Effect of Solar Radiation to the Building Materials Properties: A Review

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ABSTRACT

This paper provides a review on the effect of solar radiation to the different building materials properties. Solar radiation; watt per meter square [W/m2] is one of the cause for thermal gain in building envelopes. Buildings envelopes comprises of various materials. Different materials have different rate of heat absorption depends on their emissivity and other parameters. The three materials studied in this paper are concrete, timber and composites materials. According to the radiation heat equation, heat rate are affected by the surface area of exposed envelope (A) measure in meter (m), emissivity of the building exposed surface (ε) and the temperature difference between envelope exposed surface (Ts) and temperature of equivalent atmosphere (Tsky) measure in ^{0}C. Based on the parameters, research methodology was adopted either by software simulation or test field experimental. Solar radiation affects the materials in various ways, depends on parameters considered, location of testing and type of materials.

Keywords: *building materials, thermal analysis, thermal indoor comfort, solar radiation*

INTRODUCTION

Buildings are built to meet its recommended purposes, in one sense it is a buffer between man and his external thermal environment. Highly diversify forms of buildings in various part of the world is one of the difficulties to answer the question for thermal comfort [1]. Buildings are made up of structural components such as building frame, infrastructure, structure and building envelopes. Each of the component is made up from different raw materials and composite materials and every material has its own characteristic. The term material characteristic can be signified by for example physical characteristic, strength and thermal characteristics.

BUILDING MATERIAL THERMAL CHARACTERISTIC

There are diverse types of raw to composite materials in building construction sector. Materials play an important role to form different parts of a building. Each material has their own physical and mechanical characteristic when exposed to radiation heat. Building envelopes are made up from numerous types of materials. Thermal comfort of building is closely associated with building materials and this affect heat conduction, convection and radiation. Further, this paper will review most commonly used materials in building which are concrete, timber and composite materials.

Concrete

Concrete are made of filler and binder. Physical characteristics of concrete give the strength and durability which are needed to support load in structures. Shariah *et al*. [2] studied the performance of light weight concrete block (LWCB) and heavy weight concrete (HWC) in terms of solar heat radiation which were used for roof structure in Amman and Aqaba. Shariah *et al.* [2] tested the materials for the absorption factor (α) range from 0.0 to 1.0 for roof materials and other surface fixed at 0.5 absorption factor. This absorption factor relies on the materials or surface colour which showed that the dark colour one absorbed more heat compared to those of light colour. The research concluded that HWC higher thermal conductivity compared to those of LWCB. Din *et al.* [3], investigated the thermal effect by solar radiation on building wall surface for brick, granite, white concrete tiles and concrete in urban city. They studied the thermal effect of urban heat island that happened in urban area. Each of the materials has different emissivity (Ɛ) which are brick 0.93, granite 0.94, tiles 0.97 and concrete 0.94. It showed that the range of the emissivity are slightly differ. Din *et al.* [3] concluded the highest absorbent and stores heat was in the following order; brick>concrete>granite>tiles. These also show the absorbed and stores heat order could be affected by the emissivity factor as the factor number are also in the same order.

The most common concrete defect is crack due to shrinkage and creep. Cracks are formed when restraint shrinkage happened due to internal reinforcement and external boundary conditions stimulate a tensile stress in concrete then the stress reaches the tensile strength, reducing the concrete resistance to chloride and carbon dioxide (CO_2) exposure [4]. Solar heat radiation contributed to increasing of temperature in concrete hence accelerated shrinkage and creep. Asamoto *et al.* [4] studied on the effect of solar radiation and rain on shrinkage, shrinkage cracking and creep of concrete. The research concluded that solar radiation increased the possibility of concrete crack at surface and decreased hydration related to tensile strength. Concrete mix design plays an important role in shrinkage cracking behaviour. Water to cement ratio and nearby environmental conditions cause different shrinkage cracking behaviour. Concrete creep are accumulated by frequent temperature rise due to solar radiation when the concrete is not exposed to rain. Huang and Tsai [5] studied on effects of exterior sunshades on heat transfer by solar radiation. Huang and Tsai [5] separated the effect of solar radiation into two concrete specimens which one specimen with covered sun shading net and other without sun shading net. The specimens were exposed outside with actual solar heat radiation. Thermal flux meter was used to indicate the flux transferred from specimen's surface to below specimen's surface and the thermocouple was used to capture the specimen's temperature. The research concluded that sun shading net blocked 36.2% heat absorption to the concrete and reduced 61% of heat flow into lower concrete surfaces. This effect increases the heat absorption period and avoid severe changes in wall temperature.

