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Innovative Weathering Course Composites & Secondary Roofing System for Thermal Insulation of Flat Roofs

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Abstract

Thermal insulation of terrace concrete slab is vital for imparting comfort to the inhabitants. This investigation assess the performance of thermal insulation systems such as secondary roofing, cool tile, clay tile, light weight aggregate and aerocon aggregate weathering courses in terms of strength, durability and thermal insulation properties for use in flat terrace slabs. Strength studies conducted includes compressive strength test on weathering course composites and flexural strength of ferrocement panels. Durability tests such as water absorption, chloride penetration and rapid chloride penetration test were conducted on polymer modified mortar which forms component of a weathering course system. Thermal insulation performance of weathering course composites and secondary roofing system was done theoretically and also experimentally in laboratory and field conditions. The tests were conducted as per the Indian / ASTM standards / guidelines of research organizations and the results were compared with unprotected control concrete slab.

Compressive strength test results indicate inferior performance of clay tile weathering course and light weight aggregate weathering course. Ferrocement panels made with crimped wire mesh exhibited improved flexural strength and ductility. Durability studies on polymer modified mortar reveals appreciably improved performance as compared to control cement mortar. Theoretical thermal performance study exhibits 50% reduction in thermal transmittance for all the tested thermal insulation systems. Thermal transmittance value in the range 2.8 – 3.2 W/m^{2}k was observed for thermal insulation systems in the laboratory studies. Field study results indicate a significant reduction in temperature of the order 20^{0}C for tested thermal insulation systems in the hot summer day. The study conducted on hot sunny-cloudy day exhibit reduction in temperature of the order of 12-15^{0}C in the day time and 4-5^{0}C increase in the night time for thermal insulation systems. Based on overall performance, it is concluded that secondary roofing and cool tile weathering course offers appreciably improved performance and recommended for industry application.

Keywords: Thermal insulation; flat RCC roof; weathering course; secondary roofing; durability; thermal transmittance

INTRODUCTION

Thermal insulation of terrace concrete slab is vital for imparting comfort to the inhabitants as compared to other potential elements such as wall, window/door openings etc. Since the upper roof surface is exposed for the longest duration directly to almost intense perpendicular solar heat radiation. The insulation of roof top, result in reduction of accumulation of heat on roof and its transmission in to the rooms below, helps lower the temperatures in the rooms significantly. This also reduces period of use of cooling devices such as coolers and air conditioners, thus saving in energy costs. The over deck insulation methods are more popular and the materials / composite used should exhibit adequate compression resistance, low water absorption, resistance to high ambient temperature and low thermal conductivity which can be measured in terms of thermal transmittance (U values) and thermal resistance (R values).

Research works has been carried out in the recent past on various thermal insulation materials, techniques and strategies. Transient thermal analysis of hollow clay tiled concrete roof for energy conservation and comfort for the typical Indian climatic conditions was studied by Vijay Kumar et al. (1) and found with energy savings of the order of 38 – 63% as compared to conventional weathering course roof. Pablo and Umberto (2) studied the comfort and energy savings with active green roofs by adopting variable insulation strategy. Harry Suehrcke et al. (3) studied the effect of roof solar reflectance on the building heat gain in a hot climate. The significant differences in heat gain from light and dark colored roof surfaces were analyzed and an equation for the average daily downward heat flow of a sunlit roof is derived. Anna Laura and Franco (4) studied the thermal effect of an innovative cool roof on residential buildings in Italy and found to reduces the summer peak indoor overheating of the attic up to 4.7˚C and maximum overcooling reduction up to 1.2˚C in the winter. Chitrarekha (5) conducted studies on thermal performance index for dwelling roofs in the warm humid tropics to find a scientific rating scheme for roof system. Milos Lain and Jan Hensen (6) conducted study on applicability of passive and low energy cooling techniques in buildings of Czech Republic. Influence of presented climate, buildings and systems analysis on potential of passive and low energy cooling technologies was studied. Vangtook and Chirarattananon (7) investigated the application of radiant cooling as a passive cooling option in hot humid climate. Kruger et al. (8) conducted study on Indirect Evaporative Cooling Systems (IECS) characterized by the use of wetted roof or wall surfaces for structural cooling without increasing indoor air humidity; consist of an interesting bio climatic strategy in Brazil. Madhumathi et al. (9) carried out research work to find the suitable roof constructions for naturally ventilated residential buildings in warm humid climates of India. Lee et al. (10) investigated the applicability of ferrocement as an alternative material for secondary roofing slabs. The performance of ferrocement slabs was compared with cellular concrete slabs and commercially available hollow blocks. Masood et al. (11) studied the performance of ferrocement panels under normal, moderate and hostile environment created by using potable and saline water for mixing and curing with fly ash as partial replacement and varying numbers of woven and hexagonal mesh layers.

From the research studies, it is recognized that the green roofing has become an emerging concept in recent days for energy conservation in buildings. The increase in heat in the country, due to unprecedented climatic changes caused by global warming necessitates research on study of solar reflectance of different construction materials for it use in weathering course or secondary roofing materials to offer improved thermal insulation. Considerable research has also been carried out on light weight aggregates, cool roof coatings, cool tiles, etc. and found with advantage of thermal insulation but its moderate or inferior mechanical properties causes early distress and leads to severe durability related issues. Secondary roofing concept using ferrocement panel was also employed to offer better thermal insulation to terrace slabs. This resulted in series of research work in developing ferrocement panel to offer excellent durability and strength properties. The current knowledge on weathering course system adopted by the construction industries lack strength / durability / thermal insulation performance. This necessitates the development of innovative thermal insulation systems / weathering courses using commercially available materials such as brick bat coba, light weight aggregates, broken aerocon block, etc. Polymers need to be introduced in the weathering composite to improve durability and trouble free service life to weathering course and building components such as slab, wall, etc.

Materials and Mix Proportion for Cement Mortar / Concrete

The materials used in the study includes; cement, sand, course aggregate and water for preparing concrete or cement mortar; 20 mm aerocon aggregate, hematite light weight aggregate, cool tiles and clay tiles for making thermal insulation composites; and polymers such as acrylic polymer and styrene acrylate co-polymer for enhancing waterproofing to weathering course composites. Galvanized wire mesh and crimped square wire mesh was used to fabricate ferrocement panels. Potable water was used for making cement concrete or mortar.

Commercially available Portland pozzolana cement confirming to IS 1489 (12) was used. River sand sieved through 2.36mm sieve was used as fine aggregate. Commercially available blue granite metal passing through 20mm sieve was used as course aggregate. Table 1 shows the properties of fine aggregate and coarse aggregate used in the study (13). Physical properties of commercially available light weight aggregate such as hematite and aerocon aggregates were found by conducting test as per IS:2386 (13). Table 2 shows the properties hematite and 20mm aerocon block aggregate. Commercially available cool tiles and pressed clay tiles of size 12’’ x 12’’ was used. Table 3 shows the properties of cool tiles and pressed clay tiles. Commercially available polymers such as styrene acrylate co-polymer and acrylic polymer was used in the study. Acrylic polymer was used for application of water proofing coating in combination with cement as filler material. Styrene acrylate co-polymer was employed to modify mortar at 2%, 5% by weight of cement. Table 4 shows the basic properties of the polymers used in this study.

Galvanized wire mesh of 1mm diameter, 12.5mm grid spacing and crimped wire mesh of 2mm diameter with 10mm square opening was used in the study. Figure 1 shows the view of galvanized and crimped wire mesh. Cement mortar mix of 1:2 with optimized water/cement ratio obtained through conduct of flow table test as per ASTM C 1437 (14) was used. Manual mixing was adopted for the preparation of mortar. The water cement ratio for control mortar is 0.5% and the corresponding values for 1% and 2% polymer modification is 0.49% and 0.48% respectively for the similar workability. Mix design for M20 concrete was carried out as per IS10262:2009 - Concrete mix proportion – Guidelines (15). The obtained Mix proportion are 1 (Cement) : 1.73 (Fine Aggregate) : 3.38 (Coarse Aggregate) with w/c ratio : 0.5.

