughout the year.

5.2 Two-pitched roof building

Initially, the results are presented in the two-pitched roof configuration. The thermal environment inside the building is analyzed in terms of indoor air temperature and cooling energy use. Both these variables are evaluated hourly for two different days in order to investigate the hourly fluctuations. The minimum temperature day on 06th March and the maximum temperature day on 18th June 2011 were selected as design days for these evaluations. However, before examine the indoor thermal conditions, the roof exterior surface temperature is evaluated as this significantly affects the indoor climate. Effects of roof covering material, ceiling material and configurations, roofing orientation are evaluated later. Initially, the building was oriented to the east-west.

5.2.1 Roof exterior surface temperature

The roof exterior surface temperature is a major indicator for determining the thermal performance of the building as this significantly affects the downward heat transfer during the daytime (Givoni B. , 1998). Due to exposure to direct solar radiation, the roof becomes the hottest element of the building envelope. As discussed in the roof heat transfer theory in a previous section, the roof surface partly absorbs and reflects solar radiation. The absorbed part of which has an effect on surface temperature and indoor temperature of the building (Givoni B. , 1998). As such, roof outer surface temperature is a key parameter, which essentially determines the solar induced downward heat transmission through roof into the room below. As the upper surface temperature of roof decreases, heat flow into the building simultaneously reduces. As a result, lower peak temperature exists in the building. To simplify the simulations, for all cases a bare roof (with no ceiling) exposed to the direct sun is considered.

The 1st case simulated is the roofing constructed with old cement fibre sheets. This is a typical situation of a roof made with this material in tropical climates. As in the literature, during the first three years of newly constructed cement fibre sheet roofing, the top surface degrades and as a result, the absorptivity and thermal emissivity reduced in the order of 10% - 30% of its original values (Eilert, 2000). Therefore, the 1st roofing alternative, old asbestos sheet roof represent the entire lifespan of a roof constructed with this particular material. As discussed earlier, average upper surface temperatures of five different types of roof covering material used for this study were evaluated hourly on this minimum temperature day and is demonstrated in Figure 5.1 below.

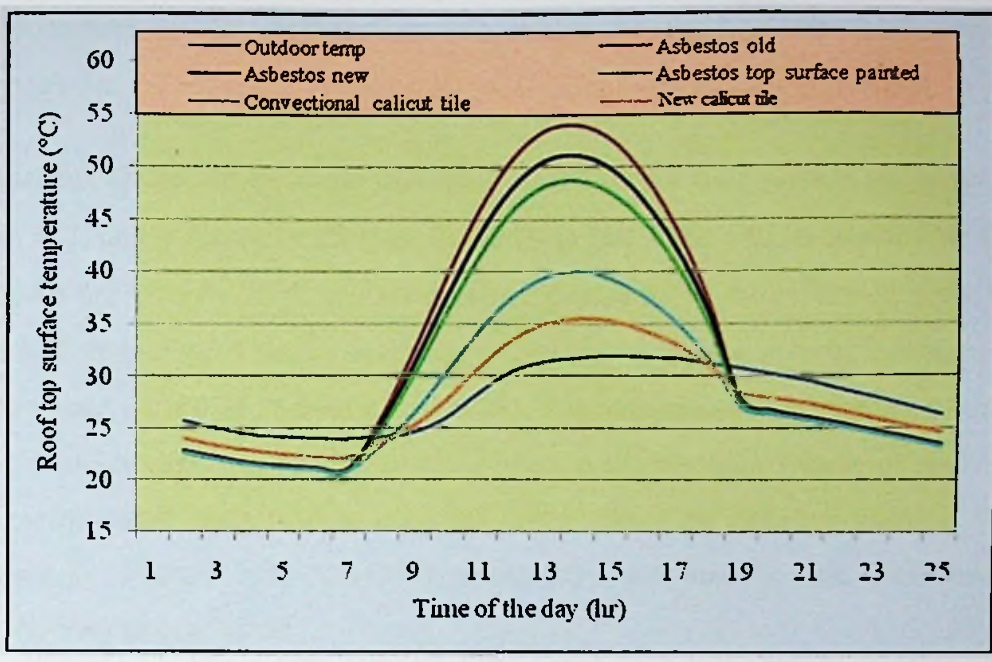


Figure 5.1: Hourly outer surface temperatures of roofing materials at east-west orientation on 06th March, 2011

The graphs illustrate that all roofing material show a similar trend in roof external surface temperature fluctuations. It started to rise up from the morning (simultaneously as the solar radiations is getting increased) to reach the peak around 1400hrs (a little later the sun was at its meridian or solar noon), and then starts to decrease at its lowest surface temperature around 1800hrs irrespective of material type. The results obtained show a significant difference in external surface temperatures of roofing material.

As expected, the type-A; the old asbestos sheet roofing which has the highest solar absorptivity ($\alpha = 0.75$) shows the record highest exterior roof surface temperature as high as 55^{0}C at 1400hrs. The higher surface temperature of the bare roof indicates that a high level of solar radiation is absorbed by the asbestos roof during the daytime. As this material has the highest thermal emissivity as well ($\varepsilon = 0.95$), the night time radiation cooling caused by long-wave infrared radiation emission from the exterior roof surface to the lower sky temperature consequently causes the lowest possible exterior surface temperature during the night. During the night, the sky temperature decreases even by

20^0C compared to the roof surface temperature accelerating the thermal radiation exchange (thermal emission) between the roof surface and the sky (Givoni B., 1998).

The analysis of the results found that the lowest exterior roof surface temperature was around 35^0C and is shown by the type-E; the burnt clay calicut tile product. This shows a significant decrease by 20^0C, a 36% decrease compared to the reference case; the old asbestos sheet roofing. This is mainly due to its lower solar absorptivity compared to the reference case ($\alpha = 0.30$ instead of $\alpha = 0.75$). The analysis also showed that, compared to the reference case, this roofing material show a slightly higher exterior roof surface temperature during night time as it causes lower night time radiation cooling with the sky due its slightly lower thermal emissivity compared to the reference case ($\varepsilon = 0.90$ instead of $\varepsilon = 0.95$).

The figure above clearly demonstrates that all roofing material show close results in the absence of solar radiation (i.e.: before the sun has risen and it has set). Further, the roof external surface temperature drops even below the outdoor air temperature as the solar radiation intensity drops, suggesting that the influence of thermal mass of roofing material has a little effect on the roof external surface temperature.

5.2.2 Effect of roofing material on indoor temperature

The 1st set of simulations was carried out for a building constructed with two-pitched roofing and with no ceiling configuration. The simulations were performed merely to elaborate the effect of different roofing material used for a bare roof on the indoor thermal climate. This represents the Sri Lankan residential building sector which comprises mostly low income range as they do not have enough income to integrate a ceiling for their roofing system. Though, this poor income category does not use expensive clay tile (type E), however, the simulations were performed including this roof tile so that a comparison between all roofing materials could be done. The indoor thermal environment was simulated during the warmest day of the month; 6th March

2011. Figure 5.2 presents the hourly indoor temperature results. The maximum outdoor air temperature was around 32^{0}C.

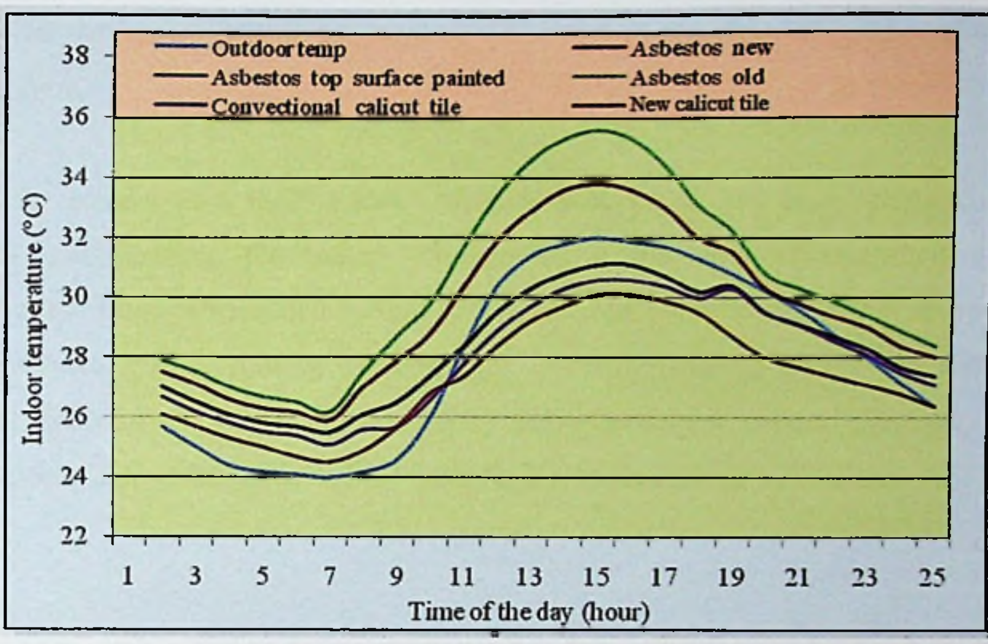


Figure 5.2: Hourly indoor temperatures at east-west orientation on day of 06th March, 2011

According to the above results, it is apparent that the hourly indoor temperature profiles followed a similar pattern as the outdoor temperature during early in the morning and late in the afternoon as there is no solar effect during these periods. However, during the daytime (0630hrs-1800hrs), the temperature curves show a distinct difference. The analysis of hourly indoor temperature fluctuations shows that the lowest room temperature occurs early in the morning, most often at 0600hrs, just after the sun has risen, regardless of the roofing material type. However, during early hours, all roofing solutions show somewhat higher indoor temperature than outdoor air temperature. As the minimum outdoor temperature at 0600hrs is 24^{0}C this day, the roofing constructed with old (fungi developed, $\alpha = 0.75$ and $\varepsilon = 0.95$) cement fibre sheet, the indoor temperature increases as 26.2^{0}C, a 9% increase compared to outdoor temperature at this time. The new cement fibre sheet roof ($\alpha = 0.60$ and $\varepsilon = 0.95$) shows a comparatively less indoor temperature (25.9^{0}C) compared to old fungi developed roofing sheet while top surface painted roofing sheet of the same material ($\alpha = 0.35$ and $\varepsilon = 0.90$) registered the lowest indoor temperature (25.5^{0}C) at the time of minimum outdoor temperature.

When the cement fibre roofing sheet category is replaced with burnt clay calicut tile roofing configuration, the indoor temperature at the time of minimum outdoor temperature, both calicut tiled roofing configurations show lower indoor temperature than its cement fibre roofing counterparts. When the roofing is covered with high surface finished ($\alpha = 0.30$ and $\varepsilon = 0.90$) new developed calicut tile, the indoor temperature shows the lowest 24.5^{0}C while the conventional calicut tile roof shows 25.1^{0}C.

As expected, and as demonstrated in Figures 5.1 & 5.3, this fungi developed old-cement fibre roofing sheet roofing material registered the highest indoor temperature all the day long and reached to a maximum indoor temperature (35.6^{0}C), a 11% increase compared to outdoor temperature at this time. Except very few hours, the indoor temperature with this roofing material exceeds 28^{0}C (around 16hrs), so the achievement of thermally comfortable indoors is not easy. The worst time period is especially during daytime (1100hrs-1900hrs) in which the indoor temperature even exceeds 32^{0}C and sometimes reaches to 35.6^{0}C (at peak indoor temperature of this roofing type). This suggests that, during this worst period, the achievement of indoor thermal comfort with ordinary ventilation with mechanical fans (indoor air speed $\leq$0.4m/s) is difficult. However, if higher indoor air velocities above 0.4m/s is provided, the indoor thermal comfort could be marginally achieved; that needs higher energy cost.

The 2nd roofing alternative is an un-painted new cement fibre roofing sheet. This case represents a newly constructed roof with new asbestos sheets. This material shows the second highest external roof surface temperature and the maximum temperature recorded by this roofing solution was 51.1^{0}C, approximately a 3^{0}C compared to previous case. When this is considered in place of old fungi developed one, the maximum indoor temperature decreased to 33.8^{0}C from 35.6^{0}C (5% decrease compared to previous old one). This is mainly due to the lower solar absorptivity of the new roofing sheet ($\alpha = 0.60$ instead of $\alpha = 0.75$). All these two types show always higher indoor temperatures than outdoor temperature all the day long.

For the 3ra alternative, top surface painted cement fibre sheet roofing is considered. This type of coloured asbestos sheet roofing is now popular in Sri Lankan residential building sector. Though, painted asbestos sheets are available in different colours (from dark colour to very light colours), in this study, a light red colour roofing sheet (which looks similar to burnt clay roofing tile) was selected. This roofing material demonstrates 3rd highest exterior surface temperature during the cause of a day. The maximum exterior surface temperature reached was close to 49^{0}C, a 5^{0}C lower than the old asbestos sheet (1st alternative) due to its lower solar absorptive ($\alpha = 0.35$ instead $\alpha = 0.75$).

As explained in the previous section, heat energy transfers indoors due to a combined effect of the thermal radiation as well as temperature difference between outdoors and indoors. With this painted asbestos roof covering, a significantly lower indoor temperature compared to 1st alternative was observed. The maximum indoor temperature recorded was 31.1^{0}C; a 13% decrease compared to fungi developed old cement fibre sheet roofing. As demonstrated in Figure 5.2 above, this roofing solution shows lower indoor temperatures for approximately 10hrs (from 1000hrs-2100hrs) than that of outdoor temperatures and for very few hours, the indoor temperature has exceeded 30^{0}C. During the entire remaining hours of the day, the indoor temperature was closer or less than 28^{0}C, which suggests that with very little effort, with mechanical ventilation means, a thermally comfortable indoor condition could be achieved marginally.

The remaining two roof covering materials both comprise with burnt clay calicut tiles. As depicted in Figure 5.2 above, the results demonstrate that, in comparison to asbestos roof materials discussed previously, significantly lower exterior roof surface temperatures were obtained during the entire day. The conventional calicut tile roof, shows quite significantly lower maximum roof top temperature (40^0C) , 14^0C decrease (26% decrease) compared to old asbestos roof discussed previously due to its lower solar absorptivity ($\alpha = 0.30$). As presented in the Figure 5.1 above, the indoor temperature profile show that most of the day time, the room temperature was below 29^0C. This graph further indicates that only very hours of the day, the room temperature was above 30^0C. In comparison to previous asbestos roof coverings, the conventional calicut tile roof demonstrate a favourable indoor thermal environment for the occupants, that is with a low air velocities (approximately $v = 0.25 m/s$) provided by artificial ventilation could be sufficient to make indoors thermally comfortable.

When the 4th roofing alternative is replaced with the recently introduced new calicut tile, the lowest possible exterior roof surface temperature profile was obtained. The maximum roof top temperature recorded as 35.5^0C, 18.5^0C decrease compared to old asbestos roof. In comparison to 1st alternative, this shows a quite significant decrease (34%) in roof surface temperature. The results of indoor temperature provided by this new calicut tile roofing solution consequently presented the lowest possible temperature profile during the entire day. The peak indoor temperature was 30.1^0C (a decrease of 15% compared with fungi developed old asbestos roofing). As demonstrated in Figure 5.1 above, though these two roofing material show quite close results, the new calicut tiled roof provides most favourable indoor thermal environment than the conventional clay tiled roof. The results show that houses constructed with this roofing alternative is more effective in reducing the indoor temperature below the outdoor temperature especially during daytime when solar loads are high. However, during early hours of the day, a slightly higher indoor temperature than outdoors was observed as in all previous cases.

As shown in the Figure 5.2 above, achievement of thermally comfortable indoors with new calicut is easy during night time without even mechanical ventilation, as this roofing material registers indoor temperatures lower than 28^{0}C. However, especially during daytime (1100hrs to 1900hrs), if little ventilation is provided (air velocity around 0.25m/s) using mechanical fans etc, indoor thermal comfort could be easily achievable. In contrast, the conventional calicut tile roofing requires somewhat higher indoor air velocities to achieve a thermally comfortable indoors during daytime, however, during night time, similar to new calicut tile roof, thermally comfortable indoors can be achieved even without mechanical fans.

This heat is then transferred to the bottom surface of the roofing material and thereby due to the combined effect of conduction, convection and thermal radiation, the heat transfers indoors. This validates previous researches that the roof surface temperature is highly dependent on the solar radiation availability.