Benammar *et al*. [6], investigated the solar heat for the use of concrete curing via steam curing. The effect of water cement towards the compressive and flexural strength is influenced by cement type and curing method. Benammar *et al*. [6] studied the influence of curing method by comparing four types of curing method; water curing, air curing, steam curing at 29^{o}C and steam curing at 45^{o}C. However, the concrete cured by steam shows strength reduction for 28 days. Benammar *et al*. [6] concluded that steam curing gave advantages on accelerating concrete hardening, good strength and high electrical energy saving for precast concrete production.

Timber

Timber and wood materials are used in many parts of buildings, for example wall, roof and floor. Timber and wood materials are considered as sustainable building material as growing process of tree stored carbon compared to other building material production processes [7]. Looking back, timber is widely used as wall and partition in building mostly in rural area. As construction sector grows and develops, wall materials are then changed to concrete and bricks. Human spends much on their time in this confined spaces for thermal indoor comfort. Air cooling and conditioning system are used to provide comfortable confined spaces. Air cooling and conditioning system consume a lot of energy hence emitted carbon to surrounding. Timber has air gaps in its cell which provides good air ventilation and also the characteristic of timber with heat convection and conduction has made it as an option for problem solving. Kairys *et al.* [8] investigated on heat flux through the timber walls under summer climate conditions in Eastern Europe. The research aim to compare the heat transfer through the lightweight timber wall containing materials with different physical parameters in terms of thermal conductivity, density, thickness, specific heat capacity and others. Because of the different physical characteristic, it is important to estimate accurately the design values of different material physical parameters and the effect of their dependency to the heat storage and heat flux variation inside the wall. Heat flux density was measured for two conditions of wall with air gaps and without air gaps. On inner and outer surfaces of the wall without air gap, inner and internal air gap surfaces of the wall with air gap. Thermo-physical parameters considered in Kairys *et al*. [8] are heat flux density, thermal inertia, time constant, thermal resistance, time lag, decrement factors and others. This research take into account the solar radiation and thermal inertia impacts and results were obtained by thermal receptivity calculation method.

Akpabio *et al*. [9] studied on thermal response of six types of Nigerian woods for passive cooled building design. Thermal properties investigated in the research are conductivity, absorptivity, emissivity and diffusivity of heat. The variation between temperature and thickness of wood sample are used to monitor thermal conductivity or insulation of the wood sample with subject to solar radiation. From the results, Akapabio *et al*. [9] concluded, the sample with highest thermal diffusivity (λ=91.60 +/- 0.004 m^2s^{-1} x 10^{-7}) and lowest absorptivity (α=1.993+/-0.111 m^{-1}) are suitable for design of passively cooled building. Other criteria for a good thermal insulation was low thermal conductivity signifies with high thermal resistivity. Akapabio *et al.* [9] suggested the samples to be used in ceiling panels, doors, windows. Conduction heat transmissions require stiff bound of molecules to drive more energy and weak bound of molecules drive less energy. Radiation heat depends on temperature to transport within the material. Radiation is high at higher temperature while temperature difference within solid materials depends on thermal conductivity, specific heat capacity, density, thermal absorptivity and diffusivity to determine whether the materials can be used as heat conductor or insulator [9].