Table 1: Properties of fine aggregate and coarse aggregate

Sl. No.	Property	Obtained value	
		Fine Aggregate	**Coarse Aggregate**
1	Specific gravity	2.332	2.79
2	Bulk density	1.536 Kg/l	1.3 Kg/ltr
3	% water absorption	5.756	2.25
4	Fineness modulus	2.89	4.61
5	Grading Zone	I as per IS:383	-

Table 2: Physical properties of hematite and aerocon aggregate (20mm)

Sl. No.	Property	Obtained values	
		Hematite	**Aerocon (20mm)**
1	Specific gravity	1.311	1.81
2	Bulk density	0.542 Kg/l	551 Kg/m^3
3	Grading Zone	II	-
4	Thermal conductivity	-	0.12 W/m-k*

***Obtained from the manufacturer data.**

Table 3: Properties of cool tiles and pressed clay tiles

Sl.No.	Property	Obtained value *	
		Cool Tiles	**Pressed Clay Tiles**
1	Appearance	White	Reddish Brown
2	Compressive strength	2.13 MPa	1.56 MPa
3	Flexural strength	1.66 MPa	-
4	Thermal emissivity	0.935	0.75
5	Solar reflectance index	99%	36%
6	Water Absorption	-	13%

***Obtained from the manufacturer data.**

Table 4: Physical properties of polymers used in the study

Property	Obtained value	
	Acrylic polymer	**Styrene acrylate co-polymer**
Density (Kg/ltr)	1.163	1.040
pH	6.20	6.78
Colour	Milky White	Milky White
Solid content (%)	26	25

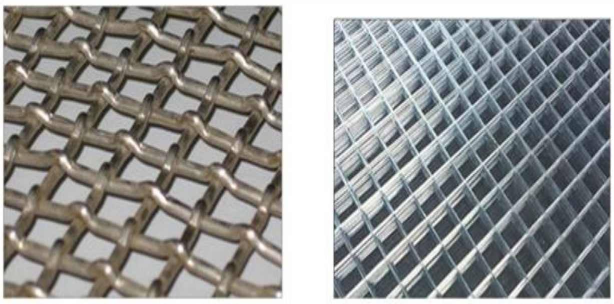


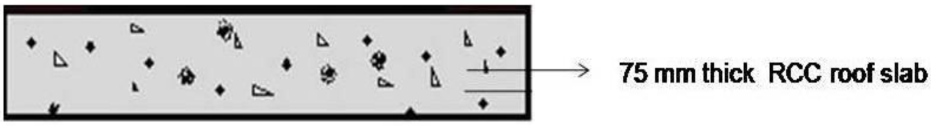
Figure 1: View of crimped and galvanized wire mesh

Thermal Insulation Systems

Different weathering course composites were formulated using the materials such as cement, sand, hematite light weight aggregate, aerocon light weight aggregate, polymers, clay tiles and water in addition to secondary roofing system using ferrocement panels. The performance of thermal insulation systems provided over a control concrete slab is assessed in terms of strength, durability and thermal insulation properties and the results were compared with unprotected control concrete slab. Table 5 shows the details of different weathering course systems. Concrete of M20 grade was used to cast the control slab of 75mm thickness. Figure 2 shows the schematic and cross sectional view of concrete slab (System I).

Table 5: Details of different weathering course systems

System	Designation	Insulation material used
I	Control	No protective material
II	Secondary roofing	Air gap encompass by Ferro cement panels
III	Cool tile weathering course	Cool tiles
IV	Clay tiles weathering course	Brick bat coba topped with Clay tiles
V	Light weight aggregate mortar weathering course	Light weight aggregate mortar
VI	Aerocon aggregate concrete weathering course	Aerocon aggregate concrete

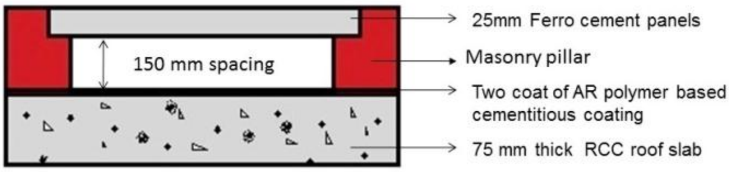


a. Schematic of control slab

b. Cross-sectional view of control slab

Figure 2: Unprotected control concrete slab (System I)

System-II refers to terrace slab applied with two coats of acrylic based polymer cementitious coating and covered with ferrocement panels by providing 15cm air gap. Figure 3 shows the schematic and cross sectional view of secondary roofing system.

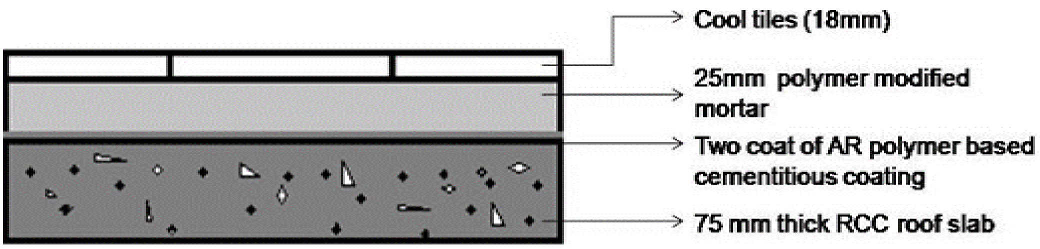


a) Schematic of secondary roofing

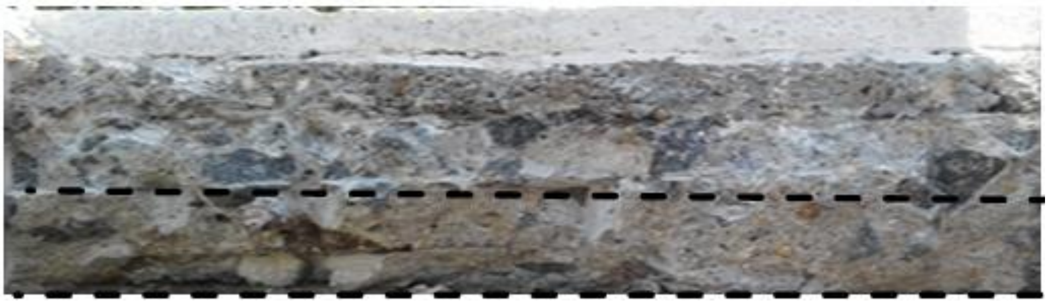
b) Cross sectional view

Figure 3: Schematic and cross sectional view of Secondary roofing (System-II)

Terrace slab applied with two coats of acrylic polymer cementitious coating and laid with cool tiles over 25mm thick styrene acrylate co-polymer modified mortar forms system-III. Figure 4 shows the schematic and cross sectional view of cool tile weathering course.



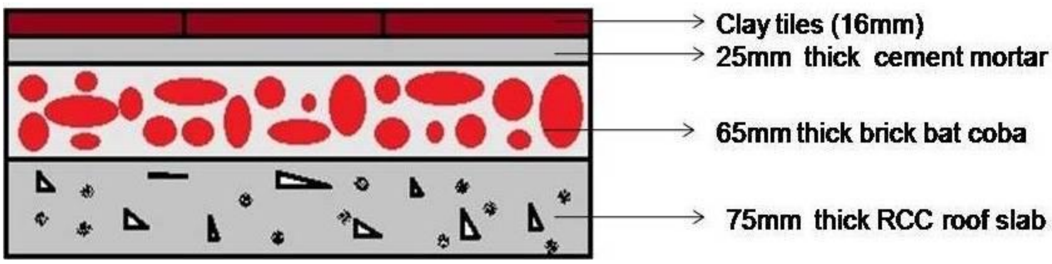
a) Schematic



b) Cross-sectional view

Figure 4: Schematic and cross sectional view of cool tiles weathering course (System - III)

System-IV comprises of terrace slab laid with 65mm thick brickbat coba followed by 25mm thick cement mortar and clay tiles laying. Figure 5 shows the schematic and cross sectional view of clay tile weathering course.