5.2.3 Effect of ceiling material on indoor temperature

The previous simulations were carried out to find the effect of roofing material used in a bare roof (with no ceiling) on the indoor climate. In this section, different ceiling configurations are included together with roofing material so that the relative effect of roofing ceiling combination is identified. Basically, cement fibre sheet (asbestos) and wooden plank material are used and sloping and flat suspended ceiling are included; totally four ceiling configurations are discussed.

- **Sloping cement fiber ceiling**

In this case, the roof was constructed integrating sloping cement fibre sheet ceiling. The bottom surface (surface face to interior volume of house) was painted with white colour. All roof covering materials included in this study are used and simulations were performed to obtain indoor temperatures. The house was constructed so that the ridge is parallel to the east-west orientation. The Figure 5.3 presents hourly fluctuations of indoor temperature for this roofing/ceiling configuration on the lowest temperature day; 6^{th} of March 2011.

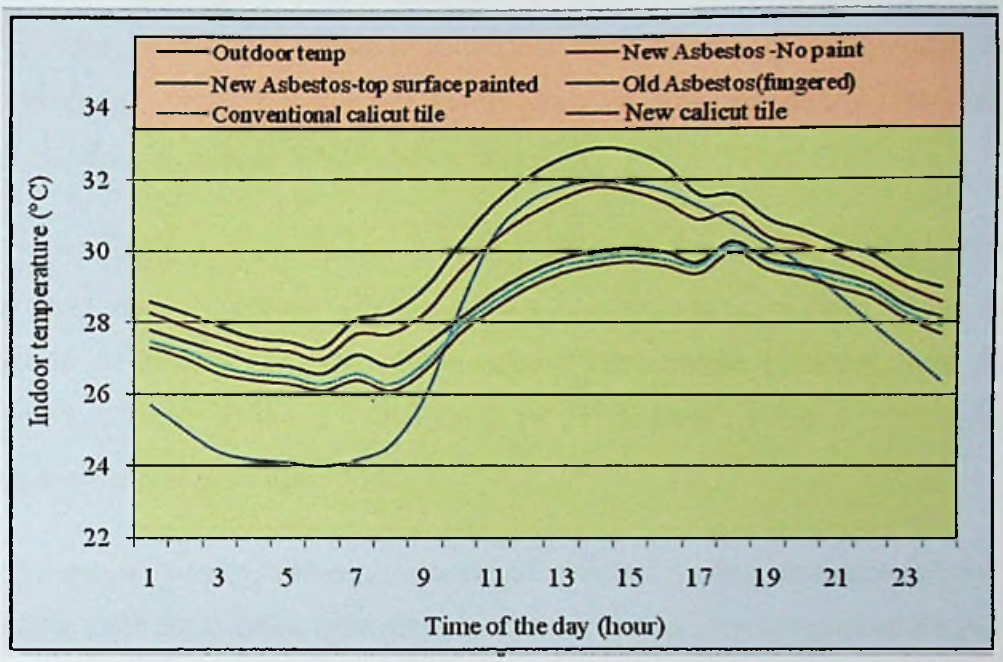


Figure 5.3: Hourly indoor temperatures with sloping cement fiber sheet ceiling at East-West orientation on 06^{th} March, 2011

This indoor temperature profiles showed a similar trend as observed in the previous simulations with no ceiling configurations, however, showed a comparatively lower indoor temperature in almost all cases. The minimum indoor occurred early in the day around 0630hrs and the maximum indoor temperature occurred around 1400hrs. As expected, the fungi developed old cement fibre sheet roof showed the highest indoor temperature of 32.9^0C, a 8% decrease compared to previous case; no-ceiling configuration. As demonstrated in the Figure 5.3 above, as the indoor temperature with this old asbestos roofing material integrated with slope ceiling (with same material) combination exceeds 28^0C most of the time of the day, a thermally acceptable indoor conditions could be marginally achievable.

As illustrated in the Figure 5.3 above, when the roofing material is changed to the un-painted cement fibre sheet (new asbestos sheet), a lower indoor temperature profile during the whole day compared to the previous case was observed. Further, this configuration registered a lower maximum temperature of 31.8^0C compared to the previous case (33.8^0C, 6% decrease). Achieving a thermally comfortable indoor condition during 1100hrs-2100hrs is hardly possible with mechanical ventilation as indoor temperature exceeds 30°C during this period.

An analysis of hourly indoor temperature with 3rd alternative roofing configuration; the painted (top surface) cement fibre sheet roofing showed a slightly lower indoor temperature conditions. The maximum indoor temperature recorded was 30.3^0C compared to 31.1^0C in the 2nd alternative (a 3% reduction) and a 15% reduction compared to the reference case (33.8^0C).

When the sloping asbestos ceiling is considered with last roofing alternatives; burnt clay calicut tiles, both these types have shown almost a similar indoor temperature profiles. The maximum indoor temperatures were 30.2^0C and 30^0C, an 8% and 9% decrease respectively. Compared to the reference case roof material, both exhibit a 15% and 16% reduction in maximum indoor temperature. Thermal comfort indoor climate with these two roofing/ceiling configurations could be easily achievable with a little effort with mechanical ventilation.

- **Suspended cement fiber ceiling**

The previous simulations were performed with sloping cement fibre ceiling. In this section, the ceiling configuration was changed into flat suspended type, however, keeping the material type unchanged. Simulations were carried out for all roof covering materials included in the study. The results are presented in the Figure 5.4 below.

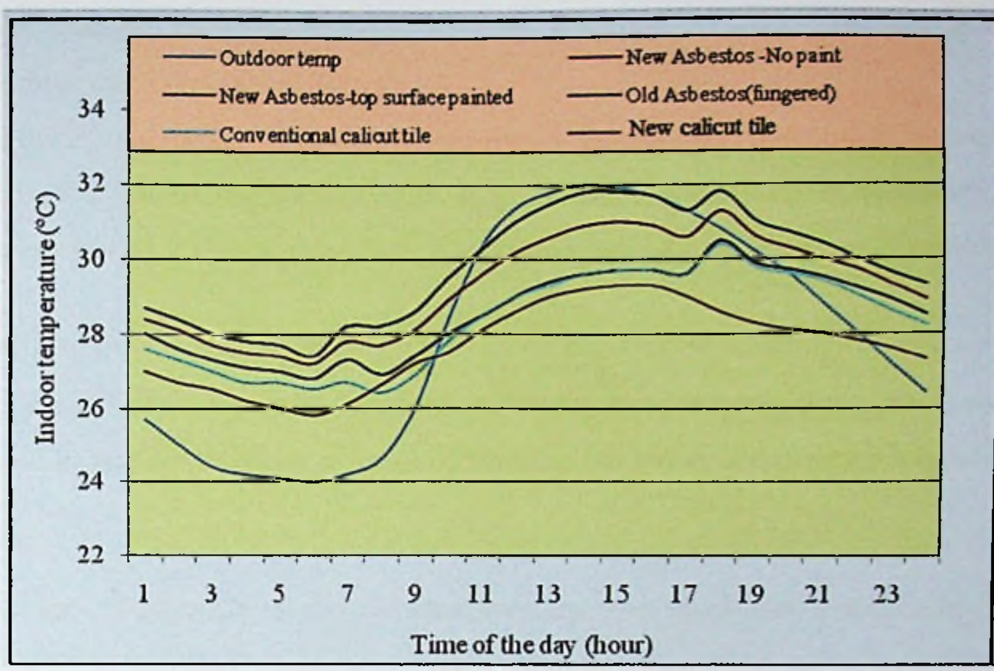


Figure 5.4: Hourly indoor temperatures with flat cement fibre sheet ceiling at South-East on 06th March, 2011

The Figure 5.4 above clearly demonstrates that the use of flat suspended ceiling has a significant effect on the indoor climate as the indoor temperature has decreased even far below the outdoor temperature.

As expected, and as observed in previous simulations, the weathered asbestos sheet roofing has registered the maximum indoor temperature, however, a lower value of 31.8^{0}C, a 3.8^{0}C reduction compared to the reference case. Compared to the sloping ceiling (of the same material) discussed above, 1.1^{0}C reduction in maximum indoor temperature was achieved with this ceiling. In both previous cases, the indoor temperature had exceeded the outdoor temperature during the daytime, however, with this ceiling configuration; the indoor temperature never exceeded outdoor temperature during the same time period. As the indoor temperature with this roofing/ceiling combination has exceeded 30°C most of the daytime, therefore, provision of thermal comfort through forced ventilation may be marginally difficult on this minimum temperature day in March.

When the 2nd alternative, the new cement fibre sheet roofing (un-painted) is considered together with this ceiling configuration, it has shown a slightly lower maximum indoor temperature of 31.3^{0}C as against 31.8 ^{0}C with previous slope ceiling configuration.

Though, the maximum indoor temperature (31.3^{0}C) is lower than the maximum outdoor temperature 32^{0}C, thermally comfortable indoor environment could be marginally achieved during the daytime, as most of the time the indoor temperature has been over 28^{0}C.

The 3rd and 4th alternatives show a similar results with maximum indoor temperatures being 30.5^{0}C and 30.4^{0}C respectively while the new calicut tiled roof with cement fibre flat suspended ceiling configuration showed as expected the lowest maximum indoor temperature 29.3^{0}C. When DSI tile and cement fibre roofing combination is considered, the indoor temperature has exceeded 28^{0}C for very few hours of the day suggesting that indoor thermal comfort could be easily achievable with little use of mechanical fan ventilation.

- **Sloping wooden ceiling**

This is the 3rd configuration of ceiling considered in this study. In this simulation, the roof is constructed with a sloping wooden ceiling. All roofing material considered in this study are used. The Figure 5.5 presents the results comparing the effects of different roofing materials with this ceiling configuration. A distinct difference in the performance of this ceiling configuration compared to previous simulations is that all roofing material exhibit lower indoor temperatures than outdoor values during the daytime. The difference of the maximum outdoor temperature and the highest indoor temperature registered (by old asbestos) due to the effect of the ceiling configuration lies within 1°C, whereas when the asbestos ceiling was considered, it was higher than the indoor temperature by the same magnitude.

- The maximum indoor temperature registered by weathered cement fibre sheet roofing material (old asbestos) when integrated with this ceiling configuration, is lower as 31.1^{0}C (6% reduction) compared to the figure given by its corresponding counterpart; the cement fibre sheet ceiling (32.9^{0}C) when used in a similar configuration. However, it is likely that forced ventilation could inhibit thermal discomfort on this minimum temperature day.

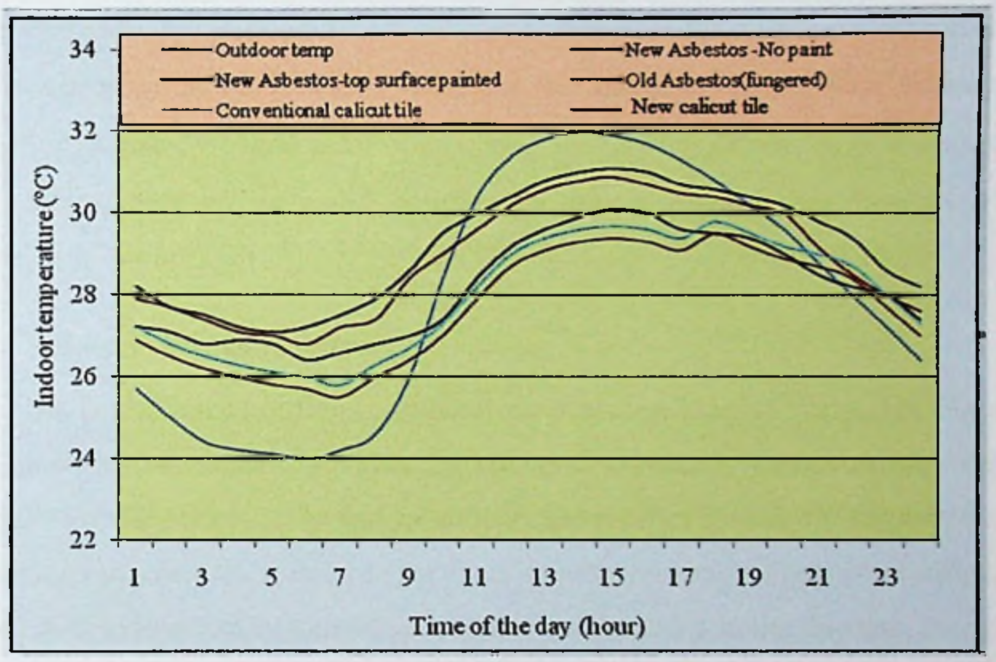


Figure 5.5: Hourly indoor temperature with slope wood ceiling at South-East on 06th March, 2011

When the 2nd alternative roof material, the un-painted new cement fibre sheet roofing is used instead of old asbestos roofing material, a slightly lower indoor temperature (30.9^{0}C) was observed. The indoor thermal comfort could be achieved by means of mechanical ventilation, as during most of the time this day, the indoor temperature has exceeded 28^{0}C.

The 3rd alternative, top surface painted new cement fibre sheet roofing is considered, as demonstrated in Figure 5.4 above, the maximum indoor temperature registered was 30.1^{0}C, a slightly lower indoor temperature compared to sloping cement fibre sheet ceiling (30.3^{0}C).

With this ceiling configuration, the maximum indoor temperature shown by the 4th and 5th alternative roof covering material lies significantly below the maximum outdoor temperature, as 29.8^{0}C and 29.5^{0}C respectively. Compared to its asbestos sloping ceiling counterpart (which registered 30.2^{0}C and 30^{0}C respectively), this has shown a slightly lower temperature as 0.5^{0}C was noticed. As the maximum indoor temperatures were always lower than 30^{0}C and most often during the daytime, it was slightly higher than 28^{0}C, achievement of thermally comfortable indoor environment through a little ventilation is not difficult.

- **Suspended wooden ceiling**

This is the last option of ceiling configurations considered in this study. The Figure 5.6 below presents the results comparing the effect of suspended wooden ceiling with roof covering material selected. The indoor temperature profiles exhibit similar patterns as in the previous simulations. Similar to previous sloping wooden ceiling, this configuration shows lower indoor temperatures than outdoor temperatures in the daytime. In contrast, during the night time, due to the slow cooling caused by thermal mass of roofing material slightly higher indoor temperatures were observed.

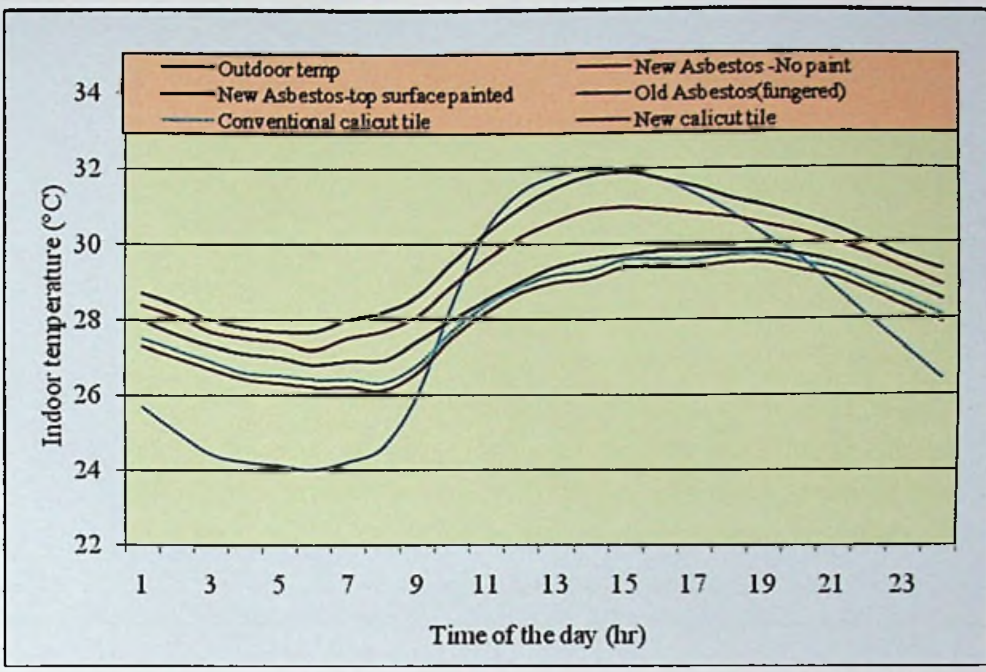


Figure 5.6: Hourly indoor temperatures with suspended wood ceiling at South-East on 06th March, 2011

- **Comparison of indoor temperatures**

In the previous sections, hourly fluctuations of indoor air temperature with different roofing and ceiling materials and their configurations for a building was discussed. The building's ridge was oriented at east-west direction in all cases. In this section, relative comparisons between all these types are discussed. A bare roof (with no ceiling) constructed with weathered asbestos (old asbestos) roofing was taken as the reference case. This study includes almost 25 roofing/ceiling configurations a two-pitched roofing design for the east-west orientation. The results are presented as the maximum temperature that occurred during the course of the day and are shown in the following Figure 5.7 and Table 5.1. As explained in the previous cases, the maximum indoor temperature occurred around 1500hrs; around 1hour lagging the occurrence of the maximum outdoor temperature.

