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ORIGINAL ARTICLE

Effect of moisture on thermal properties of acrylic polymer modified mortar reinforced with alkali treated bamboo fibres

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Abstract In this study, bamboo fibres were used as reinforcement materials for acrylic emulsion polymer modified cement bonded concrete after treatment with 10% weight of NaoH solution at 23 °C for 24 h. Thermal conductivity, thermal resistance and thermal transmittance were studied and the effects of moisture penetration at 11% wet basis were evaluated. Moisture penetration greatly reduced the thermal strength of the concrete with the exception at 10% acrylic polymer addition and 1.5% bamboo fibre inclusion. Based on the findings it can be reported that bamboo fibres greatly improved the thermal performance of the composite building material while the inclusion of acrylic polymers also hindered to a large extent the penetration of moisture into the capillary network.

Keywords Bamboo · Polymer · Conductivity · Resistance · Thermal · Transmittance

Introduction

Most parts of sub Saharan Africa are located along the tropical zone and could have peak temperature of 50 °C during the dry season. This condition leads to an uncomfortable situation within individual buildings in the region and hence the thermal comfort of such buildings becomes a problem begging for solution. Building materials are porous media in which moisture transfer occurs in both the vapour and liquid phases. Besides exercising a decisive effect on the material's durability, moisture can considerably modify both its mechanical and thermal properties. Thermal conductivity is strongly influenced by the moisture content migrating through the porous material as a result of molecular diffusion, gravity, thermal gradients and pressure gradients. The thermal gradient in moist building materials can induce moisture movement whereby water evaporates in warmer regions and begins to condense in cooler areas. These processes are accompanied by additional energy transfers such as latent heat and sensible heat, which considerably increase the thermal conductivity of the material. Therefore, heat and mass transfer are highly coupled (Bouguerra 1999). In order to have certain comfort under such situations, air coolers that normally consume an important amount of energy are used. This energy consumption can be reduced by incorporating biodegradable fibres into the construction materials which would serve as alternative to the conventional ones in order to reduce energy consumption in buildings (Ramirez et al. 2012; Benmansour et al. 2014). Natural fibre as reinforcement has proven to have improved the properties of the internal structure of composites during the setting time and eventually at the hardened state (Huijun et al. 2013) which translates to enhanced properties to prove the indispensability of wood fibres inclusion in cement composites for structural applications in most developing countries where they exist in abundance. When cellulose materials are exposed to environmental factors such as temperature and relative humidity which are variables considered between the interior and the exterior of the buildings, heat and moisture transfers occur within the medium. An important interaction develops between the

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heat and the moisture transfers and the different transport properties. This is largely due to the hygroscopic nature of the material (Taoukil et al. 2013). Some studies on effects of temperature and moisture interaction in wood-cement composites have been conducted already. Such studies include Blankenhorn et al. (1999) who evaluated the effect of moisture and temperature cycling on kraft softwood and hardwood fibers with treatment from an aqueous acrylic emulsion and alkylalkoxysilane polymers to establish their dimensional stability properties. Al Rim et al. (1999) evaluated the influence of wood aggregates on the thermal and mechanical performance of a clay-cement-wood composite. Khedari et al. (2005) developed a soil–cement block using coconut coir as reinforcement with a low thermal conductivity property. Khedari et al. (2001) investigated the thermal conductivity, compressive strength and bulk density of a lightweight material developed from cement, sand and waste fibres from durian and coconut. Benfratello et al. (2013) analysed the thermal and structural behaviour of a bio-composite concrete developed from lime with the addition of vegetal fibres from hemp and particular attention was paid to the amount of fibres and its granulometry in the mixture. As interesting as the idea sounds with the use of natural fibres as reinforcement in polymer cement composites, the need to determine their thermal properties as well as the effect of moisture when they are used in real life structural applications cannot be glossed over most especially when used in tropical regions with high intensities of rainfall and sunlight throughout the year. Therefore this study aims to address this concern. Similarly, the novelty in this study relates to the use of acrylic emulsion virgin paints as a replacement for the conventional and expensive polymer modifiers which are chemical additives used for concrete modification and a previous study conducted by the author had established their engineering properties (Akinyemi and Omoniyi 2017) which therefore validates the use in cement composites. Its adaptation would encourage most low income earners within regions with high incidence of sunlight and rainfall patterns to adopt this research in their building constructions.

Experimental work

Materials

Bamboo culms from the *Bambusa Vulgaris* species were cut and allowed to dry naturally for 30 days at 35 °C in the open field. The nodes were broken using a sledge hammer and the obtained strips were cut into bits of 200 mm to enable easy milling using hammer mill machine. The bamboo fibres that passed through a 0.20 mm sieve had maximum length of 23.74 mm with thickness of 2.31 mm and a minimum length of 5.09 mm with 1.25 mm thickness was used for the production of the composite specimen. Acrylic emulsion surface coating supplied by Chemstar Industries was used for the polymer as reported by (Scott and Nathaniel 2013; Lagerblad and Vogt 2003). River sand passing through 13 mm sieve was also used and all organic materials were removed before the sieving process was carried out. The ordinary Portland cement that conforms to ASTM Type 1 was also used as the binder while potable water was obtained from the tap within the Laboratory.