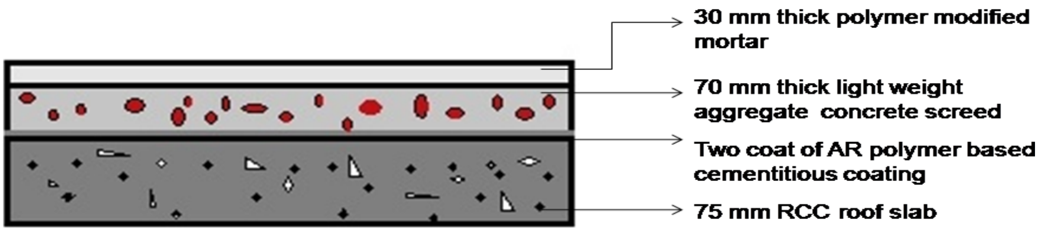


a) Schematic

b) Cross-sectional view

Figure 5: Schematic and cross sectional view of clay tiles weathering course (System - IV)

Terrace slab applied with two coats of acrylic polymer cementitious coating, laid with 70mm' thick light weight aggregate mortar and finished with 30mm thick styrene acrylate co-polymer modified mortar forms System-V. Figure 6 shows the schematic and cross-sectional view of light weight aggregate weathering course system.



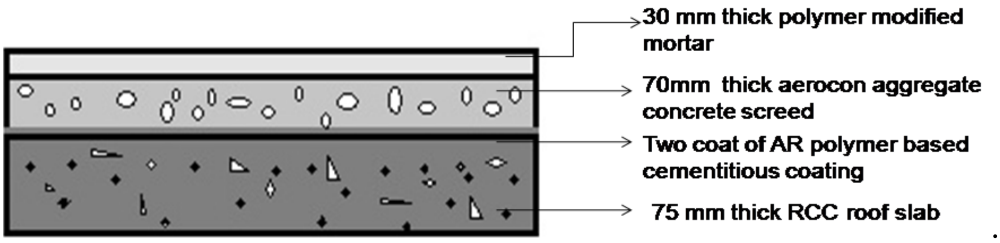
a) Schematic

b)

b) Cross -sectional view

Figure 6: Schematic and cross sectional view of light weight aggregate concrete weathering course (System - V)

Terrace slab applied with two coats of acrylic polymer cementitious coating, laid with 20mm size aerocon aggregate concrete of 70 mm thick and finished with 30mm thick styrene co-polymer modified mortar refers to system-VI. Figure 7 shows the schematic and cross-sectional view of aerocon agggregate weathering course system.



a) Schematic

b) Cross-sectional view

Figure 7: Schematic and cross sectional view of aerocon aggregate concrete weathering course (System - VI)

Experimental Investigation

Performance of thermal insulation systems were studied under three parameters viz. strength properties, durability properties and thermal insulation performance. Strength related study includes finding the compressive strength of control concrete which forms the roof slab and polymer modified mortar which forms the waterproofing screed for most of the thermal insulation systems; compressive strength of weathering course composites and flexural strength of ferrocement panels in case of secondary roofing. Durability properties of polymer modified mortar was studied by conducting tests such as water absorption test, chloride ion penetration test and rapid chloride penetration test (RCPT). Thermal insulation performance was studied by conducting laboratory and field studies and comparing the results with theoretical studies.

Compressive Strength Test

Compressive strength of control concrete, polymer modified mortar and weathering course composites were carried out in a 100kN capacity Compression Testing Machine by following the procedures outlined in IS 516 (16). The size of specimen for control concrete is 150mm cube and tested for compressive strength at the age of 7,14 and 28 days. For weathering course composite, size of specimen is 30 cm x 30 cm in which proposed weathering course were laid over base control reinforced concrete slab and subjected to compressive strength after 28 days of curing. The compressive strength of cement mortar was studied by casting 100mm cubes specimens and tested at the age of 7 and 28days. Polymer modification was done at 1%,2% and 5% by weight of cement and the results are compared with control mortar. Totally 39 specimens including 9 control concrete cube, 12 weathering course composite panel and 18 cement mortar cube were subjected to compressive strength. In case of weathering course systems, failure refers to load corresponding to crushing of weathering course layer / base concrete whichever is earlier.

Flexural Strength Test on Ferrocement Panels

The cement mortar mix of 1:2 (cement : sand) was used to cast ferrocement panels of size 900mmx300mmx25mm. Wire mesh employed in the study includes galvanized wire mesh and crimped steel wire mesh and are embedded centrally in the cement mortar. In each category three panels were cast, cured for 28 days and subjected to flexural strength test as per IS 516 (16) under four-point loading method. The performance indicators such as crack pattern, crack region, ultimate load and load deflection behavior was observed during testing. Figure 8 shows the view of flexural strength test in progress.

Figure 8: Flexural strength test in progress

Chloride ion penetration test

This test is done to study the resistance of cement mortar exposed to aggressive chloride environment under normal accelerated conditions. 100mm mortar cubes with and without polymer addition were cast, water cured for 28 days and subjected to chloride ion penetration test. Totally 12 specimens were tested. At the end of curing period, the mortar cubes were applied with polymer cementitious water proofing coating on the four vertical sides leaving the top and bottom surfaces free and immersed in 3% NaCl solution for 7 days. Then the specimens were split open into two vertical halves and sprayed with a solution containing 0.1% sodium fluorescein and 0.1N silver nitrate. The depth up to which the colour changes to white indicates the chloride ion penetration depth. The remaining greenish area represents the unaffected area. The chloride ion penetration was observed in eight different locations along the periphery of the specimen and the average value is represented as chloride ion penetration depth.

Water absorption test

Three specimens each in control and polymer modified mortar were cast to study the influence of polymer addition on water absorption characteristics of cement mortar. Totally 12 specimens of 100mm mortar cube were subjected to water absorption test. Mortar cubes of size 100 mm were cast, moist cured for 28 days and subsequently dried in atmosphere for 24 h. The specimens were kept in an oven for 24 h at 100ºC, cooled to room temperature and weighed (w_1). Then the specimens were immersed in water for a desired period, surface dried and weighted (w_2) The water absorption characteristic was monitored at different time intervals for a period of 24 h. The change in weight expressed as the percentage of initial dry mass is the water absorption.

$$\text{Water absorption (\%)} = ((W_2 - W_{1)} / W_1) \times 100$$

Rapid chloride ion penetration test (RCPT)

This test determines the ability of the cement mortar to resist the penetration of the chloride under highly accelerated condition and conducted as per ASTM C1202 (17). Totally 12 mortar cylinders of size 100mm x 200mm were cast with or without polymer modification and 50 mm thick circular slices was cut with a help of concrete angle cutter and used as test specimen. Three tests were conducted in each category. Figure 9 shows the RCPT test in progress. From the observed current values, the total charge passed (coulombs) at the end of 6 hours was calculated. Based on the "total charge passed" values, the chloride permeability behaviour of control and polymer modified mortar is compared as per ASTM C1202.

Theoretical Thermal Performance study

Theoretical study was conducted to estimate the thermal transmittance of weathering course composites and secondary roofing system which is calculated using thermal conductivity value of individual materials available in SP 41-1987 (18) and composite value estimated using Fourier's law. Attempt was made to correlate the theoretical study values with field study data. Table 6 shows the thermal properties of building / insulating materials used in the study.