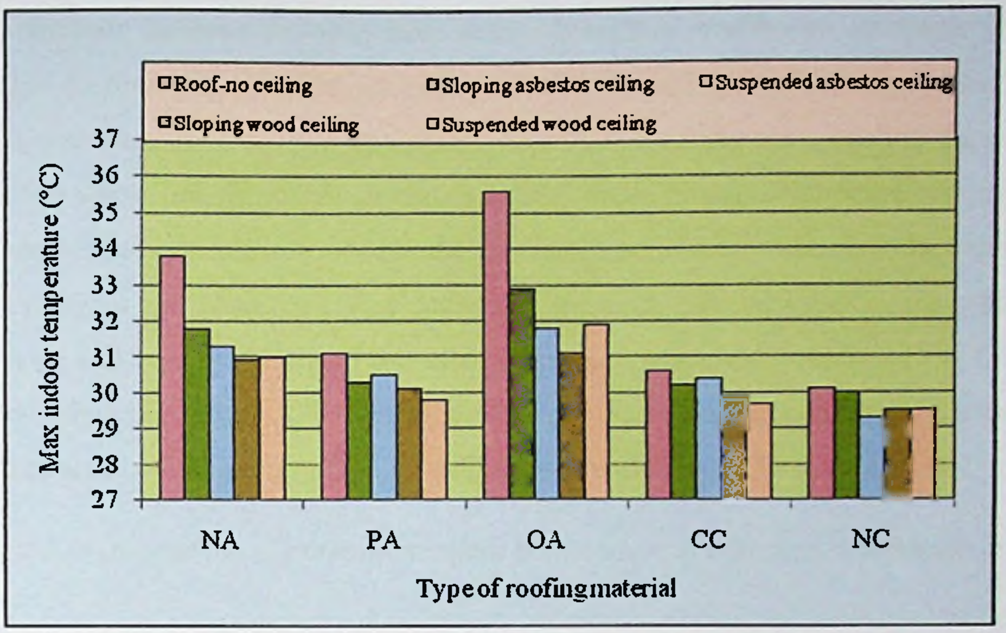


Figure 5.7: Comparison of roofing, ceiling materials/configurations at E-W orientation on 6th March 2011

According to the simulated results of 2-pitched roof building, it is apparent that the bare roof construction demonstrates the highest indoor temperatures in almost all roof covering materials. As shown in the above Figure 5.7, the maximum indoor temperature was noticed in the building constructed with bare asbestos roofing (35.6^{0}C). This indoor conditions combined with high relative humidity prevails in low lands in Sri Lanka (as explained in the sub section 4.1) is, however, difficult to inhibit the indoor thermal discomfort with mechanical ventilation, and needs to use air-conditioning even on this lowest temperature day in the year 2011.

The second highest indoor temperature is registered by the bare roof constructed with new asbestos (un-painted) as 33.8^{0}C, (1.8^{0}C, and 5.1% reduction). This result was obtained assuming solar-optical properties for a new asbestos roof surface. However, according to the previous researches (Akbari, et al., 2005), the roof exterior surface properties decayed due to weathering and fungi formation.

Their research findings indicate that, solar absorption coefficient increases (hence reflection decreases by same amount) as much as 30% during the first three years. They suggest that thermal emissivity would also decreases resulting slow cooling during the night time. Therefore, this result should definitely would change after first three years or more and hence the results obtained in the previous case; old asbestos could be expected. However, even the conditions was such, this material was included in the study to investigate and compare new and old asbestos roofing materials used in the Sri Lankan residential building sector. The third highest indoor maximum temperature was given by the old asbestos roofing with a sloping ceiling constructed with the same material.

Table 5.1: Comparison of maximum indoor temperature at east-west orientation on 6th March 2011

S/n	Roofing/ceiling configuration	Maximum indoor temperature (°C)					
		Outdoor temp	New asbestos	Painted asbestos	Old asbestos	Convectional calicut tile	New calicut tile
1	Roof- no ceiling	32	33.8	31.1	35.6	30.6	30.1
	Difference (°C)		-1.8	-4.5	0.0	-5.0	-5.5
	% Difference		-5.1	-12.6	0.0	-14.0	-15.4
2	Sloping asbestos	32	31.8	30.3	32.9	30.2	30.0
	Difference (°C)		-3.8	-5.3	-2.7	-5.4	-5.6
	% Difference		-10.7	-14.9	-7.6	-15.2	-15.7
3	Suspended asbestos	32	31.3	30.5	31.8	30.4	29.3
	Difference (°C)		-4.3	-5.1	-3.8	-5.2	-6.3
	% Difference		-12.1	-14.3	-10.7	-14.6	-17.7
4	Sloping wood	32	30.9	30.1	31.1	29.8	29.5
	Difference (°C)		-4.7	-5.5	-4.5	-5.8	-6.1
	% Difference		-13.2	-15.4	-12.6	-16.3	-17.1
5	Suspended wood	32	31.0	29.8	31.9	29.7	29.5
	Difference (°C)		-4.6	-5.8	-3.7	-5.9	-6.1
	% Difference		-12.9	-16.3	-10.4	-16.6	-17.1

Note: Negative (-) marks indicate a reduction

5.2.4 Effect of roofing material on cooling energy use

The previous series of simulations were carried out to evaluate the indoor temperature with different roof/ceiling material and configurations. In these simulations, it was observed that, in most situations, the indoor temperature was high enough and in few cases it was severely so that ordinary mechanical ventilation would not be sufficient to mitigate the worst thermal discomfort conditions prevailing in the building. As such, occupants tend to use at least a master bed room with air-conditioned. Therefore, in this section, cooling energy use with same roof/ceiling material and configurations are analysed. In order to minimize the complexity of the simulations, fluctuations of hourly cooling energy use was evaluated for the roofing materials with no ceiling configurations. However, all roofing materials selected are used. Subsequently, the cooling energy use of the rest of the roofing/ceiling configurations are analysed as daily total basis on the minimum temperature day.

- **Hourly fluctuations of cooling demand**

In this section, the results of the simulations are presented as hourly fluctuations of cooling energy use. The simulated results help us to identify the size of the cooling equipment (air-conditioner) to be installed in the building resulting from the peak load analysis.

The comparison of hourly cooling loads is shown in the Figure 5.8 below. It is apparent that the cooling load profiles followed a similar pattern during the early hours of the day and late in the afternoon. However, during the day time (0700-1800hrs) the load curves get separated and show a distinct difference with the change of roofing material. The analysis of hourly fluctuations showed that peaks and troughs occurred at the same time regardless of material type. The analysis furthers showed that the lowest cooling demand occurs early in the morning; around 0600hrs irrespective of the roof covering material. However, as presented in the Table A-1 in the Appendix, except new and old asbestos material, other three materials show approximately no cooling demand during 0400-

0600hrs as during this time period, the indoor temperature recorded was around 25^{0}C or less. During this time, the solar radiation is not available.

Once the solar radiation is getting increased, the cooling demand also increased continuously during the daytime and reached their peaks in the afternoon, around 1400hrs for all roofing materials and thereafter getting decreased. After 1800hrs the decrease is more noticeable and load profiles come closer to each other. On the contrary, during the night, the reverse phenomenon occurs; the roof heat flows upward due to the radiation heat exchange between the roof surface and the lower sky temperature. This is more pronounced in early hours of the day causing very low and sometimes no cooling load in the building (inside temperature is 25^{0}C or less).

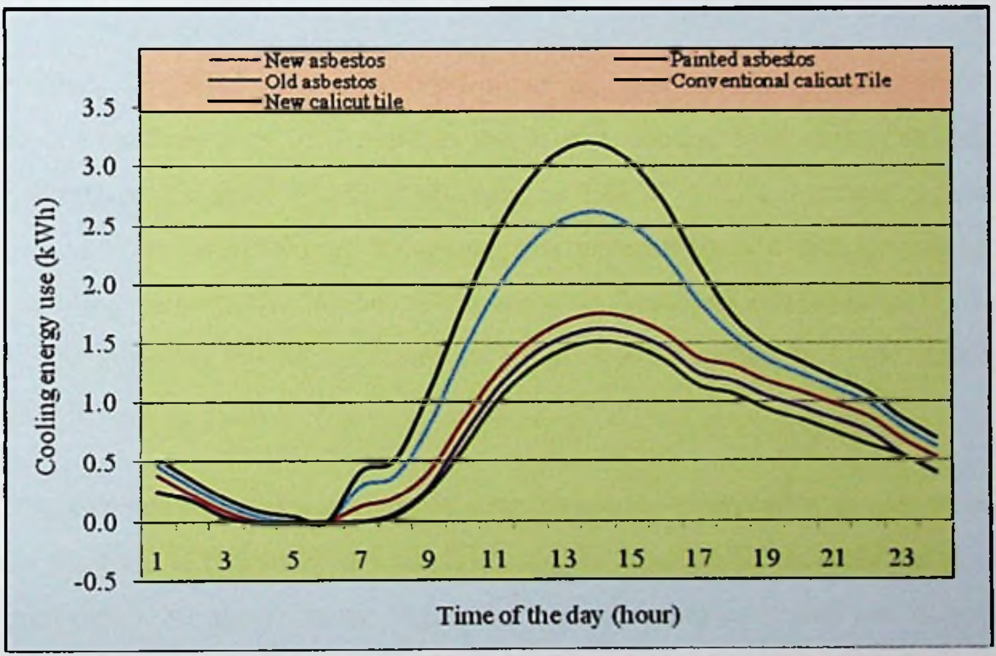


Figure 5.8: Hourly cooling energy demand at E-W orientation on 6th March 2011

These load profiles suggest that indoor cooling load is strongly affected by the outdoor solar radiation and outdoo r air temperature. During this month (March), the sun travels directly overhead and as the building was oriented east-west direction, the roof's expose time length for the direct sun is higher. As a result, the roof material which has higher solar absorptivity values receives higher magnitudes of solar energy. This absorbed energy then transfers downward and becomes the cooling load sometimes later (according to the thermal mass and time lag of the roofing material).

The analysis of results indicates that, the weathered asbestos roofing demonstrated the maximum peak cooling demand of 3.2kW caused by its inherent higher solar absorptivity ($\alpha = 0.75$). When the un-painted new asbestos material was used (absorptivity decrease from $\alpha = 0.75$ to $\alpha = 0.60$) instead of old one (reference case), the highest peak cooling demand also decreases to 2.6kW from 3.2kW (18.3% decrease). As this material get discoloured due to fungi formation and dust after few years of use without any surface treatment, in actual situation, unfortunately the previous results could be expected.

As expected, the third alternative roof material; the painted asbestos with lower absorptivity coefficient of 0.35 exhibits the lowest cooling load among the asbestos family, however, the third lowest in all cases as 1.8kW (45.2% decrease compared to reference case). From the Figure 5.8 above, this material show a distinct difference of hourly cooling demand fluctuations compared to its previous counterparts. This result suggests that lowering the solar absorptivity of the exterior surface of a roof material can result in low cooling loads.

When the asbestos material was changed with burnt-clay calicut tiles, both conventional and new tile used in this study showed fairly similar hourly cooling demands as well as maximum peaks. As shown in the Figure 5.8 above, during early and late hours of the day, cooling demand profiles coincided each other. Compared to the reference case, these two materials registered quite significantly lower cooling demands; 1.6kW and 1.5kW respectively (decrease of 49.3% and 52.6% respectively).

According to these simulated results, the last alternatives; calicut tile roofing material provided the lowest, as half of the reference case, cooling peak demands. This could minimize the size of an air-conditioner by half reducing both the capital as well as the operational cost incurred for energy.

- **Daily cooling energy use**

In the previous section, cooling energy fluctuations were studied on hourly basis on the lowest temperature day. For that, only bare roofing types were selected. In order to study the impact of roof/ceiling material and configurations on buildings cooling energy performance, a series of simulations were performed varying material type and configurations. In this case, daily total energy use was analysed for the same day and all roofing/ceiling configurations (which include 25 no of configurations) were used. The results are presented in the following Figure 5.9 and Table 5.2. The building modeled in the study was a standard 6mx5m with ceiling height of 3m. Further, a specific energy use per unit floor (kWh/m² day) were also evaluated, and these results are presented in the Table 5.3 below.

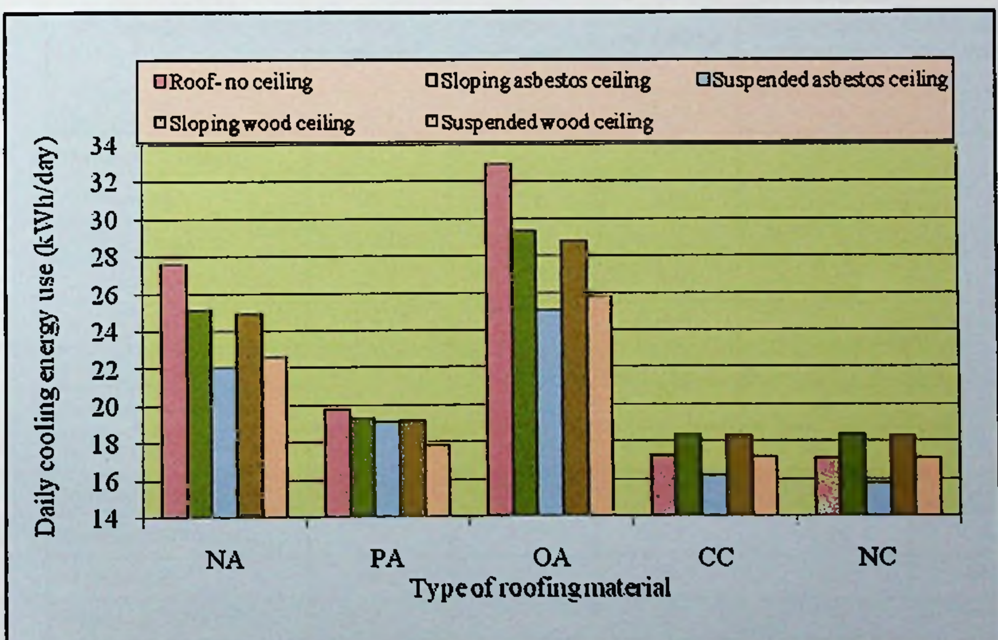


Figure 5.9: Comparison cooling energy use at south-east orientation on 6th March 2011

According to these results, out of the 25nos of configurations, the old asbestos roofing with no ceiling model (reference case) showed the highest daily total cooling energy use of 32.9kW (specific energy use of 1.1 kWh/m² day). Another highlighting fact is that, in the previous simulations (sub section 5.2.3.5) which was carried out to characterise the indoor temperature fluctuations, this same roof/ceiling configuration demonstrated the highest maximum indoor temperature. The second highest daily cooling load was given by the same roofing material; old asbestos, however, when it is integrated with sloping asbestos ceiling. Compared to the reference case, this has demonstrated a slightly lower daily cooling demand as 29.3kW (a decrease of 3.6kW, 10.9%) which is subsequently equal to 0.98 kWh/m² day compared to1.1 kWh/m² day in the reference case. However, this combination showed the 3rd highest indoor peak temperature when simulated for indoor temperature fluctuations.