Composite Materials

Building insulation is important in a building operation to reduce the consumption of energy by mean of air cooling and conditioning systems. Materials for building insulations are often comprise of numbers of composite materials. Jalilluddin *et al*. [10] presented research on the relation of density of materials with the thermal conductivity characteristic. The research use sand-cement blocks combined with Kenaf fiber (*Hibiscus cannabinus L.*) to represent wall. Hot-box method was used and four numbers of 60 Watt bulb as heat radiation source. Thermal conductivity rate was obtained by the amount of heat flow from hot side to the cold site of the block. It showed that sand-cement blocks with Kenaf enhanced the thermal conductivity and reduced the density. Good thermal insulator are that materials with lower values of thermal conductivity hence with lightweight features. Reduce in density was due to the porous nature of Kenaf. Kenaf fiber has a hollow and cellular materials that provide air trapping between the fibers thus reduce the heat transfer mechanism. Ozel [11] compared the effect of different position of insulation in a wall which exposed to periodically solar radiation and outdoor environmental conditions and inside surface exposed to air maintained at constant indoor design temperature. The study also looked into the thermal characteristic of cooling and heating transmission loads, time lag and decrement factor. The walls are made up from brick block, extruded polystyrene, cement plaster and the insulation located at outside, inside and middle of the wall. Results showed the transmission loads decreases as the insulation thickness increased. However, the result is insignificant showing that yearly transmissions loads are unaffected by insulation location. For yearly averaged time lag and decrement factor, decrement factor decreased and time lag increased as the insulation thickness increased as expected. It is concluded that the best thermal performance is obtained when insulation is placed at outside of wall.

Roof is the major building envelopes that exposed extremely to solar heat radiation subjected to the location of the building. The amount of radiation heat received by each building roof differ for each country. Oliveti *et al*. [12] investigated the relation of thermal radiation exchange between horizontal surfaces to indicate roof with outdoor surfaces. Figure 1 and Equation 1 show the relation of thermal flow of surface and outdoor surroundings. Figure 1 indicates qc convective flow exchange with the outside air, qr the net radiative flow in the long infrared, qi the conduction flow through wall, G the solar radiation subjected to the wall and Ɛc wall emittance. The horizontal specimen consists of internal plaster, brick-cement roof insulation of expanded polyurethanes and placed outside is painted steel sheet. Oliveti *et al*. [12] investigated on more complex approach in calculating thermal radiation exchange by taking into account the infrared radiation emitted from the ground. The research was done for 185 recorded data in May 1998 to April 1999. The emittance values in the long infrared Ɛl0.90 and in the solar band Ɛc0.60. The research concluded the net infrared flow is always outgoing from the surface and was not negligible in the calculation of absorbed solar radiation flow to convection flow. The results received validated the calculation of radiation heat flow rate using the relation qr=hr(Ts-Tsky). In the end, the authors stressed to use Tsky=Ta to calculate hr coefficient and qr so the net infrared heat flow rate of excessive underestimated will be achieved.

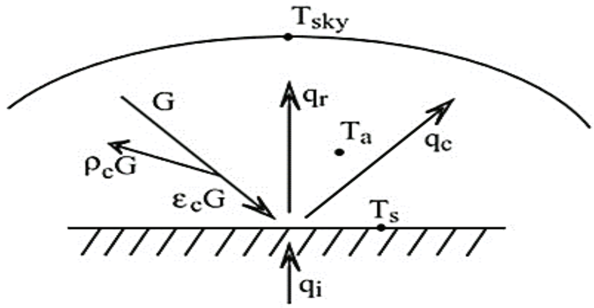

Figure 1: Thermal flow between the surface and the outdoor surroundings [12]

$$q_r = \varepsilon_l \sigma \left[T_s^4 - T_{sky}^4 \right] \quad (1)$$

For the typical roof structure used in climatic conditions of Saudi Arabia, Al-Sanea [13] studied and evaluated the thermal performance of building roof elements subject to steady periodic changes under ambient temperature, solar radiation and nonlinear radiation exchange. The research presented the dynamic R-value of the roofs subjected to Riyadh climatic conditions representing days for July and January. Mathematical model with assumptions of there is no heat generation was formulated. The layers were in good contact and the interface resistance was negligible, the variations of thermal properties was negligible, the thickness of the composite roof was small compared to the other dimensions. Then a one-dimensional temperature variation was assumed, lastly the convection coefficient was constant based on the direction of heat flow and daily average wind speed. The types of six roof structures studies represent uninsulated roofs with different foam concrete, insulated roofs with different insulation materials which are; molded polystyrene, extruded polystyrene and polyurethane separately. Materials forming the roof are; paving tile, mortar bed, sand fill, molded polystyrene, extruded polystyrene, polyurethanes, water proofing membrane, foam concrete, reinforced concrete and cement plaster. At the end, it is confirmed that the contribution of the radiation exchange was more than twice compare to heat convection. The energy balance for the roof for diurnal, summation of outside surface heat convection, absorbed solar radiation, radiation exchange between outside-surface and sky are correspondingly to inside-surface heat transfer and under steady periodic surroundings conditions.