Figure 9: Rapid chloride penetration test in progress

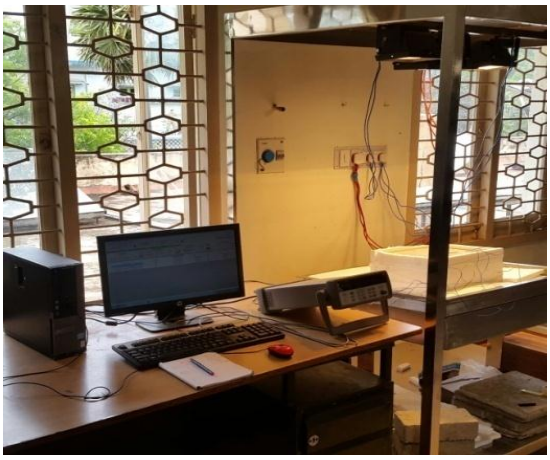
Laboratory Investigation of Thermal Performance

The test for determining the thermal insulation behavior of different weathering course system including control roof was performed in the Solar Laboratory, Institute for Energy Studies, College of Engineering, Anna University, Guindy.

Table 6 : Thermal properties of building and insulating materials

Materials	Density (Kg/m^3)	Thermal Conductivity (W/mK)	Specific heat (J/Kg. K)
Reinforced cement concrete	2288	1.58	880
Cement mortar	1648	0.719	920
Brick bat coba	1892	0.798	880
Light weight aggregate concrete	1762	0.721	840
Aerocon aggregate concrete	1320	0.285	880
Cool Tile	1950	0.500	837
Clay Tile	1900	0.840	800

The specimens were covered with an insulation material (thermocole) on the four vertical sides leaving the top and bottom to ensure one dimensional heat flow and placed in the test setup. Halogen lamps of known power was used as heat source and placed above the specimen at specific height. A lux meter was used to monitor the intensity of heat falling on top of the specimen. Thermocouples were placed on the top and bottom surface of specimen to capture the temperature development. The signals from the thermocouple were fed to a data logger which is interfaced with the computer. The test was terminated after the temperatures at the top and bottom surface of the specimen became uniform for an appreciable time. This indicates uniform and complete heating of top surface which after conduction and convection offers a uniform temperature rise in the bottom surface of specimen. The difference in top and bottom temperature indicates the thermal insulation performance of developed weathering course composite. Figure 10 shows the laboratory thermal performance test in progress.



(a)Test set up

(b) Measurement of local flux density using lux meter

Figure 10: Laboratory thermal performance test in progress

Field Investigation of Thermal Performance

In order to determine the performance of different weathering course systems, six model buildings were constructed in the Construction Materials and Technology Laboratory, B.S. Abdur Rahman University. Size of the model house is 1.5 m (L) x 0.9 m (B) with front opening to facilitate inside temperature measurement. All the other sides are fully covered with masonry wall. The model building is constructed in N-E orientation with ample open space surrounded it. Figure 11 shows the view of model buildings laid with different weathering course system on roof slab. For eliminating the effect of boundary change on the temperature measurement, uniformly spaced measurement points were fixed over the roof slab such that there is no discontinuity or joint are present (19). Figure 12 shows the schematic plan view of temperature measurement locations. An infrared thermometer was used to measure the surface temperature and the temperature on the top surface of weathering course and bottom surface of terrace RCC slab was monitored at regular intervals. Whereas in case of secondary roofing, the temperature at top surface of ferrocement panel and bottom surface of terrace RCC slab was noted during the test period.

Figure 11: View of model buildings with different weathering course system

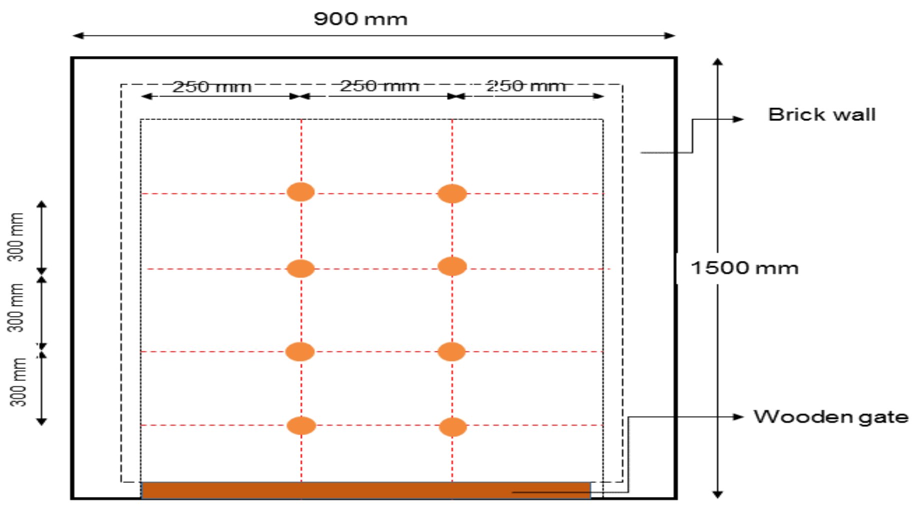


Figure 12: Schematic plan view of temperature measurement locations

RESULTS AND DISCUSSION

Figure 13 shows the comparison of compressive strength of control concrete used for terrace slab at different ages. It can be seen that strength attained by control concrete at 7 days is 16.02 MPa which is 60.2% of the 28 days target mean strength of 26.6 MPa. Whereas, at the age of 14 days, strength attained is 73.30%. 28 days strength test results revealed a similar strength value as compared to target mean strength of concrete estimated theoretically. It can be inferred that the proposed mix design ratio is adequate to offer M20 grade concrete.

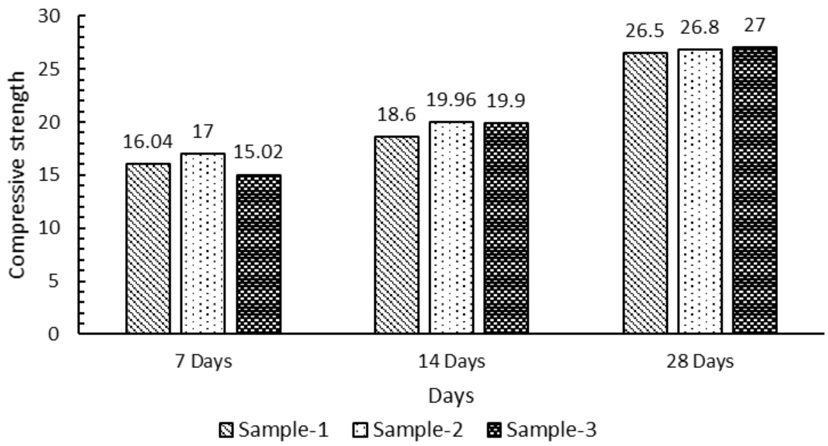


Figure 13: Comparison of compressive strength of control concrete at different ages

Table 7 shows the observation on compressive strength of control concrete slab and different weathering course composite specimens used in the study. It can be noted that density of control concrete is 2453 Kg/m^3 with average compressive strength of 26.60 MPa. Cool tile weathering course composite offered an adequate compression strength of 25.34 MPa which is significantly higher as compared to other weathering course composites tested and is comparable with control concrete slab. The density of cool tile composite is 2278 Kg/m^3 which is marginally lesser than the value observed for control concrete slab. Clay tile and light weight aggregate concrete weathering course offered marginally reduced density values as compared to control slab and the compressive strength development is in the range of 1.55-1.70 MPa. Aerocon aggregate concrete weathering course offer similar density as compared to control concrete but with significantly reduced average compressive strength of 15.98 MPa.