Table 5.2: Comparison of daily cooling energy use at E-W orientation on 6th March 2011

S/n	Roofing/ceiling configuration	Daily total cooling energy use (kWh/day)				
		New asbestos	Painted asbestos	Old asbestos	Convectional calicut tile	New calicut tile
1	Roof- no ceiling	27.6	19.8	32.9	17.3	17.1
	Difference (kWh/day)	-5.3	-13.1	0.0	-15.6	-15.8
	% Difference	-16.2	-39.8	0.0	-47.5	-47.9
2	Sloping asbestos	25.1	19.3	29.3	18.4	18.4
	Difference (kWh/day)	-7.8	-13.6	-3.6	-14.5	-14.5
	% Difference	-23.6	-41.3	-10.9	-44.0	-44.2
3	Suspended asbestos	22.0	19.1	25.1	16.2	15.8
	Difference (kWh/day)	-10.9	-13.8	-7.8	-16.7	-17.1
	% Difference	-33.0	-41.9	-23.7	-50.8	-51.9
4	Sloping wood	24.9	19.2	28.8	18.3	18.3
	Difference (kWh/day)	-8.0	-13.7	-4.1	-14.6	-14.6
	% Difference	-24.2	-41.7	-12.5	-44.3	-44.4
5	Suspended wood	22.6	17.8	25.8	17.2	17.1
	Difference (kWh/day)	-10.3	-15.1	-7.1	-15.7	-15.8
	% Difference	-31.4	-45.8	-21.6	-47.8	-47.9

Note: Negative (-) marks indicate a reduction

The 3rd highest daily cooling demand is offered by the same roofing type; old asbestos one (reference case), however, this time when integrated with a sloping wood ceiling. The daily cooling energy use has reduced to 28.8kW from 32.9kW of the reference case (4.1kW, a 12.5% reduction compared to reference case). In the previous indoor temperature simulations, this model showed moderately low maximum indoor temperature. The specific energy consumption was 0.96 kWh/m² day, 4.1% reduction compared to the reference case.

The bare roof (no ceiling) constructed with new asbestos material showed the 2nd highest peak indoor temperature in previous simulations, however, when simulated for daily cooling energy use, this configuration exhibited the 4th highest daily cooling demand. The change of old asbestos roofing with this new asbestos (no ceiling) configuration has reduced the daily energy use to a 27.6kW, a 16.2% decrease compared to the reference case.

The analysis of daily cooling energy demand showed that, the newly introduced calicut tile roof material with suspended asbestos ceiling configuration demonstrated the lowest daily cooling energy use by almost half, among the 25 no of roof/ceiling configurations with a quite significant decrease by nearly 52% to the reference roofing material (to 15.8kW from 32.9kW of the reference case). The specific energy consumption has decreased to 0.53 kWh/m² day from 1.1 kWh/m² day.

As shown in the Figure 5.9 and Table 5.2 above, when the new calicut tile roof is replaced with the conventional tile material, keeping the same ceiling configuration as in the lowest case, this configuration demonstrated the 2nd lowest daily cooling load, with significant decrease from 32.9kW to 16.2kW (a decrease of 16.2kW, a 50.8% compared to the reference case).

Table 5.3: Comparison of specific cooling energy use at S-E orientation on 6th March 2011

S/n	Roofing/ceiling configuration	Total specific cooling energy use (kWh/m² day)				
		New asbestos	Painted asbestos	Old asbestos	Convectional calicut tile	New calicut tile
1	Roof- no ceiling	0.92	0.66	1.10	0.58	0.57
	Difference (kWh/m² day)	-0.18	-0.44	0.00	-0.52	-0.53
	% Difference	-16.2	-39.8	0.1	-47.5	-47.9
2	Sloping asbestos	0.84	0.64	0.98	0.61	0.61
	Difference (kWh/m² day)	-0.26	-0.46	-0.12	-0.49	-0.49
	% Difference	-23.6	-41.3	-10.9	-44.0	-44.2
3	Suspended asbestos	0.73	0.51	0.84	0.54	0.53
	Difference (kWh/m² day)	-0.37	-0.59	-0.26	-0.56	-0.57
	% Difference	-33.0	-53.9	-23.7	-50.8	-51.9
4	Sloping wood	0.83	0.64	0.96	0.61	0.61
	Difference (kWh/m² day)	-0.27	-0.46	-0.14	-0.49	-0.49
	% Difference	-8.0	-13.7	-4.1	-14.6	-14.6
5	Suspended wood	0.75	0.59	0.86	0.57	0.57
	Difference (kWh/m² day)	-0.35	-0.51	-0.24	-0.53	-0.53
	% Difference	-31.4	-45.8	-21.6	-47.8	-47.9

Note: Negative (-) marks indicate a reduction

- **Sensitivity analysis of roofing/ceiling configuration on cooling energy use**

The relative effect of ceiling configuration with the roofing solutions is presented in the Table 5.4 below. According to the simulation results, the bare roof models always have shown the highest cooling demands compared to their other ceiling configurations. On the contrary, however, when any type of ceiling is included, the cooling energy use decreases. Compared to the suspended ceiling configurations, the sloping models presented high cooling loads in all cases. This may be due to the fact that the attic volume is small in sloping ceiling models compared to its suspended type counterpart, and thereby resulting convective heat transfer from the attic to the outdoor is small. When the results are analysed further, it is apparent that the asbestos sheet material used in sloping ceilings demonstrated high cooling energy use. In contrast, however, when the suspended ceiling type is considered, an opposite result is observed. In many cases, wooden plank suspended ceiling configuration has demonstrated higher cooling demands.

Table 5.4: Sensitivity analysis of cooling energy use with different roofing/ceiling configurations at south-east orientation on 6th March 2011

S/n	Roofing/ceiling configuration	Daily total cooling energy use (kWh/day)				
		New asbestos	Painted asbestos	Old asbestos	Convectional calicut tile	New calicut tile
1	Roof- no ceiling	27.6	19.8	32.9	17.3	17.1
2	Sloping asbestos	25.1	19.3	29.3	18.4	18.4
	Difference (kWh/day)	2.4	0.5	3.6	-1.1	-1.2
	% Difference	8.8	2.6	11.0	-6.6	-7.1
3	Suspended asbestos	22.0	19.1	25.1	16.2	15.8
	Difference (kWh/day)	5.5	0.7	7.8	1.1	1.3
	% Difference	20.1	3.6	23.8	6.3	7.8
4	Sloping wood	24.9	19.2	28.8	18.3	18.3
	Difference (kWh/day)	2.7	0.6	4.2	-1.1	-1.1
	% Difference	9.6	3.2	12.6	-6.2	-6.7
5	Suspended wood	22.6	17.8	25.8	17.2	17.1
	Difference (kWh/day)	5.0	2.0	7.1	0.1	0.0
	% Difference	18.1	10.0	21.7	0.6	0.0

***Note:** Negative (-) marks indicate a reduction*

When the results is analysed further, the asbestos roofing material demands high energy compared to calicut tile material. The old asbestos roofing solution has shown always high cooling demands caused by its higher absorptivity. However, when new asbestos sheet roofing is considered, a significant reduction was observed. Subsequently, as shown in the Figure 5.2 above, for example, a daily cooling load reduction of 5.3kW from 32.9kW to 27.6kW (a 16.2% reduction) was obtained when old asbestos sheet roofing was replaced with a new roof covering with the same material. A more positive benefit is gained when all the previous asbestos sheet coverings are replaced with a coloured asbestos roof material. As shown in the Figure 5.2 above, for all ceiling configurations, coloured sheet covering material has resulted significantly lower energy demands than its previous counterparts; old and new asbestos materials. For example, when the bare roof construction is concerned, the coloured asbestos material has reduced the daily energy demand to 19.8kW from 32.9kW and 27.6kW from than its old and new asbestos material types respectively (39.8% and 16.2% reduction).

An analysis of daily energy use show that both these calicut tile models show almost similar cooling energy demands. These types have shown quite significantly lower cooling demands always. As shown in the Tables 5.2 & 5.3, it is apparent that a change of ceiling type has a slight effect for both these calicut tile roofing. For the conventional calicut tile material, a change in a ceiling configuration has affected the daily cooling load by 2.6kW when it is changed from a suspended asbestos ceiling (15.8kW, the lowest for this model) to sloping asbestos ceiling (18.4kW the highest for this model). Another interesting fact is that, these two calicut tile roofing models show a little higher energy demands when they are integrated with sloping ceiling configuration compared to other bare roof materials.

A similar trend could be seen in the painted asbestos sheet roofing. A change in ceiling type has a quite significantly lower effect as 2kW on the daily indoor cooling energy use when it is changed from a bare roof (19.8kW, the highest for this type) to the suspended wood ceiling (17.8kW, the lowest).

When the new asbestos sheet material is considered in place of painted asbestos roofing, a different trend is noticed. The characteristics of new asbestos material is such that, a change in ceiling type has affected moderately; a daily cooling energy change of 5.6kW (a decrease from 27.6kW in bare roof to 22kW for suspended asbestos ceiling). A change in ceiling configuration on the daily cooling energy use was clearly observed with the old asbestos roofing material. A change from the bare roof to the suspended asbestos ceiling has affected the cooling load most significantly as 7.8kW. As shown in the Table 5.4, both sloping ceiling models have a close energy use to the bare roof building.

5.2.5 Effect of orientation on indoor thermal climate

The previous simulations were performed setting the roof ridge at east-west orientation of a two-pitched roof building. To investigate the effect of orientation on the indoor temperature and cooling energy use with different roof/ceiling configurations of the same building design (2-pitched model), several simulations were performed keeping the roof ridge aligned to north-south orientation.

- **Effect of orientation on roof exterior surface temperature**

Initially, simulations were carried out to obtain exterior surface temperatures of roof covering materials. As explained in the sub section 5.2.1 previously, the roof exterior surface temperature significantly affects the indoor temperature and cooling load of the building. The results are presented in the Figure 5.10 below.

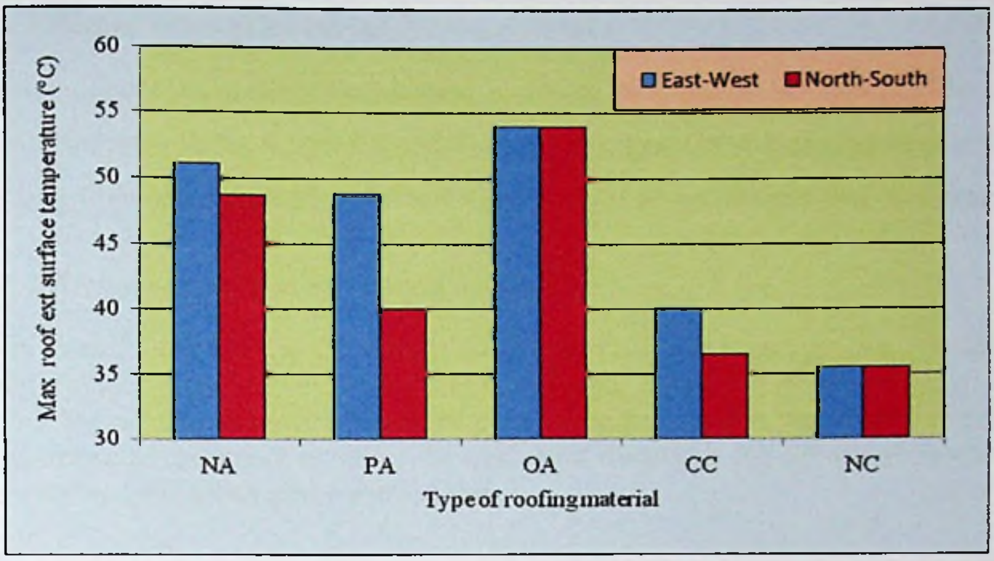


Figure 5.10: Comparison of maximum roof exterior surface temperature (^{0}C) for E-W and N-S orientations on 6th March 2011

As demonstrated in the Figure 5.10 above, slightly higher average exterior surface temperatures were recorded on all roof covering materials when the house is oriented at east-west direction than it is aligned with the north-south direction for this month. This is mainly due to the sun's position of this particular month; March. During this month, the sun is at overhead position of the sun-path diagram relevant to Sri Lanka. As a result, the entire roof (both sides of the roof) receives higher amount of solar energy. In contrast, when the house is oriented to the north-south direction, the sun crosses the roof and consequently, in the morning, the east oriented roof exposes to the sun while the west oriented roof getting shaded and the reverse phenomena happen in the afternoon. The result is that the whole roof area does not receive direct solar energy as in the east-west oriented house. As demonstrated in the Figure 5.10, though the old asbestos sheet roofing recorded the highest ever exterior roof temperature, a change in orientation has a fairly low effect on the roof top temperature. However, other roofing materials show a difference in roof surface temperature when the orientation was changed.

- **Effect of orientation on indoor temperature**

When the indoor temperature is concerned, a similar temperature profile could be noted. The results shown in the Table 5.2 and Figure 5.4 suggest that a change in orientation has a fairly little effect on the indoor temperature when a two pitched roof is concerned.

- **Effect of orientation on cooling energy use**

As explained in the above, the results of the daily cooling energy use for the two building models oriented to east-west and north-south directions were evaluated. In the Table 5.7 below, the results are presented comparing the effect of building's orientation with reference to the previous case; the east-west direction. All 25nos of roof/ceiling configurations were taken into consideration.

Table 5.5: Comparison of daily cooling load for east-west & north-south orientations on 6th March 2011

S/n	Roofing/ceiling configuration	Daily total cooling energy use (kWh/day)									
		New asbestos		Painted asbestos		Old asbestos		Convectional calicut tile		New calicut tile	
		East-West	North-South	East-West	North-South	East-West	North-South	East-West	North-South	East-West	North-South
1	Roof- no ceiling	27.6	27.1	19.8	19.4	32.9	31.7	17.3	17.0	17.1	16.9
	Difference (kWh/day)		0.5		0.4		1.2		0.2		0.3
	% Difference		1.7		1.9		3.6		1.4		1.7
2	Sloping asbestos	25.1	24.7	19.3	18.9	29.3	28.9	18.4	18.1	18.4	18.0
	Difference (kWh/day)		0.4		0.4		0.4		0.3		0.4
	% Difference		1.8		2.3		1.3		1.9		1.9
3	Suspended asbestos	22.0	21.6	19.1	18.6	25.1	24.9	16.2	15.8	15.8	15.5
	Difference (kWh/day)		0.4		0.5		0.2		0.4		0.3
	% Difference		1.8		2.7		0.9		2.3		1.7
4	Sloping wood	24.9	24.5	19.2	18.7	28.8	28.4	18.3	18.0	18.3	17.9
	Difference (kWh/day)		0.4		0.4		0.4		0.4		0.4
	% Difference		1.7		2.3		1.3		1.9		1.9
5	Suspended wood	22.6	22.2	17.8	17.4	25.8	25.4	17.2	16.9	17.1	16.8
	Difference (kWh/day)		0.4		0.4		0.4		0.3		0.3
	% Difference		1.8		2.2		1.5		1.8		1.8

Note: Negative (-) marks indicate a reduction

According to the simulated results, when the building was oriented to north-south direction, all roofing/ceiling configurations showed a slightly lower cooling demands compared to east-west direction which they were oriented initially. Although the north-south oriented building performs marginally better, a distinct difference cannot be found between the two roof orientations. The differences in the daily cooling demand due to the effect of building's orientation lies within a very small and narrow range. The highest percentage difference was observed in the bare roof constructed with old asbestos sheet material (the reference case) and was as little as 3.6% (a decrease in 1.2kW compared to previous east-west orientation). In most cases, except the bare old asbestos roof, the difference in cooling energy use was lies within 0.5kW. the results suggest that the effect of orientation has no any appreciable significance on the daily cooling energy demand. The results justify the research findings of (Jayasinghe, Priyanvada, & Jayawardena, 2001) where they used cement fibre sheet roof material with sloping and suspended ceilings with the same material to characterize the effect of orientation on the buildings thermal environment. Thus, through the results of this two-pitched roof building, it can be concluded that there is no any significant effect of the orientation on the buildings cooling demand.

5.3 Four pitched roof building

So far, the thermal climate was discussed in detail in two-pitched roof buildings. In order to investigate the thermal performance of a four-pitched roof residential building, a computer model of a four-pitched design was done and a series of simulations were performed. The same roof/ceiling materials and configurations were used as in the previous case.

5.3.1 Indoor temperature

Initially, the indoor temperature of the building was simulated for two different orientations; east-west & north-south. The maximum indoor temperature was observed. The Figure 5.11 below presents the results of the east-west oriented building constructed with different roof/ceiling configurations. A more detail comparison is presented in the Appendix B-Table B1.