Meyn and Oke [14] characterised the relation between storage heat flux and the heat balance in cities by six different roof assemblies. Studies cooperate net-all-wave radiation and the heat flux conducted into and out of the materials that form cities envelopes thus combine the average amount to give bulk heat storage. The contribution of roof to total heat storage may be fairly negligible compared to walls and ground covering due to the low inclination to store workable heat. The location of roof in building provided it to highly windy condition hence roof are well insulated that increases convection heat losses and reduce the fraction of radiation directed into diurnal storage. This research applies Simplified Transient Analysis of Roofs (STAR) as method of data analysis.

Morris *et al.* [15], studied the heat flux and proportion of heat through roof, ceiling and wall for naturally ventilated building cooperated with tropical climate. A model of test building was developed hence simulated using Thermal Analysis Software, RadTherm. The three ways of heat gained through building which are conduction, convection and radiation. All materials are listed in Table 1.

Table 1: Test cell building material

Construction materials	
Roof	Cement roof tile cemboard
Ceiling	Ceiling
	Fiberglass
Window	Glass
Door	Timber
Wall	Plaster
	Brick
	Plaster
Floor	Cast concrete

Results from the research concluded that the heat flux via radiation is the highest through all studied areas which are roof, ceiling and wall. From the research, it was strongly agreed that roof received highest heat rate flux compared to other building envelopes as roof are exposed to diurnal to solar radiation otherwise the rate of heat flux is lower during night.

THERMAL ANALYSIS METHOD

There are different methods used to estimate the thermal heat transmissions for certain materials and conditions. Table 2 describes the analysis method used by authors to calculate the heat flow for materials selected. Location of the research took place are important to be notified as to give a brief information on the climatic and environmental conditions prior to the experimental done. Based on Table 2, the most preferred methodology are field experiments compared to computer software and mathematical modelling. It was observed that selection of methods used are not based on climatic conditions nor materials selections. It could be on author's personals preferences.

Table 2: Authors, location, method, materials and structures done for thermal analysis

Research studies	Location	Analysis methods	Materials	Structures
Shariah *et al.* [2]	Jordon	TRNSYS simulation programme	Light weight concrete, heavy weight concrete	Loose materials
Oliveti *et al.* [12]	Italy	Experimental field measurements	Plaster, brick-cement, expanded polyurethane insulation, painted steel sheet	Roof
Al-Sanea [13]	Saudi Arabia	Numerical method	Paving tiles, mortar bed, sand fill, polystyrene, polyurethane, water proofing membrane, foam concrete, reinforced concrete, cement plaster	Roof
Kairys [8]	Eastern Europe	Experimental and calculation	Timber	Wall
Kehrer & Schmidt [16]	Germany	Mathematical modelling	Timber/wood	Roof
Harijaona *et al.* [7]	France	Numerical method, field measurement	Timber/wood	Wall, floor, ceilings
Meyn & Oke [14]	Canada	STAR (Simplified Transient Analysis of Roofs) Model	Gravel, asphalt, shingles, bitumen	Roof
Akpabio *et al.* [9]	Nigeria	Experimental measurement	Timber/wood	Loose samples
Yao & Yan [17]	China	DeST-h simulation toolkit	Tiles, cement, brick, plaster, coating, plaster	Wall