Compressive strength of different weathering composite was arrived based on the resistance of topping layer of composite and not on the complete crushing failure of different layer in the composite including base RCC slab. This test was carried out to understand the compressive strength of different weathering composites when exposed to real time application areas. It can be concluded that cool tile weathering course composite offered excellent compressive strength value as compared to other weathering composites. This may be due to improved resistance against compression offered by cool tiles in the composite. The better performance of aerocon aggregate concrete composite may be due to usage of good quality crushed aerocon block, sizing of broken aggregate and good bond developed at the interface between rough angular surface of aggregate and cement mortar used in the study. Test results of clay tile and light weight aggregate weathering course suggest that care is needed in terms of usage and maintenance of terrace slab laid with these systems.

Table 7: Observation on compressive strength of control slab and weathering course composites

Sl. No.	Type of thermal insulation system	Weight (Kg)	Size of specimen L x B x T (mm)	Density (Kg/m^3)	Compressive strength (MPa)
1	Control Slab (System - I)	11.04	300 x 300x 75	2453	26.60
2	Cool Tile (System -III)	18.45	300 x 300 x 118	2278	25.34
3	Clay tile (System - IV)	22.02	300 x 300 x 181	2128	1.55
4	Light weight aggregate concrete (System - V)	20.98	300 x 300 x 175	2119	1.70
5	Aerocon aggregate concrete (System - VI)	24.12	300 x 300 x 175	2436	15.98

Figure 14 shows the comparison of compressive strength of control and polymer modified mortar. It can be inferred that polymer modification at 1% marginally reduces the compressive strength of cement mortar. Whereas addition of polymer at 2%, 5% appreciably increases the compressive strength of cement mortar of the order of 15%, 31% respectively as compared to control cement mortar. Table 8 shows the observation of flexural strength test on ferrocement panels. It can be noted that ferrocement panel with centrally embedded galvanized mesh offered a ultimate load of 6.27 kN with a maximum central deflection of 12 mm. Whereas ferrocement panel with crimped wire mesh exhibited maximum failure load of 9.88 kN which is 58% more than the value observed for galvanized wire mesh. There is a two-fold increase in deflection at ultimate load was also observed for ferrocement panels with crimped wire mesh as compared to galvanized wire mesh. Irrespective of the type of wire mesh failure region was observed in the middle 1/3rd span of the ferrocement panel. But galvanized mesh ferrocement panel was observed with brittle failure with the formation of single major crack. Whereas crimped wire mesh ferrocement panel exhibited brittle failure with multiple cracks formation along the span and major failure crack in the middle 1/3rd span. Figure 15 shows the view of crack pattern on ferrocement panels after flexure test. It can be concluded that energy absorption capacity and ductility of crimped wire mesh ferrocement panel is significantly higher as compared to galvanized wire mesh panels since it exhibits maximum failure load and deflection.

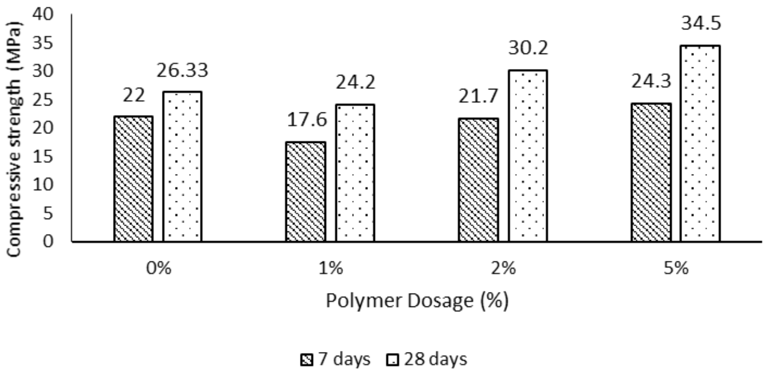


Figure 14: Comparison of compressive strength of control and polymer modified mortar

Table 8: Observation of flexural strength test on ferrocement panels

Sl. No.	Description	Failure region	Ultimate load (kN)	Maximum deflection (mm)	Flexural Strength (N/mm^2)
1	Galvanized wire mesh ferrocement panel	Middle one-third span	6.27	12	32.70
2	Crimped wire mesh ferrocement panel	Middle one-third span	9.88	24	51.45

Figure 16 shows the time versus water absorption behavior of control and polymer modified mortar. It can be seen that control mortar exhibited enhanced water absorption as compared to styrene acrylate co-polymer modified mortar specimens irrespective of dosage levels. The water absorption observed at the end of 24 hours period is 6.2%. There is a marginally reduced water absorption characteristic for polymer modification at 1% as compared to control mortar with 24 hours water absorption at 5.4%. Whereas polymer modification at 2%, 5% appreciably reduced the water absorption behaviour of cement mortar during the entire test period as compared to control mortar. The 24 hours water absorption is estimated as 4.5%, 4.2% for polymer modification at 2%, 5% respectively. It can be concluded that addition of polymer at 2%-5% reduces the 24 hours water absorption of the order of 32% as compared to control mortar.

Figure 17 shows the time versus current behavior of control mortar and styrene acrylate co-polymer modified mortar specimens in RCPT test. It can be seen that control mortar offered higher current development initially as compared to polymer modified mortar. Although initial current development for 1% polymer modified mortar is appreciably less, there is a similar current development as that of control mortar at the end of test period. 5% polymer modification offered significantly reduced current values as compared to control and polymer modification at 1%,2% by weight of cement.

(a)Galvanized wire mesh ferrocement panel

(b) Crimped wire mesh ferrocement panel

Figure 15 : View of crack pattern on ferrocement panels after flexure Test

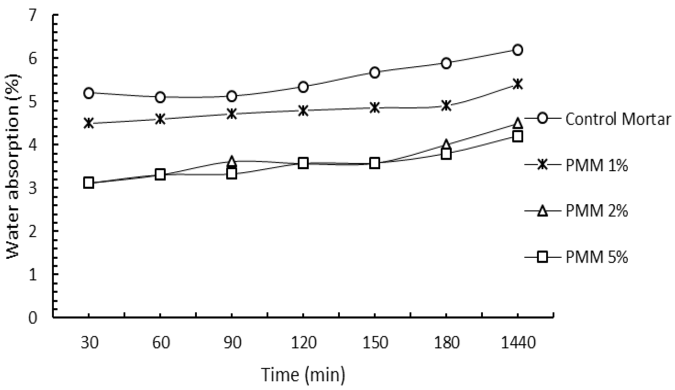


Figure 16 : Time Vs water absorption behaviour of polymer modified mortar

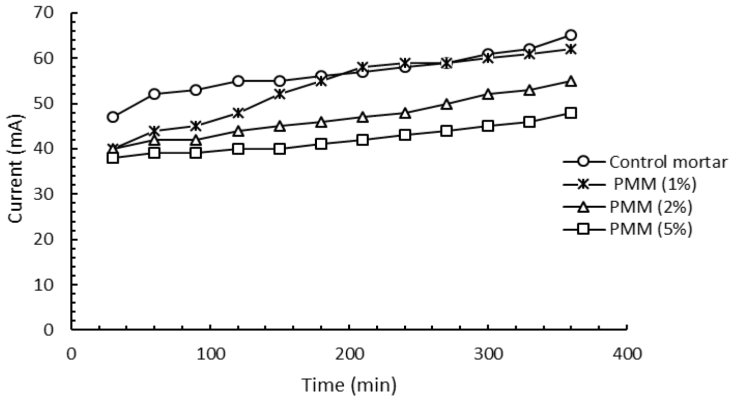


Figure 17: Time vs. current behavior of control mortar and polymer modified mortar specimens in RCPT test

Figure 18 shows the comparison of charge passed in control mortar and polymer modified mortar specimen in RCPT test. It can be seen that control mortar exhibited 1123 coulombs as total charge passed at the end of 6 hour test period. This is marginally higher than the value obtained for 1% polymer modified mortar and appreciably higher than values obtained for 2%,5% polymer modified mortar. According to ASTM criteria control mortar and 1% polymer modified specimens exhibit low chloride permeability, since charge passed values are in the range 1000-2000 coulombs. Whereas 2% and 5% polymer modified mortar offered low chloride permeability since observed total charge values are less than 1000 coulombs.