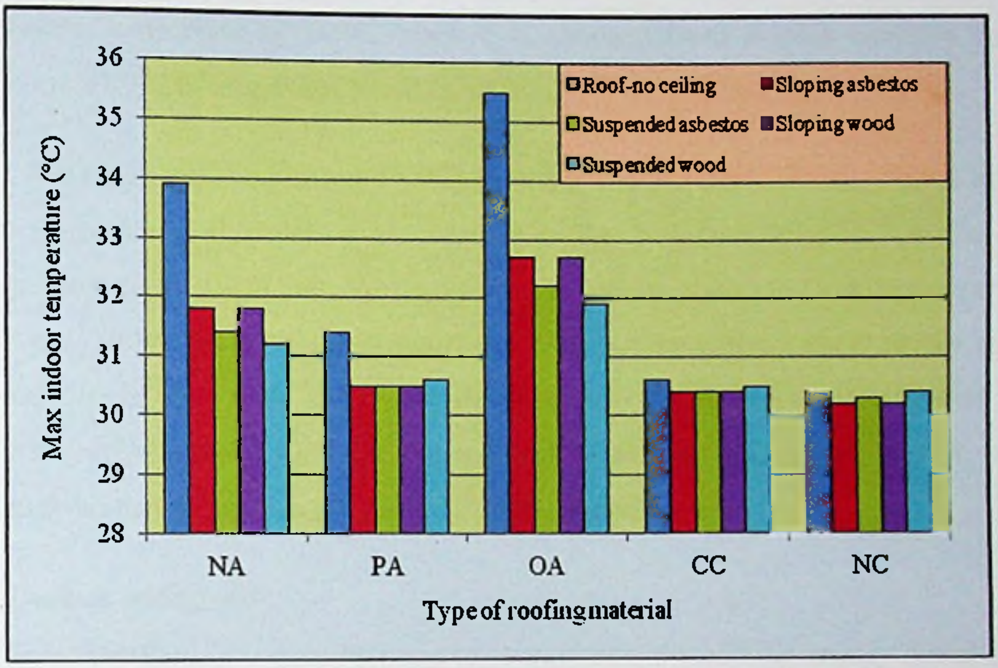


Figure 5.11: Comparison of maximum indoor temperature (^{0}C) of a 4-pitched roof building for the east-west orientation on 6th March 2011

The most highlighting fact is that the 4-pitched roof building also demonstrates similar results as the 2-pitched building. According to the simulated results, the bare roof building (no-ceiling) configurations show the highest indoor temperature always in all cases. Both calicut tile roof designs show lower temperatures. As in the 2-pitched roof building, the old asbestos bare roof shows the highest maximum indoor temperature of 35.5^{0}C. The new asbestos roof model exhibits the second highest indoor temperature similar to 2-pitched roof (33.9^{0}C). Both calicut tile designs give lower temperature as observed in the previous case.

Similarly, inclusion of any type of ceiling has a more effect on the indoor temperature when the roof is constructed with old asbestos material. As presented in the above

Figure 5.11 and Table B1 in Appendix B, the indoor temperature reduces by 2.8^0C from 35.5^0C (no-ceiling) to 32.8^0C (sloping asbestos ceiling). On contrast, with the same roof covering material, change of a ceiling type has not significantly affected to the indoor temperature; a decrease by 0.9^0C when it is changed from sloping asbestos ceiling (32.9^0C) to 31.9^0C of suspended wood ceiling.

In the 4-pitched roof building, all other building models demonstrate almost similar indoor temperatures fluctuations as observed in the 2-pitched building. On the other hand, in the 4-pitched building, the change in orientations affects the indoor temperature almost negligibly. This may be due to the reason that the exterior roof surface area is nearly similar of this model and expose symmetrically to the direct solar radiation. The comparison of maximum indoor temperature on both orientations; east-west & north-south is presented in detail in the Table B1 in the Appendix B.

5.3.2 Cooling energy use

A series of simulations were performed to characterize the cooling energy demand of a 4-pitched roof building as done for a 2-pitched building previously. The same set of roof/ceiling configurations was used. The results are presented in the Figure 5.12 below.

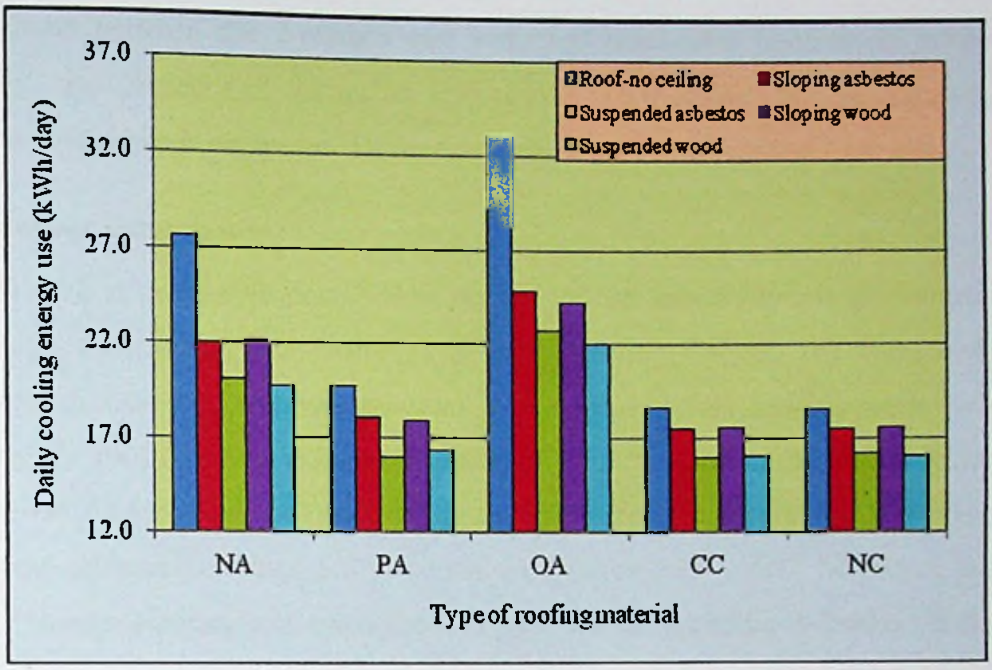


Figure 5.12: Comparison of daily cooling energy use (kWh/day) of 2 & 4-pitched roof building for the east-west orientation on 6th March 2011

According to these results, it is apparent that the cooling energy use show a similar pattern as observed in the previous 2-pitched roof building. The energy demand changes with the type of roof/ceiling configuration. It is more pronounced in cases where bare roof material is used. In all the cases simulated, the old asbestos roof material without any type of ceiling configuration demonstrated the highest cooling energy use (33kWh/day). This may be mainly due to the higher indoor temperatures prevails caused by its inherent high solar absorptivity as already discussed in previous cases. Except the new asbestos material with no-ceiling configuration which showed the second highest cooling energy use (27.6kWh/day), all ceiling combinations with old asbestos roof covering demonstrated high cooling demands.

5.4 Comparison of 2-pitched & 4-pitched roof buildings

This study covers both 2-pitched and 4-pitched roof buildings. So far, indoor thermal conditions of these two designs were discussed individually. In this section, a comparison between the 2-pitched and 4-pitched residential building is performed. Initially, characteristics of the indoor temperature are discussed and subsequently the cooling energy use is compared. The same roof/ceiling configurations were used.

5.4.1 Indoor temperature

In this section, a relative comparison on the indoor temperature is performed. The maximum temperature was evaluated in both building designs and compared. The characteristics of the indoor temperature of the two building designs were evaluated keeping the roof covering material unchanged. In each case, the ceiling configuration was varied. Consequently, all roof/ceiling configurations are covered. The results of the east-west oriented buildings are presented in Figures 5.13 - 5.17 below. A detailed comparison considering both orientations is presented in Appendix B-Tables B2 & B3.

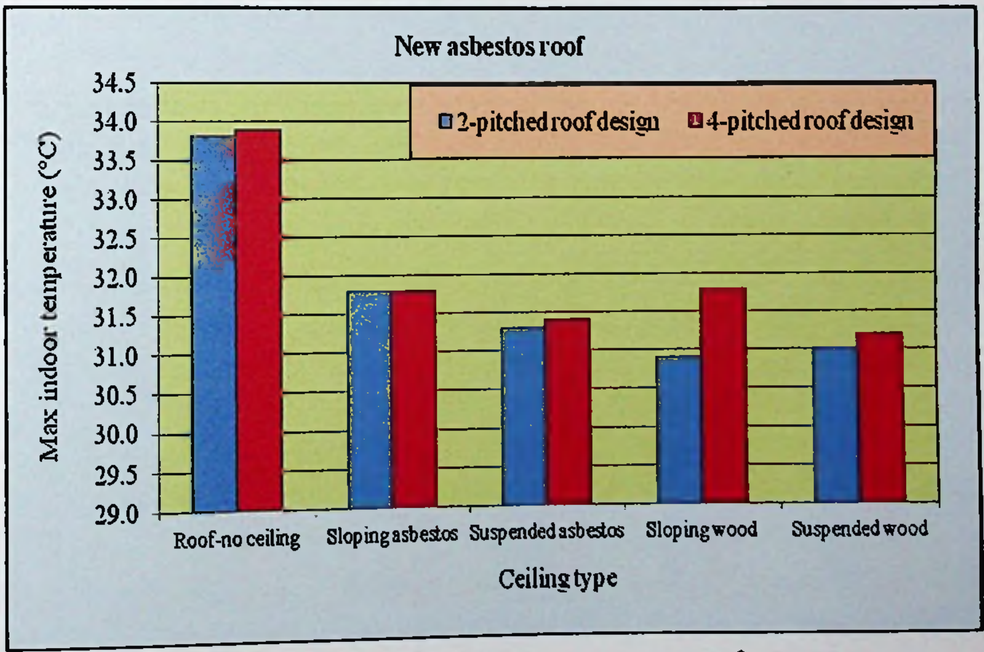


Figure 5.13: Comparison of maximum indoor temperature (^0C) for 2-pitched & 4-pitched roof building with new asbestos roof material

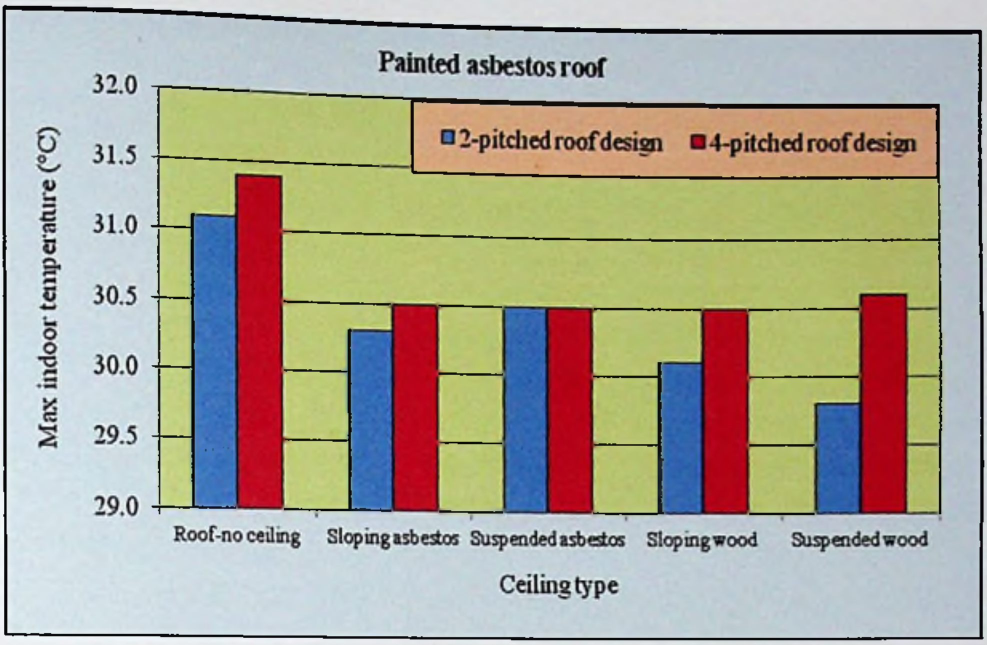


Figure 5.14: Comparison of maximum indoor temperature (^{0}C) for 2-pitched & 4-pitched roof building with painted asbestos roof material

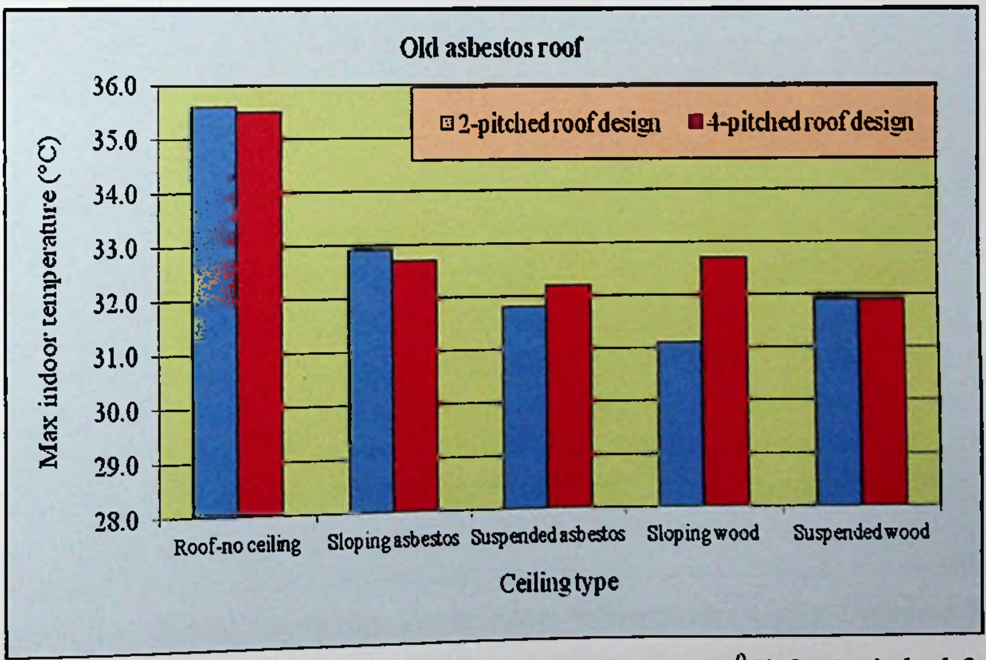


Figure 5.15: Comparison of maximum indoor temperature (^{0}C) for 2-pitched & 4-pitched roof building with old asbestos roof material

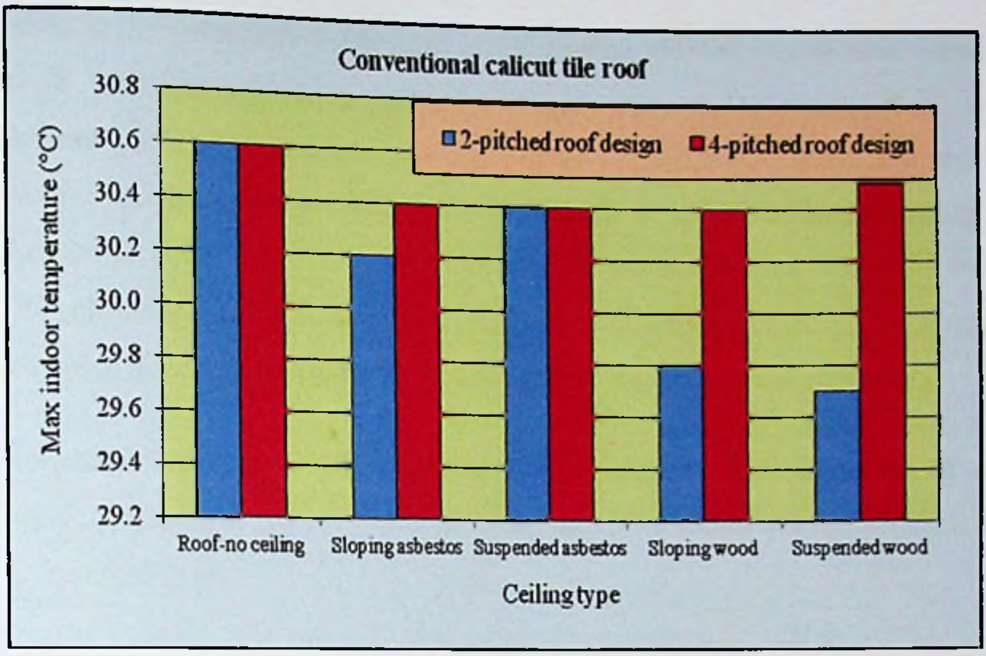


Figure 5.16: Comparison of maximum indoor temperature (^{0}C) for 2-pitched & 4-pitched roof building with conventional calicut tile roof material

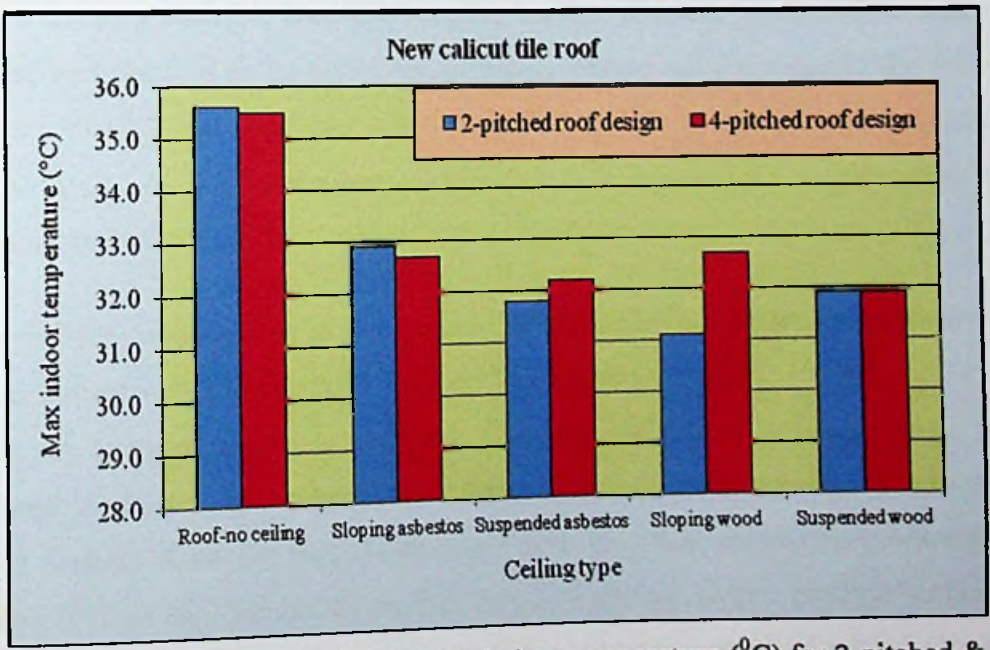


Figure 5.17: Comparison of maximum indoor temperature (^{0}C) for 2-pitched & 4-pitched roof building with new calicut tile roof material

According to the comparative ananlysis of the results obtained at east-west oriented 2-pitched & 4-pitched residential buildings, it is apparent that except very limited cofigurations (old asbestos sheet roofing with no-ceiling and sloping asbestos sheet ceiling), the 4-pitched designs showed a slighly higher indoor temperatures. In most cases (as shown in the Table B2 in the Appendix B), the temperature difference was less than 1°C (difference was less than 3%). When the building orientation was changed to the noth-south direction, an appreciably noticeble difference was not observed.