Asamoto *et al.* [4]	Japan	Experimental measurement	Concrete	Loose materials
Morris *et al.* [18]	Malaysia	Experimental measurements	Mineral wool, fiberglass	Roof
Md Din *et al.* [3]	Malaysia	Experimental measurements	Brick, concrete, granite, concrete tiles	Wall
Morris *et al.* [15]	Malaysia	Thermal analysis software ThermoAnalytics, RdTherm version 9.3.1	Cement roof tile, cemboard, fiberglass, glass, timber, plaster, brick, concrete	Roof, ceiling, window, door, wall, floor
Jalilluddin *et al.* [10]	Malaysia	Experimental measurements	Sand-cement blocks with kenaf fibre	Loose materials
Huang & Tsai [5]	Taiwan	Experimental measurements	Concrete	Loose materials
Ozel [11]	Turkey	Mathematical modelling	Brick, polystyrene, cement plaster	Wall
Benammar *et al.* [6]	Algeria	Experimental measurements	Concrete	Loose materials

Parameter Involved in Reviewed Method for Thermal Analysis

Reviewed of selected literature reveals some commons parameters as listed in Table 3. From Table 3, temperature is the most crucial parameter in thermal flow analysis despite of different methods selected by the authors. The different parameters used for each study are to comply the method used, research objectives and further research gaps.

Table 3: Parameters involved in measuring building performance from literature reviewed

Research studies	Parameters																	
	Absorption (α)	Area (A) m^2	Capacitance (C) $kJ/^0C$	Heat transfer coeff. (h) $kJ/h\text{-}m^2\text{-}^0C$	Reflectance (ρ)	Humidity (ω)	Temperature (T) ^oC	Transmittance (τ)	Wind speed (W) m/s^2	Conductivity (k) w/m^2	Emissivity (Ɛ)	Stefan-Boltzmann (σ) $W/m^2 K^4$	Specific heat (c) J/kg K	Solar intensity (I) W/m^2	Convection heat (q_c) W/m^2	Radiation heat (qr) W/m^2	Diffusivity (λ)	Resistivity (r)
Shariah *et al*.[2]	√	√	√	√	√	√	√	√	√									
Md. Din *et al*. [3]							√			√	√		√	√				
Asamoto *et al*. [4]						√	√											
Huang & Tsai[5]							√				√	√		√			√	
Harijaona *et al*. [7]						√	√		√									
Kairys *et al*. [8]				√			√							√	√			
Akpabio *et al*. [9]	√			√			√			√	√		√	√			√	√
Jalilluddin *et al*. [10]		√					√			√								
Ozel[11]				√	√		√			√			√	√			√	
Oliveti *et al*. [12]		√		√			√				√	√						
Al-Sanea[13]				√			√				√	√	√	√	√	√	√	
Meyn&Oke[14]			√				√			√			√			√		
Morris *et al*. [15]							√			√			√		√	√		
Kehrer& Schmidt[16]	√				√		√				√			√				
Morris *et al*. [18]							√			√								√

CONCLUSION

This paper presents a literature review on the effect of solar radiation, the parameters involved and the methods used to calculate the thermal analysis. It has been seen that, concrete exposed to solar radiation would absorb heat and the amount of heat absorbed by concrete depends on its colour, darker colour absorb more heat. Heat that absorbed by concrete increased the moisture lost in concrete, hence crack was initiated. The amount of heat absorbed can be minimised by applying net shading on top on the concrete surface.

Studies done on effect of solar radiation to timber focused on the value of heat flux through the material. Composite materials made up an insulated wall and roof. Insulation means wall and roof were layered between bricks and roof materials hence the amount of heat absorbed differ by the location of the insulation materials.

A summary on the methods involved in the thermal analysis also presented. It could be noted that software simulation can be performed to validate the values obtained from experimental testing. The thermal parameters between both simulation and experimental were not much different.

An overview on parameters involved in thermal analysis was also presented. There are numbers of parameters used by researches, it depends on the availability data that can be gathered. Some researchers assumed the value of parameters while others used data based on standard or by previous research reported. However, none of the researchers neglect the value of temperature hence prove that temperature value is the most important parameter in thermal analysis especially for solar radiation.

There are many studied done on thermal analysis of solar radiation. The studies were varied in terms of material selection, parameters involved, method used, locations and many more. These gave a big opportunity for researchers to study and compare the results gained and hence in future the data collected can become references for future development in building construction and also for other related industries.

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