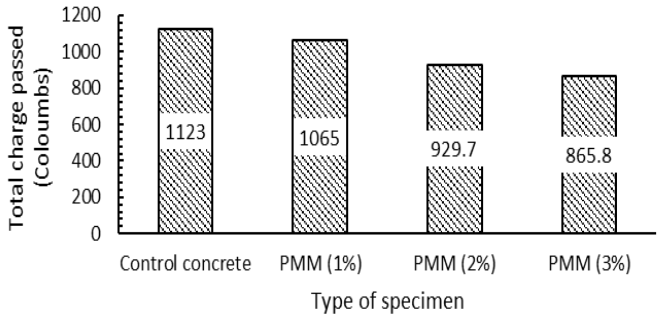


Figure 18: Comparison of charge passed in control and polymer modified mortar specimens

Figure 19 shows the chloride ion penetration at different measurement location for control and styrene acrylate co-polymer modified mortar. It can be seen that control mortar offered higher chloride ion penetration as compared to polymer modified mortar specimen irrespective of measured locations. Polymer modification at 2%

provided improved resistance against chloride penetration as compared to 5% and 1% polymer modification in mortar. Since appreciably less chloride ion penetration depth was noticed in all the measurement locations. Figure 20 shows the comparison of average chloride ion penetration depth of control and polymer modified mortar specimens. Control mortar offered chloride penetration up to 12.68 mm which is significantly high as compared to polymer modified mortar irrespective of dosage level of addition. The reduction in chloride ion penetration depth for 1%,2% and 5% polymer modification was found of the order of 28.50%, 39.74% and 56.62% respectively as compared to control mortar.

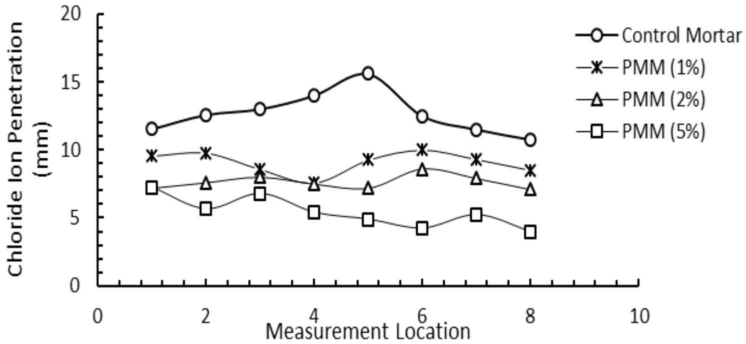


Figure 19: Chloride ion penetration at different measurement locations for control and polymer modified mortar specimens

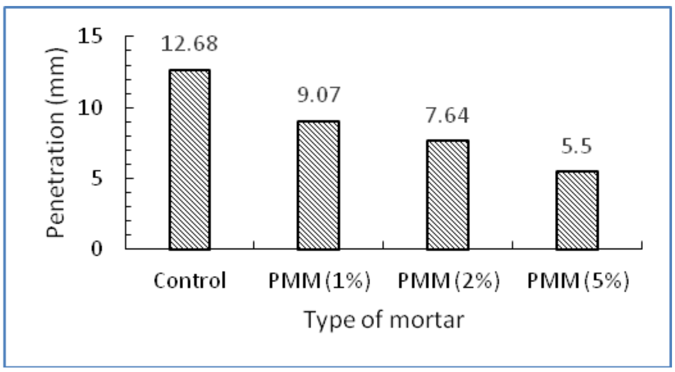


Figure 20: Comparison of average chloride ion penetration depth of control and polymer modified mortar specimens

Figure 21 shows the comparison of theoretical thermal transmittance of different weathering course systems and secondary roofing. It can be seen that thermal transmittance of secondary roofing and aerocon aggregate weathering course is in line with allowable maximum thermal transmittance value of 2.33 W/m^2K as per SP 41 for both hot dry and humid & warm humid conditions. There is a marginal increase from allowable thermal transmittance value of the order 11-20% for other weathering course systems studied. Whereas 2.1 fold increase in thermal transmittance value for control concrete slab as compared to allowable thermal transmittance value. It can be concluded that proposed thermal insulation systems possess necessary thermal transmittance control ability and satisfy the requirements as per SP 41:1987.

Table 9 shows the observation on laboratory thermal performance test. It shows the details of change in temperature (from top to bottom surface), temperature gradient (dT/dx), thermal conductivity (W/mK) (considered from SP 41), total thermal resistance (m^2K/W), thermal transmittance (W/m^2K) and thermal time constant (hr).

Table 9: Observation on laboratory thermal performance test

Type of system	Temperature difference (dT)	Temperature gradient (dT/dx)	Thermal conductivity (W/mK)	Total Thermal Resistance (m^2K/W)	Thermal transmittance (W/m^2K)	Thermal Time Constant (hours)
I	2	26.6	3.3	0.179	5.1	3.1
II	15	60	1.466	0.327	2.9	4.5
III	14	118.64	0.741	0.316	3.2	6.8
IV	15	82.87	1.061	0.327	3	11.2
V	16	91.42	0.962	0.339	2.8	9.6
VI	15	85.71	1.026	0.327	3.04	10

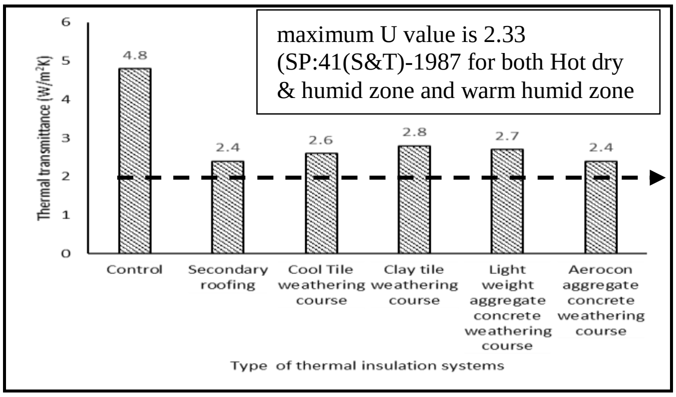


Figure 21 : Comparison of thermal transmittance of weathering course systems and secondary roofing

It can be observed that control concrete slab provides only 2^0C reduction in temperature from top to bottom surface, where as thermal insulation systems offers 14 - 16^0C reduction irrespective of type. The thermal transmittance value of all the tested weathering course composites and secondary roofing system are in the range of 2.8-3.2 W/m^2K with light weight aggregate weathering course offers minimum value and cool tile weathering course offering maximum values. Whereas control concrete slab exhibit a thermal transmittance value of 5.1 W/m^2K which is significantly higher than the value obtained for tested thermal insulation systems. It can be found that irrespective of type of weathering course and secondary roofing system, the observed thermal resistance values are higher than the allowable thermal transmittance value of 2.33 W/m^2K estimated as per SP 41. Thermal time constant value reveals that control RCC roof slab offers only 3.1 hr whereas secondary roofing system and cool tile weathering course offers 4.5 hr,6.8 hr respectively.

Higher thermal time constant value in the range of 9.6-11.2 hours were observed for light weight aggregate weathering course, aerocon aggregate weathering course and clay tile weathering course systems. As per codal provisions of SP 41, minimum thermal time constant for the roof slab provided with any heat insulation material is 20 hours. All the tested weathering course composites and secondary roofing systems offered with thermal time constant of less than 20 hours which may be due to variables such as specific heat capacity, surface co-efficient of outer roof surface, etc. involved in estimation of thermal time constant and also due to test constraints.