The comparative results of both buiding designs suggest that, in terms of indoor temperature fluctuations, there is no appreciably noticeble difference in 2-pitched and 4-pitched roof buildings.

5.4.2 Cooling energy use

In this section, in order to investigate the cooling energy fluctuations in 2-pitched and 4-pitched building designs, the daily cooling energy use was compared. Initially, the building was oriented to the east-west direction. Results are presented in the following Figures 5.18-5.22. The same procedure was followed as in the previous comparison (sub section 5.4.1). A detail comparison done for both orientations is presented in the Appendix B, Table B4 & B5.

In the previous comparison, in most cases, the maximum indoor temperatures in the 4-pitched houses were slightly high compared to 2-pitched models. However, in contrast to that an opposite results is obtained when the daily total cooling energy use is compared. According to the simulated results, except very limited case, it is high in 2-pitched designs. A similar trend is observed even the other orientation (north-south) is considered. This may be due to the fact that in 4-pitched house, the roof surface area exposed the direct sun at a particular orientation is low as compared with the 2-pitched model (same floor area is maintained in both cases). The comparative results suggest that 4-pitched houses provide fairly better cooling energy savings than those constructed with 2-pitched roof.

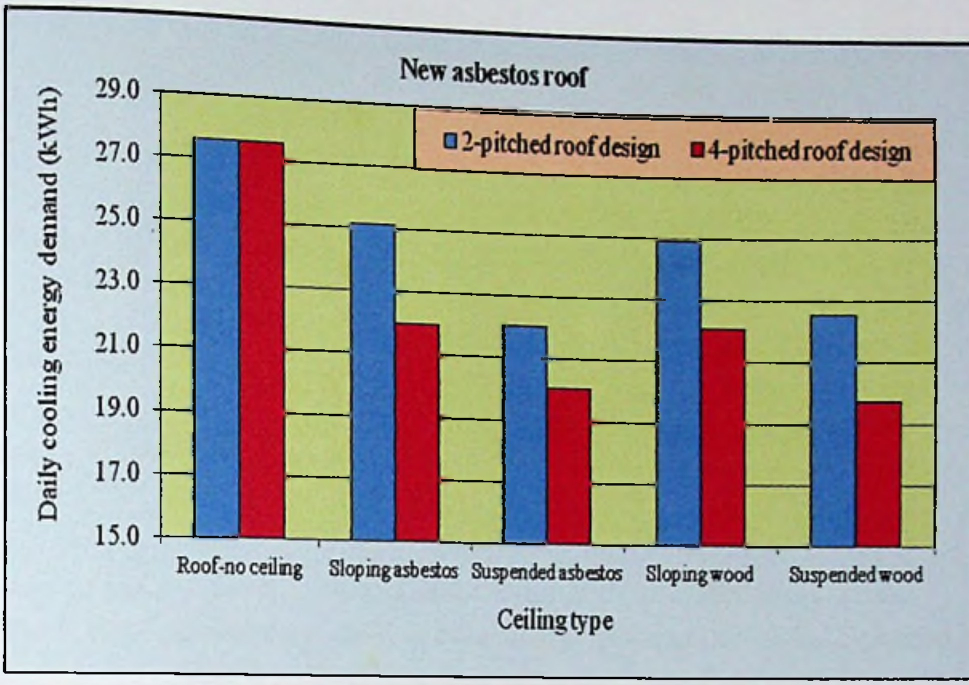


Figure 5.18: Comparison of daily cooling energy demand (kWh) for 2-pitched & 4-pitched roof building with new asbestos roof material

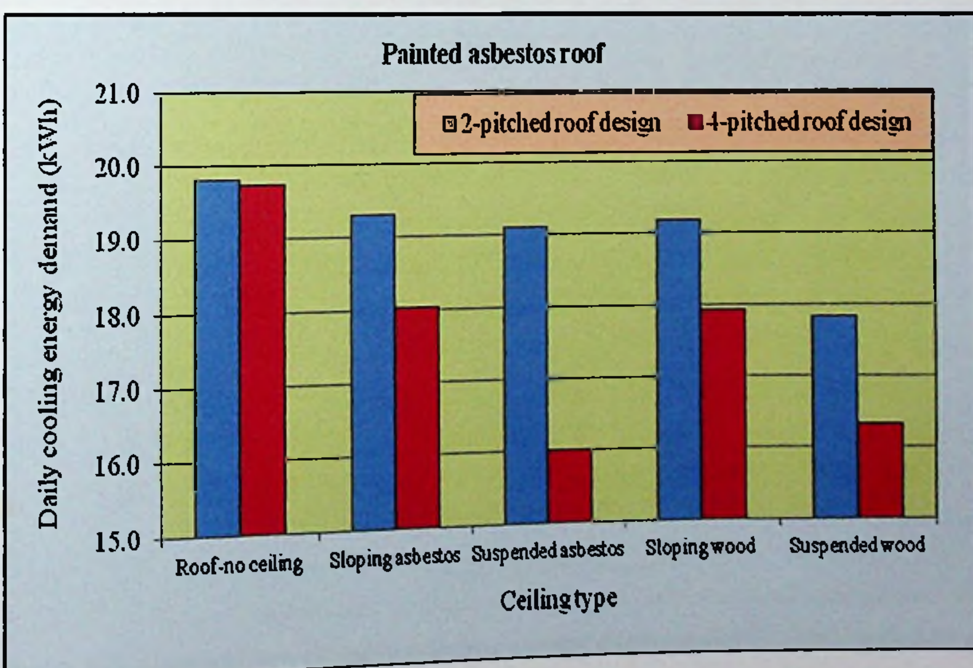


Figure 5.19: Comparison of daily cooling energy demand (kWh) for 2-pitched & 4-pitched roof building with painted asbestos roof material

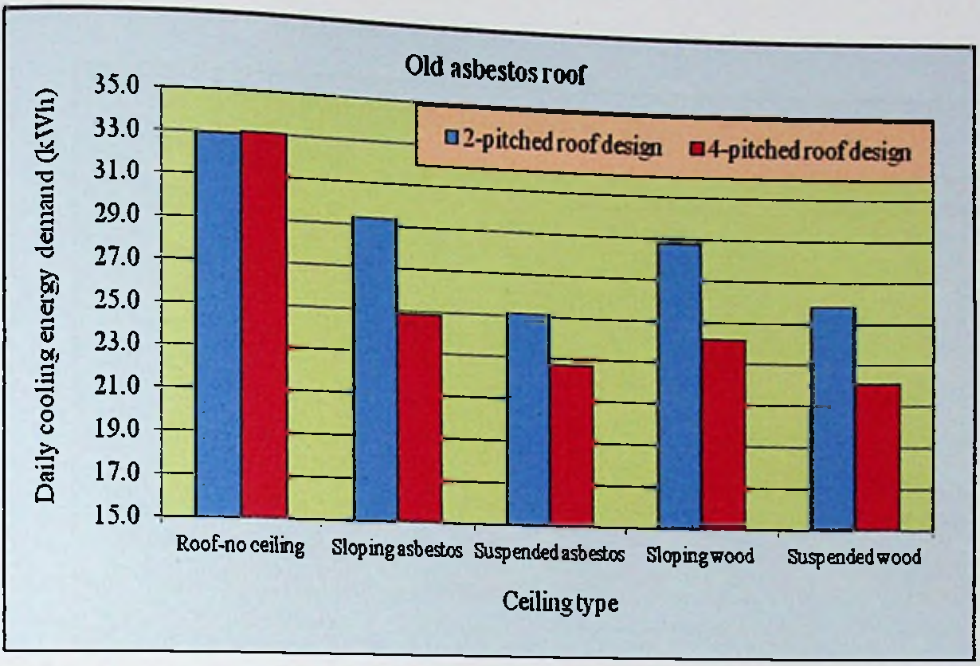


Figure 5.20: Comparison of daily cooling energy demand (kWh) for 2-pitched & 4-pitched roof building with old asbestos roof material

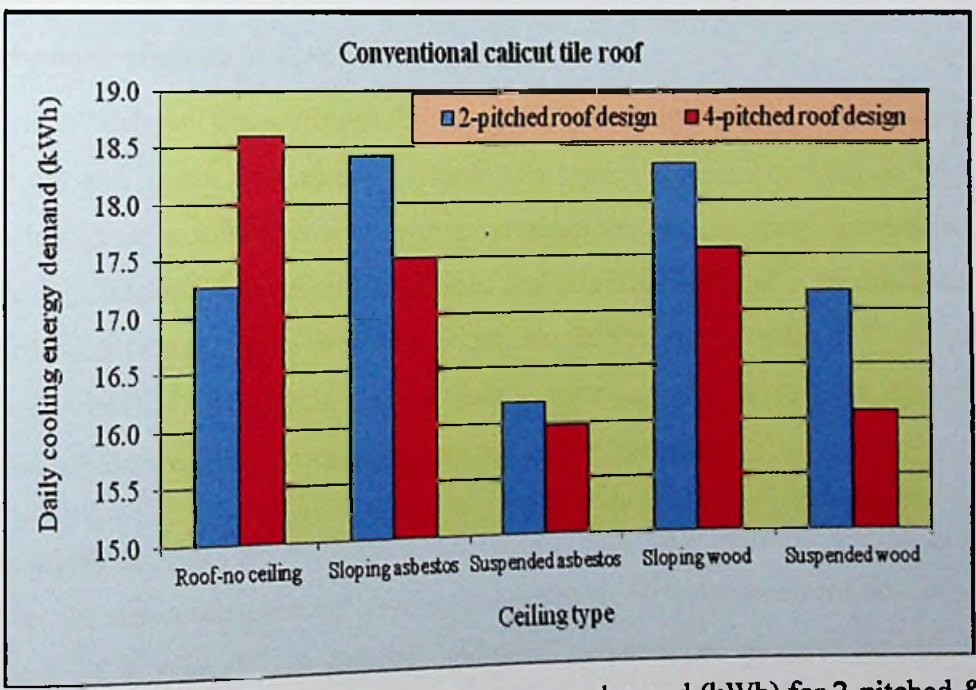


Figure 5.21: Comparison of daily cooling energy demand (kWh) for 2-pitched & 4-pitched roof building with conventional calicut tile roof material

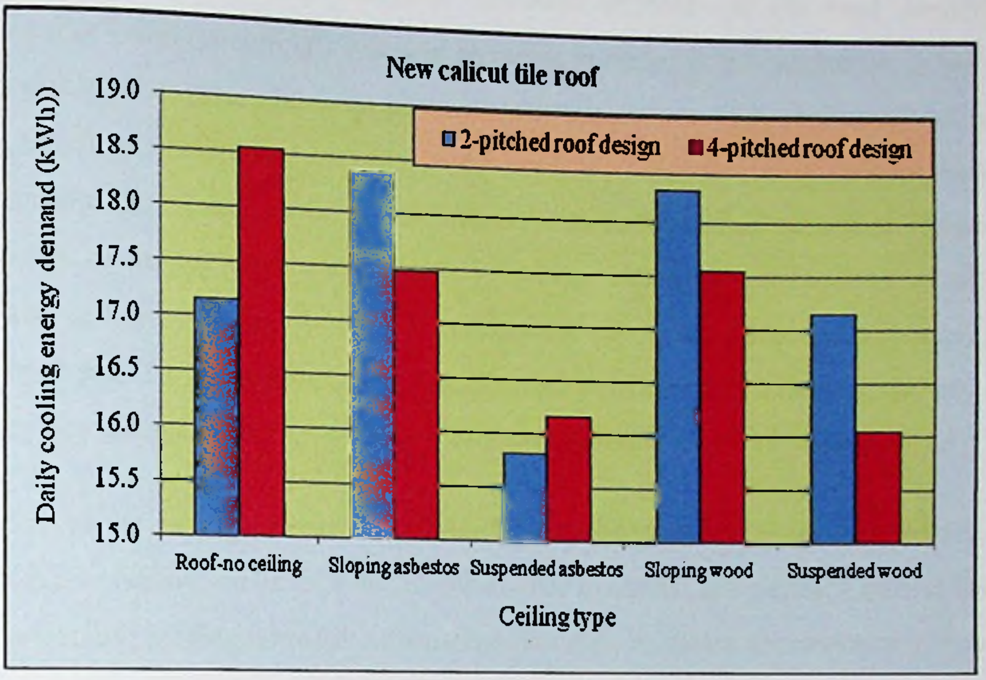


Figure 5.22: Comparison of daily cooling energy demand (kWh) for 2-pitched & 4-pitched roof building with new calicut tile roof material

5.5 Economic analysis of roof/ceiling products

In previous sections, the roofing/ceiling alternatives selected were analyzed for cooling energy use and indoor thermal environment of a basic residential building in Sri Lanka. According to the results drawn from these simulations, several conclusions were made considering indoor temperature fluctuations and cooling energy use. In this section, an economic analysis or a cost-benefit analysis was performed in order to investigate the economic viability of applying the different roof/ceiling alternative over the reference case; old asbestos roofing (with no-ceiling, type C) of the study.

This analysis provides an estimate of simply payback only. The estimation is mainly based on the net cooling energy saving (compared to the reference roof design) during the cause of a year (2011) and the additional expenditure incurred to construct a particular roof/ceiling configuration. In this case, it was assumed that each building model was air-conditioned throughout the year. The room temperature set point was at

25^0C always. The additional cost was estimated reference to the base design; old asbestos roof (with no-ceiling). The cost elements included in the estimation is based on the present market price and from personal communications with engineers/contractors in the building construction industry in the country. This sensitivity analysis includes 10% transportation cost as well. Considerations such as future fuel escalation rates or the time value of money were not accounted for. The economic performance results are presented in Figure 5.8 below. As no such significant variations in cooling energy use between 2-pitched & 4-pitched roof designs and between both orientations, pay back periods were estimated for a 2-pitched building oriented at east-west direction only.

Referring to the average payback periods, it is evident that the economic performance varies over a narrow range of 0 to 3.5 years. For example, the payback period for this best performing roofing material; new calicut tile, type E, varies approximately from one (01) to 3.3 years.

Based on the results of this analysis, it can be concluded that the all roofing/ceiling designs are cost effective and worth paying for. Though, the initial capital cost of calicut tile designs are too much expensive, incorporation of those designs also worth paying in terms of cooling energy use.

Table 5.6: The economic analysis of different roof/ceiling configurations versus reference roof design

S/n	Ceiling type	Description		New asbestos	Painted asbestos	Old asbestos	Conventional Calicut tile	New Calicut tile
				Roofing material				
1	No-ceiling	Roofing material cost (Rs/m²)		802	1390	802	950	2240
		Roof structural cost (Rs/m²)	Material	485	485	485	5375	5375
			Labour	360	360	360	2675	2675
		Total cost (Rs/m²)		1812	2459	1812	9900	11319
		Additional expenditure (Rs/m²)		0	647	0	8088	9507
		Energy use (kWh/m²day)		0.92	0.66	1.10	0.58	0.57
		Annual energy use (kWh/m²)		336	241	401	210	209
		Annual energy cost (Rs/m²)		6713	4821	8014	4202	4173
		Annual energy cost saving (Rs/m²)		1301	3193	0	3812	3841
		Simple payback period (yrs)		**0.0**	**0.2**	**0.0**	**2.1**	**2.5**
2	Sloping asbestos	Ceiling structural cost (Rs/m²)	Material	784	784	784	784	784
			Labour	1605	1605	1605	1605	1605
		Total cost (Rs/m²)		4440	5086	4440	12528	13947
		Additional expenditure (Rs/m²)		2628	3274	2628	10716	12135
		Energy use (kWh/m²day)		0.84	0.64	0.98	0.61	0.61
		Annual energy use (kWh/m²)		306	235	357	224	224
		Annual energy cost (Rs/m²)		6119	4697	7134	4481	4470
		Annual energy cost saving (Rs/m²)		1895	3317	880	3533	3544
		Simple payback period (yrs)		**1.4**	**1.0**	**3.0**	**3.0**	**3.4**
3	Suspended asbestos	Ceiling structural cost (Rs/m²)	Material	784	784	784	784	784
			Labour	1605	1605	1605	1605	1605
		Total cost (Rs/m²)		4440	5086	4440	12528	13947
		Additional expenditure (Rs/m²)		2628	3274	2628	10716	12135
		Energy use (kWh/m²day)		0.73	0.64	0.84	0.54	0.53
		Annual energy use (kWh/m²)		268	232	305	197	192
		Annual energy cost (Rs/m²)		5362	4648	6105	3939	3848
		Annual energy cost saving (Rs/m²)		2652	3366	1909	4075	4166
		Simple payback period (yrs)		**1.0**	**1.0**	**1.4**	**2.6**	**2.9**

S/n	Ceiling type	Description		Roofing material				
				New asbestos	Painted asbestos	Old asbestos	Conventional Calicut tile	New Calicut tile
4	Sloping wood	Ceiling structural cost (Rs/m²)	Material	1145	1145	1145	1145	1145
			Labour	1605	1605	1605	1605	1605
		Total cost (Rs/m²)		4837	5484	4837	12925	14344
		Additional expenditure (Rs/m²)		3025	3672	3025	11113	12532
		Energy use (kWh/m²day)		0.83	0.64	0.96	0.61	0.61
		Annual energy use (kWh/m²)		303	233	350	223	223
		Annual energy cost (Rs/m²)		6066	4666	7001	4461	4452
		Annual energy cost saving (Rs/m²)		1948	3348	1013	3553	3562
		Simple payback period (yrs)		**1.6**	**1.1**	**3.0**	**3.1**	**3.5**
5	Suspended wood	Ceiling structural cost (Rs/m²)	Material	1145	1145	1145	1145	1145
			Labour	1605	1605	1605	1605	1605
		Total cost (Rs/m²)		4837	5484	4837	12925	14344
		Additional expenditure (Rs/m²)		3025	3672	3025	11113	12532
		Energy use (kWh/m²day)		0.75	0.59	0.86	0.57	0.57
		Annual energy use (kWh/m²)		275	217	314	209	209
		Annual energy cost (Rs/m²)		5495	4337	6278	4178	4172
		Annual energy cost saving (Rs/m²)		2519	3677	1736	3836	3842
		Simple payback period (yrs)		**1.2**	**1.0**	**1.7**	**2.9**	**3.3**

CHAPTER: 6: CONCLUSIONS

6.1 Introduction

This study was carried out to investigate the effect of roofing/ceiling material type and their different combinations on the indoor thermal environmental conditions of a basic residential building in Sri Lanka. In this regard, five (05) types of roof covering materials and two (02) types of ceiling material types commonly used in the local building sector were taken. Each roofing material was combined with four (04) different ceiling configurations (sloping & suspended). In addition, simulations were performed for bare roof (no-ceiling) configurations as well. As a result, building oriented at a particular orientation covers almost twenty five (25) roof/ceiling configurations. As the particular building design (i.e. 2-pitched one) was simulated for two orientations, there have been fifty (50) configurations in the study. When the building is constructed with 4-pitched roof, the study totally covers hundred no's of roof/ceiling configurations. Based on the simulated results, the following conclusions were drawn.

6.2 Conclusion from the hourly fluctuations analysis of roof exterior surface temperature

As the roof exterior surface temperature is a major indicator for determining the thermal performance of the building, initially, simulations were performed to characterize the exterior surface temperatures of roofing materials selected. The fluctuations of top surface temperature was analysed on an hourly basis on 6th March 2011, the design minimum temperature day. All the roofing alternatives were used. The analysis of hourly fluctuations showed that, exterior surface temperature curves are quite close to each other early in the morning and late in the afternoon; in the absence of solar radiation irrespective of orientation. The study also indicated that peaks and troughs tend to occur around the same time regardless of the material type. However, with the continuous increase in solar radiation on earth level, the curves showed a remarkable change in temperature. The lowest temperature was obtained usually early in the morning; most often at around 0700hrs (just after the sun has risen) irrespective of the material type. Further, the peak temperature also appeared at the same time interval;

most often around 1400hrs during which the high intensity of solar radiation is available at earth surface level. The results showed that the roof exterior surface temperature is strongly affected by the sun path diagram relevant to the building and thus the intensity of solar radiation available.

One important finding was that the reference roofing material; old asbestos sheet (type C) showed the highest peak surface temperature while the new calicut tile (type E) demanded the lowest peak top surface temperature in almost all cases. This is mainly due the difference in solar absorptivity of the exterior surface of the roofing material; higher the absorptivity, higher the top surface temperature and vice versa. This situation is more pronounced whenever the outdoor solar radiation intensity is high.

This finding from hourly simulation suggest that the selection of roofing material is especially important for the situation where high solar radiation intensity prevails as this causes higher magnitudes of solar driven downward heat transfer caused by higher exterior surface temperatures.

6.3 Conclusion from the hourly temperature fluctuations analysis-no ceiling

In the study, after the evaluation of roof exterior surface temperatures, the indoor air temperatures were analysed for a two-pitched building constructed with roof covering materials, however, with no ceiling inclusion. The same day was selected for simulations.

The results of the simulations show a similar indoor temperature profiles as in the roof exterior surface temperatures. The minimum and maximum indoor temperatures occurred simultaneously irrespective of the roofing material type, however, a little time delayed by around 20-30mins. This may be due to the time lag effect of roofing material. Another important finding was that, in this simulation as well, the same material which showed the highest and lowest peak exterior surface temperature in the previous case also registered the maximum and minimum indoor temperatures. All other roofing material demonstrated the similar temperature patterns.

This suggest that roofing material show comparatively similar indoor temperature results as it's exterior surface temperatures, however, with low magnitudes, if no effective insulation cover underneath is provided.

6.4 Conclusion from the hourly temperature fluctuations analysis–with ceiling

In the previous part, indoor temperature fluctuations were compared with no ceiling inclusions. This case, the roof is constructed with the inclusion of different ceiling configurations. According to the results obtained, the general observation was that the inclusion of any type of ceiling configuration reduces the peak indoor temperature. The effect was more pronounced when the roofing material was selected from old asbestos and was significant with new asbestos roofing. However, even though, ceiling inclusion could reduce indoor temperatures, the effect is fairly low when painted asbestos, and two calicut tiled roof are considered.

Another important finding was that in most of the cases, asbestos sheet ceiling configurations give higher indoor temperatures than their counterparts; wooden plank ceiling design. Sloping ceiling models give comparatively higher indoor temperature climate than suspended version. This suggest that, inclusion of any type of ceiling design with a particular roof covering could modify (reduces) the indoor temperatures for better thermal environmental conditions and the ceiling material type and their configurations could always effect in changing the same in different magnitudes. Even though wooden plank ceiling design is little expensive than asbestos model, in the long run, addition of wooden ceiling could benefit for the occupants.

6.5 Conclusion from the hourly cooling energy fluctuations analysis

Once the indoor temperature fluctuations were analyzed, the next step was to evaluate the cooling energy use. In this case, the indoor temperature was set at 25°C throughout the day and the resulting cooling energy demand was estimated. Initially, the characteristics of cooling energy use was analysed on an hourly basis. All the roof/ceiling alternatives were used. The analysis of hourly fluctuations showed that, on the cooling demand curves are quite close to each other early in the morning and late in the afternoon; in the absence of solar radiation irrespective of orientation. The study also indicated that peaks and troughs tend to occur around the same time regardless of the roof material type.

However, with the continuous increase in solar radiation on earth level, the curves showed a remarkable change in cooling demand. The lowest load was obtained usually early in the morning; most often at around 0700hrs (just after the sun has risen) while the peak cooling demand was observed in the afternoon; somewhere around 1400hrs irrespective on the orientation and month. The results showed that the cooling demand is strongly affected by the sun path diagram relevant to the building and thus the intensity of solar radiation available in particular month.

One important finding was that the reference roofing material; old asbestos sheet (type A) showed the highest peak load while the newly introduced calicut tile (type E) demanded the lowest peak load in almost all cases. Another important finding was that the effect of roofing material type on cooling energy use is significant whenever the outdoor solar radiation intensity is high. Further, from this hourly cooling energy simulation, it was observed that, painted asbestos and two calicut tile roof materials show fairly similar results. As the cooling energy demand is highly affected by the variation of indoor temperature, similar profiles were observed as in the previous hourly temperature fluctuations and a similar conclusion could be drawn as done in the previous case.

This finding from hourly cooling energy simulation suggest that the selection of roofing/ceiling configuration is especially important for the situation where high solar radiation intensity prevails as the peak load determines the size of the air-conditioning equipment which results in high initial investment as well as the operational cost. Also, this finding reveals that the most popular roofing material in Sri Lanka; old asbestos sheet could be replaced by calicut tile material so that lower peak demand could be achieved.

6.6 Conclusion from the daily cooling energy use analysis

In this study, cooling energy performance of roofing/ceiling configuration was simulated for a whole day on 6th March 2011; the design maximum temperature day. The general observation was that the daily cooling energy use fluctuates as a function of outdoor solar radiation with all roofing/ceiling types; that is daily cooling load curves has similar pattern, but in varying magnitudes. Results indicate that the roofing/ceiling type generally had a more significant effect on the cooling energy use on the situations where high outdoor solar radiation intensity prevails. Results at the east-west oriented roofs showed that the cooling demand was more significantly affected by a change in roof material type. Note, however, that cooling was affected by at least 24% by a change in roofing type at this orientation (suspended asbestos ceiling with old asbestos roof). Overall, a change in roof/ceiling configuration affected cooling by 0-24% reference to the old asbestos roof (with no-ceiling). This finding suggests that the optimum roof/ceiling solution was strongly dependant on solar radiation intensity incident on the roof top surface.

In general, results indicate that the bare roof (no-ceiling) constructed with old asbestos sheet material (type C-reference case) almost always yielded slightly higher daily energy use than all other configurations while new calicut tile (type E) roofing material with suspended asbestos ceiling configuration demonstrated better results, 51% lower cooling energy use compared to reference case. All roof/ceiling combinations with both calicut tile designs performs better in all cases while even the same ceiling configurations are used with old asbestos material, it gives comparatively opposite results. However, painted asbestos roofing material gives moderate results.

6.7 Conclusion from the economic analysis of roofing products

The cost-benefit or an economic analysis was performed in order to investigate the economic viability of applying the different roof/ceiling alternative over the reference case; old asbestos roofing (with no-ceiling, type C) of the study. The estimation was performed for 2-pitched roof building designs oriented at east-west direction.

Based on the results of this analysis and as shown in the Table 5.8 in the previous sub section 5.5, it can be concluded that almost all roof/ceiling models are cost effective and worth paying. The simple pay back periods were less than 3.5 years in all cases.

CHAPTER 7: FUTURE WORK

Results and conclusions drawn from this research study were reached through computer simulations of the indoor temperature and energy performance of a basic residential building with the occupancy of three (03) inhabitants. Results were not compared with experimental data or else and should be considered in the light of the assumptions involved in the simulations.

The materials for roofing and ceiling types were selected form commonly used types from the residential building sector in Sri Lankan. For the computer simulations, thermo-physical properties such as thermal conductivity, density, specific heat etc as well as solar-optical properties such as absorptivity, reflectivity, and surface emissivity were obtained as close as to the actual values, however, from various literature. In the local context, most of the roofing/ceiling materials do not have experimentally validated parameters.

As all the simulations were performed using computer software, it was able to cover a wide scope of the topic area. Therefore, a much better results could have been obtained if few experimental models of similar configurations discussed in this study had been included. Therefore, it could be suggested that, the results obtained through this study could be further validated through experimental models as the study covers all most all roof/ceiling configurations commonly available in Sri Lankan residential building sector. Those results would be more accurate than those obtained from computer simulations.

Nowadays, many residential buildings incorporate different insulation materials, and as the study did not attempted to evaluate indoor thermal performance of roof/ceiling design with the inclusion of any type of insulation materials, therefore, a much work remains to carry out further research with the addition of those materials. A further better indoor thermal climatic condition may be obtained.

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APPENDIX A

Appendix A1: Indoor temperature (°C) for different roofing materials for east-west & north-south orientations on 6th March 2011.

Hour	Outdoor temp (°C)	Asbestos old		Asbestos new		Asbestos top surface painted		Convectional calicut tile		DSI tile	
		E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S
1	25.7	27.9	27.6	27.5	27.3	27	26.8	26.7	27.1	26.1	27.1
2	25	27.5	27.2	27.1	26.8	26.5	26.4	26.2	26.6	25.7	26.6
3	24.4	27	26.7	26.6	26.4	26.1	25.9	25.8	26.2	25.3	26.2
4	24.2	26.7	26.4	26.3	26.1	25.8	25.7	25.5	25.9	25	25.9
5	24.1	26.5	26.2	26.2	25.9	25.7	25.5	25.4	25.8	24.7	25.8
6	24	26.2	26	25.9	25.7	25.5	25.3	25.1	25.6	24.5	25.6
7	24.2	27.5	27.1	27	26.6	26.1	25.8	25.6	25.9	24.9	25.9
8	24.6	28.7	27.4	27.9	27.1	26.5	26	25.7	25.8	25.7	25.7
9	26	29.8	29.6	28.8	28.6	27.4	27	26.6	26.6	26.8	26.5
10	28.4	31.7	31.2	30.4	30.1	28.4	28.4	27.8	28.1	27.4	28
11	30.4	33.4	32.9	31.9	31.6	29.5	29.6	28.9	29.1	28.4	28.9
12	31.4	34.6	34.1	32.9	32.7	30.3	30.4	29.7	29.8	29.2	29.6
13	31.8	35.3	34.8	33.6	33.3	30.8	30.9	30.3	30.3	29.7	30
14	32	35.6	35.1	33.8	33.5	31.1	31.1	30.6	30.6	30.1	30.3
15	31.9	35.3	34.8	33.6	33.3	31.1	31.1	30.6	30.6	30.1	30.4
16	31.7	34.4	34	33	32.8	30.7	30.8	30.4	30.5	29.9	30.3
17	31.3	33.1	32.8	32	31.8	30.2	30.3	30	30.1	29.5	30
18	30.8	32.2	31.8	31.5	31.1	30.4	30.2	30.3	30.5	28.7	30.4
19	30.2	30.8	30.6	30.3	30.2	29.5	29.5	29.5	29.9	28	29.9
20	29.6	30.3	30.1	29.8	29.6	29.1	29.1	29.1	29.6	27.7	29.5
21	28.8	29.9	29.7	29.4	29.2	28.7	28.7	28.6	29.1	27.4	29.1
22	28	29.4	29.2	29	28.8	28.3	28.2	28.1	28.6	27.1	28.6
23	27.2	28.9	28.6	28.4	28.2	27.7	27.6	27.5	28	26.8	27.9
24	26.4	28.4	28.1	28	27.7	27.4	27.2	27.1	27.5	26.4	27.5
	32	35.6	35.1	33.8	33.5	31.1	31.1	30.6	30.6	30.1	30.4
Ave temp (°C)	28.3	30.8	30.4	29.9	29.6	28.5	28.4	28.1	28.4	27.5	28.3
Max temp (°C)	32.0	35.6	35.1	33.8	33.5	31.1	31.1	30.6	30.6	30.1	30.4

Appendix A2: Indoor temperature (°C) for different roofing materials with sloping cement fibre ceiling configuration for east-west & north-south orientations on 6th March 2011.