Figures 22 and 23 shows the thermal performance behaviour of weathering course composites and secondary roofing during peak sunny hours of the hot sunny day of May, 2015. The behaviour of thermal insulation systems were compared with control concrete slab to understand the thermal insulation property. Figure 22 shows the time versus external surface temperature behavior of control RCC slab and various thermal insulation systems employed in the study. It can be seen that cool tile weathering course system offered significantly reduced top surface temperature during the entire test period which may be due to highly reflectance nature of the cool tile as compared to other systems. Secondary roofing system offered marginal reduction in top surface temperature as compared to control RCC slab and other weathering course systems except cool tile weathering course system.

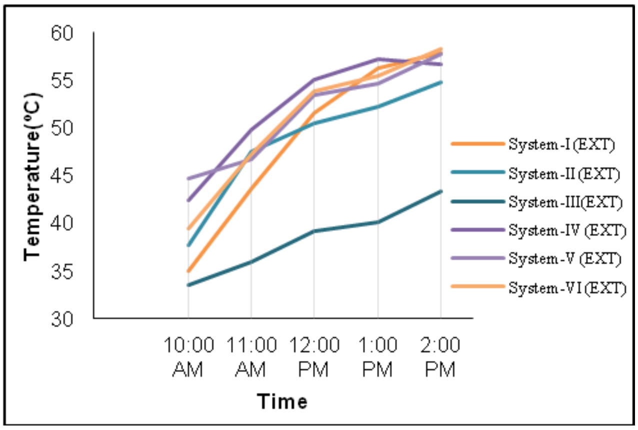


Figure 22 : Time vs. external surface temperature behaviour of control concrete slab and various thermal insulation systems

Figure 23 shows the time versus internal surface temperature behavior of control RCC slab and different thermal insulation systems. It can inferred that all the weathering course composites and secondary roofing system exhibits enhanced reduction in temperature as compared to external and internal temperature development in the control RCC slab. The reduction in internal temperature is about 20^0C as compared to top surface temperature of control RCC slab for all the thermal insulation systems irrespective of the type and exhibits the improved performance against heat transmittance. Table 10 shows the observation on field thermal study conducted on model buildings during hot sunny day of May 2015. It can be observed that maximum top surface temperature of control RCC slab is 57.90^0C and the maximum reduction in the bottom surface of slab is 6.2^0C during the test period. The maximum reduction in temperature considering top and bottom surface was observed at 12.00 noon for all the thermal insulation systems irrespective of type. Secondary roofing system offered significant reduction in inner surface temperature to the level of 25^0C as compared to control RCC slab. Whereas other weathering composites provided temperature reduction in the range of 20 – 21^0C as compared to control RCC slab. It can be concluded that all the proposed weathering course composites and secondary roofing system offers significant reduction in indoor temperatures and proves the efficacy of the thermal insulation offered by these systems.

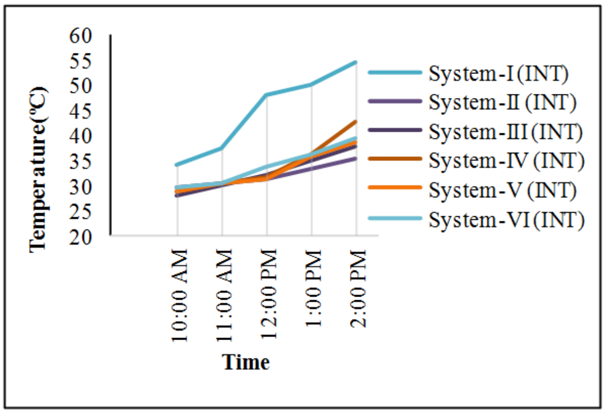


Figure 23 : Time vs. internal surface temperature behaviour of control concrete slab and different thermal insulation systems

Figures 24 and 25 shows the time versus temperature behavior of control concrete slab and thermal insulation systems in a sunny and cloudy day climate with humid night for 24 hours from 9 a.m. on 10th July 2015 to 9.00 a.m. on 11th July 2015. Figure 24 shows the time versus external surface temperature behavior of control concrete slab and various thermal insulation systems. It can be visualized that control slab and other thermal insulation systems, except cool tiles weathering course, exhibited similar behavior during the tested 24 hours. Cool tiles weathering course system offered 5 -12^{0}C reduction as compared to control and other tested systems during 9 a.m. - 5.00 p.m. Afterwards there is similar temperature behavior as compared to control concrete slab. The appreciable temperature reduction during sunny day time is due to effective reflection of heat waves by the ceramic particles in the cool tiles; and white colour of the tiles.

Table 10 : Observation on field thermal study conducted on model buildings during hot sunny day of May 2015

System	Maximum top surface temperature		Maximum reduction in top surface temperature		Max reduction in top surface temperature w.r.t control RCC slab (˚C)
	˚C	Time	˚C	Time	
I	57.9	2:00 pm	6.2	12:00 noon	6.2
II	52.0	2:00 pm	19.0	12:00 noon	25.0
III	43.3	2:00 pm	7.1	12:00 noon	21.0
IV	56.7	2:00 pm	23.6	12:00 noon	20.3
V	57.7	2:00 pm	22.2	12:00 noon	20.6
VI	58.3	2:00 pm	20.3	12:00 noon	20.1

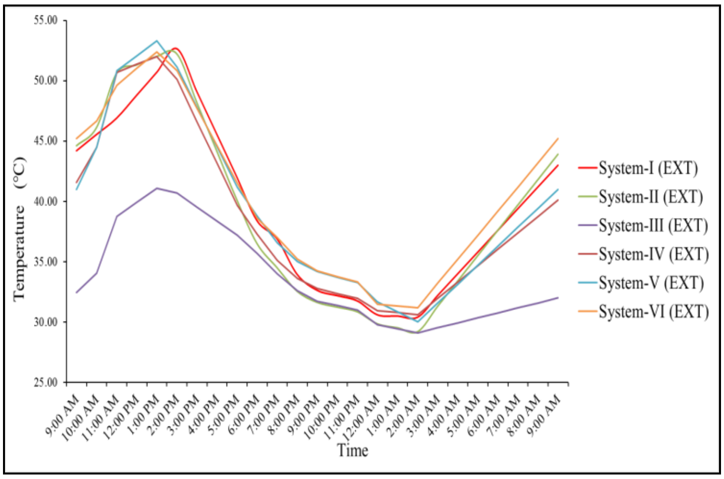


Figure 24 : Time Vs external surface temperature behavior of control concrete slab (System I) and various thermal insulation systems

Figure 25 shows the time versus internal surface temperature behavior of control concrete slab and various thermal insulation systems. It can be seen that in the core sunny time between 10 a.m. - 5.00 p.m. all the tested thermal insulation systems exhibited improved heat reduction in the range of 5-12^{0}C as compared to control concrete slab. Cool tile weathering course offered improved heat reduction followed by secondary roofing system as compared to other weathering course composites. The observation on post evening session and night reveals that cool tile weathering course behaves in similar line to the control concrete slab where as other weathering course composites and secondary roofing system offers 3-5^{0}C increase in temperature as compared to control concrete slab. This property may be advantageously used to improve the temperature conditions inside the building in cold climatic regions.