Hour	Outdoor temp (°C)	Asbestos old		Asbestos new		Asbestos top surface painted		Convectional calicut tile		DSI tile	
		E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S
1	25.7	28.6	27.4	28.3	27.0	27.8	26.5	27.5	27.1	27.3	27.1
2	25	28.3	27.1	27.9	26.7	27.5	26.2	27.2	26.8	27	26.8
3	24.4	27.9	26.7	27.6	26.4	27.2	25.9	26.8	26.5	26.6	26.5
4	24.2	27.6	26.5	27.3	26.1	26.9	25.7	26.6	26.2	26.4	26.3
5	24.1	27.5	26.2	27.2	25.9	26.8	25.5	26.5	26.0	26.3	26.0
6	24	27.3	26.0	27	25.7	26.6	25.3	26.3	25.8	26.1	25.8
7	24.2	28.1	26.9	27.7	26.4	27.1	25.7	26.6	26.0	26.4	26.0
8	24.6	28.3	27.2	27.7	27.0	26.8	26.4	26.3	26.4	26.1	26.3
9	26	29	27.9	28.3	27.7	27.4	27.4	26.9	27.0	26.7	26.9
10	28.4	30.2	28.7	29.4	28.4	28.1	27.8	27.9	27.7	27.7	27.5
11	30.4	31.3	30.1	30.3	29.6	28.8	28.2	28.6	28.5	28.4	28.2
12	31.4	32.1	31.2	31	30.5	29.4	28.8	29.2	29.0	29	28.8
13	31.8	32.6	32.0	31.5	30.0	29.8	29.2	29.6	29.4	29.4	29.1
14	32	32.9	31.9	31.8	30.2	30	29.4	29.8	29.6	29.6	29.3
15	31.9	32.8	31.5	31.7	30.9	30.1	29.3	29.9	29.6	29.7	29.4
16	31.7	32.4	31.6	31.4	30.2	30	29.0	29.8	29.5	29.6	29.3
17	31.3	31.6	31.1	30.9	29.0	29.7	29.3	29.6	29.2	29.4	29.1
18	30.8	31.6	30.1	31.1	29.4	30.3	28.4	30.2	28.7	30	28.6
19	30.2	30.9	28.9	30.4	28.4	29.8	27.8	29.7	28.5	29.5	28.4
20	29.6	30.6	28.9	30.2	28.4	29.6	27.7	29.5	28.2	29.3	28.2
21	28.8	30.2	28.6	29.9	28.2	29.4	27.6	29.2	28.1	29	28.1
22	28	29.9	28.4	29.5	27.9	29.1	27.3	28.9	27.9	28.7	27.8
23	27.2	29.3	28.0	29	27.7	28.5	27.1	28.3	27.6	28.1	27.6
24	26.4	29	27.7	28.6	27.3	28.2	26.8	27.9	27.3	27.7	27.3
Ave temp (°C)	28.0	30.0	28.8	29.4	28.1	28.5	27.4	28.3	27.8	28.1	27.7
Max temp (°C)	32.0	32.9	32.0	31.8	30.9	30.3	29.4	30.2	29.6	30.0	29.4

Appendix A3: Cooling energy demand for different roofing materials (with no ceiling) on 6th March 2011 at south-east orientation

Time (hour)	Cooling energy demand (kWh)				
	New asbestos	Painted asbestos	Old asbestos	Conventional calicut Tile	New calicut tile
1	466	386	529	256	250
2	298	228	355	187	181
3	144	85	196	45	39
4	42	0	87	0	0
5	4	0	45	0	0
6	0	0	0	0	0
7	301	128	420	2	3
8	381	196	513	66	50
9	796	411	1071	281	255
10	1406	835	1772	705	599
11	1934	1233	2408	1103	1001
12	2327	1513	2872	1383	1277
13	2551	1681	3139	1551	1445
14	2615	1754	3201	1624	1518
15	2504	1715	3041	1585	1479
16	2248	1589	2694	1459	1353
17	1854	1377	2175	1247	1141
18	1565	1312	1734	1182	1076
19	1362	1182	1483	1052	946
20	1246	1093	1347	963	857
21	1122	989	1210	859	753
22	1000	882	1077	752	646
23	792	688	865	558	552
24	629	538	698	408	402
Daily total	27586	19814	32932	17268	15823

Appendix A4: Exterior roof surface temperature (°C) for different roofing materials at east-west & north-south orientations on 6th March 2011

Hour	Outdoor temp (°C)	Asbestos old		Asbestos new		Asbestos top surface painted		Convectional calicut tile		New calicut tile	
		E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S	E-W	N-S
1	25.7	22.8	22.7	22.9	22.6	22.7	22.6	22.6	23.9	24.0	24.0
2	25	22.2	22.1	22.2	22.0	22.0	22.0	22.0	23.2	23.3	23.3
3	24.4	21.6	21.5	21.7	21.4	21.5	21.4	21.5	22.7	22.8	22.8
4	24.2	21.3	21.2	21.4	21.2	21.2	21.2	21.2	22.4	22.5	22.5
5	24.1	21.1	21.1	21.2	21.0	21.0	21.0	21.0	22.2	22.3	22.3
6	24	21.0	20.9	21.1	20.8	20.9	20.9	20.9	22.1	22.2	22.2
7	24.2	26.0	25.9	25.5	24.8	25.0	23.3	23.4	23.6	23.5	23.5
8	24.6	32.5	32.2	31.2	29.8	30.2	26.3	26.5	25.5	25.2	25.2
9	26	39.4	39.2	37.5	35.8	35.9	30.2	30.3	28.3	27.7	27.7
10	28.4	45.8	45.7	43.5	41.4	41.4	34.2	34.3	31.5	30.8	30.8
11	30.4	50.8	50.7	48.0	45.8	45.8	37.5	37.6	34.3	33.4	33.5
12	31.4	53.5	53.5	50.6	48.2	48.2	39.5	39.4	35.9	35.0	35.0
13	31.8	54.0	54.0	51.1	48.7	48.8	40.0	40.0	36.5	35.5	35.5
14	32	52.5	52.5	49.8	47.5	47.6	39.4	39.4	36.2	35.3	35.3
15	31.9	49.1	49.0	46.7	44.7	44.8	37.7	37.7	35.2	34.5	34.4
16	31.7	43.9	43.8	42.1	40.4	40.6	35.1	35.1	33.6	33.1	33.0
17	31.3	37.0	36.7	35.9	34.7	34.9	31.5	31.6	31.3	31.1	31.0
18	30.8	27.9	27.8	27.8	27.5	27.5	27.1	27.1	28.5	28.6	28.6
19	30.2	26.7	26.7	26.7	26.5	26.5	26.3	26.3	27.8	27.9	27.9
20	29.6	26.1	26.0	26.1	25.9	25.9	25.8	25.8	27.3	27.4	27.4
21	28.8	25.5	25.4	25.5	25.2	25.3	25.2	25.2	26.6	26.7	26.7
22	28	24.8	24.7	24.8	24.6	24.6	24.5	24.6	25.9	26.0	26.0
23	27.2	24.1	24.0	24.2	23.9	24.0	23.9	23.9	25.2	25.3	25.3
24	26.4	23.4	23.4	23.5	23.2	23.3	23.2	23.2	24.5	24.6	24.6
Ave temp (°C)	28.0	33.0	32.9	32.1	31.1	31.2	28.3	28.3	28.1	27.9	27.8
Max temp (°C)	32.0	54.0	54.0	51.1	48.7	48.8	40.0	40.0	36.5	35.5	35.5

APPENDIX-B

Appendix B1: Comparison of maximum indoor temperature (°C) of a 4-pitched roof building for east-west & north-south orientations on 6th March 2011

S/n	Roofing/ceiling configuration	Maximum indoor temperature (°C)									
		New asbestos		Painted asbestos		Old asbestos		Convectional calicut tile		New calicut tile	
		East-West	North-South	East-West	North-South	East-West	North-South	East-West	North-South	East-West	North-South
1	Roof- no ceiling	33.9	33.9	31.4	31.5	35.5	35.6	30.6	30.6	30.4	30.4
	Difference (°C)		0.0		0.1		0.1		0.0		0.0
	% Difference		0.0		0.3		0.3		0.0		0.0
2	Sloping asbestos	31.8	31.8	30.5	30.5	32.7	32.8	30.4	30.4	30.2	30.2
	Difference (°C)		0.0		0.0		0.1		0.0		0.0
	% Difference		0.0		0.0		0.3		0.0		0.0
3	Suspended asbestos	31.4	31.4	30.5	30.6	32.2	32.2	30.4	30.5	30.3	30.4
	Difference (°C)		0.0		0.1		0.0		0.1		0.1
	% Difference		0.0		0.3		0.0		0.3		0.3
4	Sloping wood	31.8	31.8	30.5	30.6	32.7	32.7	30.4	30.5	30.2	30.3
	Difference (°C)		0.0		0.1		0.0		0.1		0.1
	% Difference		0.0		0.3		0.0		0.3		0.3
5	Suspended wood	31.2	31.3	30.6	30.6	31.9	31.9	30.5	30.5	30.4	30.4
	Difference (°C)		0.1		0.0		0.0		0.0		0.0
	% Difference		0.3		0.0		0.0		0.0		0.0

Appendix B2: Comparison of maximum indoor temperature (°C) of a 2-pitched & a 4-pitched roof building for east-west orientation on 6th March 2011

S/n	Roofing/ceiling configuration	Maximum indoor temperature (°C)									
		New asbestos		Painted asbestos		Old asbestos		Convectional calicut tile		New calicut tile	
		2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch
1	Roof- no ceiling	33.8	33.9	31.1	31.4	35.6	35.5	30.6	30.6	30.1	30.4
	Difference (°C)		0.1		0.3		-0.1		0.0		0.3
	% Difference		0.3		1.0		-0.3		0.0		1.0
2	Sloping asbestos	31.8	31.8	30.3	30.5	32.9	32.7	30.2	30.4	30.0	30.2
	Difference (°C)		0.0		0.2		-0.2		0.2		0.2
	% Difference		0.0		0.7		-0.6		0.7		0.7
3	Suspended asbestos	31.3	31.4	30.5	30.5	31.8	32.2	30.4	30.4	29.3	30.3
	Difference (°C)		0.1		0.0		0.4		0.0		1.0
	% Difference		0.3		0.0		1.3		0.0		3.4
4	Sloping wood	30.9	31.8	30.1	30.5	31.1	32.7	29.8	30.4	29.5	30.2
	Difference (°C)		0.9		0.4		1.6		0.6		0.7
	% Difference		2.9		1.3		5.1		2.0		2.4
5	Suspended wood	31.0	31.2	29.8	30.6	31.9	31.9	29.7	30.5	29.5	30.4
	Difference (°C)		0.2		0.8		0.0		0.8		0.9
	% Difference		0.6		2.7		0.0		2.7		3.1

Appendix B3: Comparison of maximum indoor temperature (°C) of a 2-pitched & a 4-pitched roof building for north-south orientation on 6th March 2011

S/n	Roofing/ceiling configuration	Maximum indoor temperature (°C)									
		New asbestos		Painted asbestos		Old asbestos		Convectional calicut tile		New calicut tile	
		2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch
1	Roof- no ceiling	33.5	33.9	31.1	31.5	35.1	35.6	30.3	30.6	30.3	30.4
	Difference (°C)		0.4		0.4		0.5		0.3		0.1
	% Difference		1.2		1.3		1.4		1.0		0.3
2	Sloping asbestos	32.7	31.8	30.1	30.5	34.3	32.8	31.4	30.4	29.2	30.2
	Difference (°C)		-0.9		0.4		-1.5		-1.0		1.0
	% Difference		-2.8		1.3		-4.4		-3.2		3.4
3	Suspended asbestos	32.2	31.4	30.4	30.6	33.3	32.2	30.4	30.5	30.3	30.4
	Difference (°C)		-0.8		0.2		-1.1		0.1		0.1
	% Difference		-2.5		0.7		-3.3		0.3		0.3
4	Sloping wood	32.7	31.8	30.1	30.6	34.3	32.7	29.5	30.5	29.2	30.3
	Difference (°C)		-0.9		0.5		-1.6		1.0		1.1
	% Difference		-2.8		1.7		-4.7		3.4		3.8
5	Suspended wood	32	31.3	31.8	30.6	33.2	31.9	30.4	30.5	30.4	30.4
	Difference (°C)		-0.7		-1.2		-1.3		0.1		0.0
	% Difference		-2.2		-3.8		-3.9		0.3		0.0

Appendix B4: Comparison of cooling energy use (kWh/day) of a 2-pitched & a 4-pitched roof building for east-west orientation on 6th March 2011

S/n	Roofing/ceiling configuration	Daily total cooling energy use (kWh/day)									
		New asbestos		Painted asbestos		Old asbestos		Convectional calicut tile		New calicut tile	
		2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch
1	Roof- no ceiling	27.6	27.6	19.8	19.7	32.9	33.0	17.3	18.6	17.1	18.5
	Difference (kWh/day)		0.0		-0.1		0.1		1.3		1.4
	% Difference		0.0		-0.4		0.3		7.7		8.1
2	Sloping asbestos	25.1	22.0	19.3	18.0	29.3	24.8	18.4	17.5	18.4	17.5
	Difference (kWh/day)		-3.1		-1.3		-4.5		-0.9		-0.9
	% Difference		-12.5		-6.6		-15.3		-5.0		-4.9
3	Suspended asbestos	22.0	20.0	19.1	16.0	25.1	22.7	16.2	16.0	15.8	16.2
	Difference (kWh/day)		-2.0		-3.1		-2.4		-0.2		0.3
	% Difference		-9.0		-16.2		-9.5		-1.3		2.2
4	Sloping wood	24.9	22.1	19.2	17.9	28.8	24.2	18.3	17.6	18.3	17.5
	Difference (kWh/day)		-2.8		-1.3		-4.6		-0.8		-0.8
	% Difference		-11.3		-6.5		-16.0		-4.2		-4.1
5	Suspended wood	22.6	19.7	17.8	16.3	25.8	22.1	17.2	16.1	17.1	16.0
	Difference (kWh/day)		-2.8		-1.5		-3.7		-1.1		-1.1
	% Difference		-12.6		-8.4		-14.5		-6.4		-6.4

Appendix B5: Comparison of cooling energy use (kWh/day) of a 2-pitched & a 4-pitched roof building for north-south orientation on 6th March 2011

S/n	Roofing/ceiling configuration	Daily total cooling energy use (kWh/day)									
		New asbestos		Painted asbestos		Old asbestos		Convectional calicut tile		New calicut tile	
		2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch	2-Pitch	4-Pitch
1	Roof- no ceiling	27.1	28.1	19.4	20.3	31.7	33.6	17.0	19.0	16.9	19.0
	Difference (kWh/day)		1.0		0.8		1.8		2.0		2.1
	% Difference		3.8		4.2		5.8		11.7		12.5
2	Sloping asbestos	24.7	22.2	18.9	18.0	28.9	25.1	18.1	17.6	18.0	17.5
	Difference (kWh/day)		-2.5		-0.8		-3.8		-0.5		-0.5
	% Difference		-9.9		-4.5		-13.3		-2.7		-3.0
3	Suspended asbestos	21.6	20.3	18.6	16.5	24.9	23.0	15.8	16.2	15.5	16.2
	Difference (kWh/day)		-1.3		-2.1		-1.9		0.4		0.6
	% Difference		-6.0		-11.4		-7.5		2.3		3.9
4	Sloping wood	24.5	22.2	18.7	18.1	28.4	25.0	18.0	17.6	17.9	17.6
	Difference (kWh/day)		-2.3		-0.7		-3.4		-0.4		-0.4
	% Difference		-9.2		-3.6		-11.8		-2.0		-2.0
5	Suspended wood	22.2	19.7	17.4	16.3	25.4	22.1	16.9	16.1	16.8	16.0
	Difference (kWh/day)		-2.4		-1.1		-3.4		-0.8		-0.8
	% Difference		-11.0		-6.4		-13.2		-4.7		-4.6