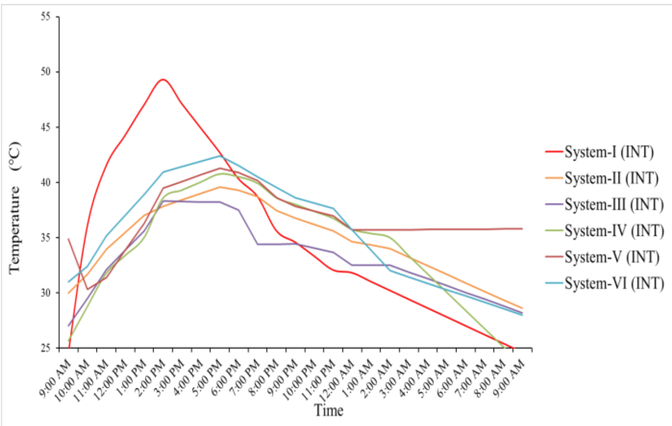


Figure 25 : Time vs. internal surface temperature behavior of control concrete slab (System I) and various thermal insulation systems

Table 11 shows the observation on field thermal study conducted on model buildings during hot sunny-cloudy day with humid night of 10-11, July 2015. It can be observed that maximum top surface temperature of control concrete slab and other tested thermal insulation systems except cool tile weathering course is in the range of 50 - 54^{0}C in the core sunny time at 1.00 p.m. Whereas cool tile offered only 41.10^{0}C which is appreciably less as compared to other tested systems. This reveals the efficiency of the cool tiles in deflecting the incident heat rays and making the surface temperature comfortable for usage. The temperature observation at 1.00 p.m. reveals that there is a significant reduction in inner surface temperature for secondary roofing (15.70^{0}C) and cool tile weathering course composite (15.10^{0}C) followed by light weight aggregate weathering course (14.40^{0}C), clay tile weathering course (13.70^{0}C) and aerocon aggregate weathering course (11.80^{0}C) as compared to top surface temperature of control concrete slab. Whereas, control concrete slab offered 3.70^{0}C reduction in inner surface temperature, which shows high thermal transmittance due to dense concrete mass. The observed temperature readings at 10.30 p.m. reveals that control and cool tile weathering course offer insignificant increase in inner surface temperature. Whereas other thermal insulation systems exhibits increase in temperature in the range 4-5^{0}C in the inner surface as compared to control concrete slab. It can be concluded that all the tested weathering course composites and secondary roofing offers significant reduction in temperature in the hot sunny duration and reduces the energy requirement for comfort cooling. Although there is marginal increase in inner surface temperature at the night times, considering the external surface temperature it may not significantly increase the energy requirement for comfort cooling.

Table 11: Observation on field thermal study conducted on model buildings in hot sunny- cloudy day with humid night on July 2015

System	Maximum top surface temperature (Day time)		Maximum reduction in temperature (˚C)	Max reduction in temperature w.r.t. control concrete slab (˚C)	Maximum top surface temperature (Night time)		Maximum reduction in temperature (˚C)	Max increase in temperature w.r.t. control concrete slab (˚C)
	˚C	Time			˚C	Time		
I	50.70	1:00 pm	3.70	3.70	32.63	10:30pm	-1.93	-1.93
II	52.00	1:00 pm	17.00	15.70	30.85	10:30pm	-7.15	-5.37
III	41.10	1:00 pm	5.50	15.10	31.00	10:30 pm	-2.65	-1.02
IV	52.00	1:00 pm	15.00	13.70	31.95	10:30pm	-4.81	-4.13
V	53.30	1:00 pm	17.00	14.40	33.25	10:30pm	-3.73	-4.35
VI	52.40	1:00 pm	13.50	11.80	33.30	10:30pm	-4.35	-5.02

Table 12 shows the cost details of various thermal insulation system employed in the study. It can be seen that aerocon aggregate weathering composite offers least cost of Rs. 950/ sq.m. ($15) which may be due to usage of waste broken aerocon blocks as coarse aggregates. The cost of conventional clay tile weathering course is Rs. 1270/ sq.m. ($20), which is nominal as compared to other thermal insulation systems except aerocon aggregate weathering course. The cost of secondary roofing system is Rs. 1900/sq.m. ($29) which highest among the tested thermal insulation systems followed by light weight aggregate weathering course (Rs. 1780/sq.m. ($27)) and cool tile weathering course (Rs.1680/sq.m.($26)). It is concluded that the cost of all the thermal insulation systems are affordable and can be recommended based on the type of application, significance and fund availability.

Table 12: Cost details of thermal insulation systems

Type of system	Cost / Sq. m. (Rs./$)
Control Concrete Slab	-
Secondary Roofing	1900 / 29
Cool tile weathering course	1680 / 26
Clay tile weathering course	1270 / 20
Light weight aggregate weathering course	1780 / 27
Aerocon aggregate weathering course	950 / 15

Rating of weathering course composites and secondary roofing system is done based on parameters such as strength and durability properties of thermal insulation systems, thermal transmittance value, thermal time constant, maximum temperature reduction, performance on reversal of temperature, heat reflection capacity and cost. Criteria has been derived for each parameter and accordingly performance evaluation is done under 5 point scale. Table 13 shows the performance rating of thermal insulation systems based on the various parameters. It can be observed that cool tile weathering course and secondary roofing system offered best performance as compared to other systems. Clay tile weathering course, light weight aggregate weathering course and aerocon aggregate weathering course offers similar behavior and significantly better than the control concrete slab without any protection. Although aerocon aggregate weathering and clay tile weathering course composites exhibit moderate performance, considering the affordable cost its usage is viable. Light weight aggregate weathering course offers similar performance as that of aerocon aggregate concrete but considering the cost it is not recommended.

Table 13: Performance rating of thermal insulation systems based on various parameters

Parameters	**Type of System**					
	I	**II**	**III**	**IV**	**V**	**VI**
Strength properties	5	5	4	1	2	3
Durability properties	0	5	4	1	2	3
Thermal performance- Theoretical study	0	4	3	1	2	5
Thermal transmittance-Laboratory study	0	4	1	3	5	2
Thermal time constant- Theoretical study	0	1	2	5	3	4
Maximum temperature reduction- Field study	0	5	4	2	3	1
Reversal of temperature –Field study	4	1	5	3	2	1
Heat reflectance capacity – Field study	3	2	5	4	2	1
Cost	5	1	2	3	1	4
Overall thermal performance	0	5	4	3	2	1
Total	17	33	34	26	24	25
Grade Point Average	0.34	0.66	0.68	0.52	0.48	0.50

6. CONCLUSIONS

Based on the experimental investigation, test results and further analysis conclusions were drawn:

- Cool tile weathering course offered similar compressive strength and aerocon aggregate weathering course found with 40% reduction in compressive strength as compared to control concrete slab.
- Clay tile weathering course and light weight aggregate weathering course found with inferior compressive strength which may be due to poor resistance offered by the topping course and needs careful service conditions. Ferrocement panels made with single layer crimped wire mesh exhibited significantly improved flexural strength, ductility and energy absorption capacity.
- Appreciable reduction in current development and charge passage for polymer modified mortar as compared to control mortar irrespective of dosage of polymer addition.
- There is an appreciable reduction in chloride ion penetration depth for

polymer modified mortar of the order of 56% as compared to control cement mortar. Polymer modification at 2%, 5% significantly reduces the 24 hour water absorption up to 32% as compared to control mortar.

- Theoretical studies revealed a 50% reduction in thermal transmittance for all the tested thermal insulation systems as compared to control concrete slab.
- Laboratory studies reveals that tested weathering course composites and secondary roofing exhibit marginal increase in thermal transmittance value as compared to allowable value of 2.33 W/m^2k but significantly less than the values observed for control slab.
- Field study on hot summer day in the core sunny hours revealed a 20^0C reduction in bottom surface temperature of tested thermal insulation systems irrespective of type as compared to control concrete slab.
- The 24 hour field study conducted on hot sunny-cloudy day with humid night exhibits reduction in inner surface temperature of model buildings of the order 12-15^0C in the core sunny hours of the day and increase in night time temperature of 4-5^0C as compared to control concrete slab.
- Based on performance rating study, it is found that secondary roofing and cool tile weathering course offers significantly improved overall performance as compared to other tested thermal insulation systems.
- The performance of the weathering course composites and secondary roofing is exhibited only when it is subjected to hot climatic conditions. In the mixed climatic conditions the working mechanism of weathering course composites and secondary roofing is not fully operative.

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