Surface treatment of bamboo fibres

Most of the debris and solid contaminants were removed during the sieving process. Bamboo fibres were then soaked in diluted 10% weight of NaoH solution for 24 h at 23 °C in a container within the laboratory. Thereafter, the solution was decanted and the fibres transferred into a big basin containing fresh water and washed manually with hands to remove the absorbed alkali on the surfaces through leaching into the water. The fibres were later spread on a flat surface and allowed to dry naturally at 23 °C within the laboratory.

Sample preparation

A predetermined value of sand was first measured out and cement was added in the 3:1 ratio (sand:cement), these were thoroughly mixed manually for 2 min. Thereafter, a predetermined value of bamboo fibres 1.5% on weight basis with respect to composite was also added to the mix and thoroughly mixed to avoid balling effect. The acrylic polymer emulsion was varied in the proportion of 5, 10 and 15% weight of cement and later measured out into separate containers. Halved portion of water in the ratio of 1:6.1 (water: polymer) was used for the dilution of the polymer in a separate container thereafter the diluted solution was mixed with the prepared constituents. The remaining halved water was added to the entire matrix and mixed thoroughly together. Cylindrical samples each of 12 mm thickness and 44 mm diameter were produced and allowed to cure naturally in the laboratory at 23 °C for 28 days as recommended by ACI 548 (2003). This procedure is in contrast to that for unmodified mortar. The reason for this difference is that for the latex to beneficially modify the properties of the mixture, it must be allowed to coalesce and form a film. The removal of water is the key step in this film formation process. These samples were designated as B (0% fibre, 5% acrylic polymer), O (1.5% fibre, 5% polymer), C (0% fibre, 10% polymer), R (1.5% fibre, 10%

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polymer), N (0% fibre, 15% polymer) and Y (1.5% fibre, 15% polymer).

Test procedure for samples

The apparatus used for the measurement of thermal conductivity is called Lee's Disc apparatus (Fig. 1) based on the principle of absolute plane parallel plate technique. This is a type direct measurement of the heat-flux which is a non-destructive method. The recorded values were then used to calculate the thermal conductivity (λ) of each sample of thickness (d) and radius (r) using the equations:

$$\lambda = \frac{e.d}{2\pi r^2 (T_B - T_A)} \left[a_s \frac{T_A + T_B}{2} + 2a_A T_A \right] \quad (1)$$

where e is calculated using

$$e = \frac{V.I}{\left[a_A T_A + a_{s\frac{T_A+T_B}{2}} + a_{h\frac{T_B+T_C}{2}} + a_B T_B + a_C T_C \right]} \quad (2)$$

where

$$a_A = a_C = \pi r^2 + 2\pi r l_d, \quad (3)$$

$a_B = 2\pi r l_d$, $a_s = 2\pi r l_s$ and $a_h = 2\pi r l_h$. l_d = thickness of disc, l_s = thickness of sample and l_h = thickness of heater. a_A, a_B, a_C, a_s and a_h = exposed surface areas of discs' A, B, C, specimen and the electric heater. T_A, T_B and T_C = temperatures of discs' A, B and C (this were subtracted from the ambient temperature to give the exact value).

Thermal resistance is denoted by R and was calculated using the equation:

$$R = \frac{l}{\lambda} \quad (3)$$

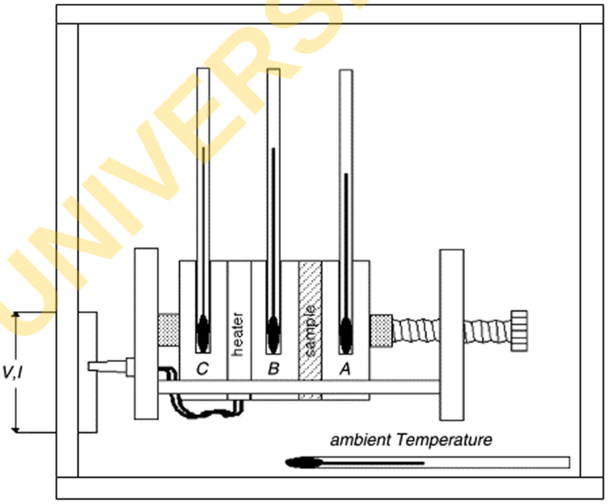

Fig. 1 Schematic diagram of Lee's disc thermal conductivity arrangement

where R = thermal resistance in metres squared Kelvin per Watt (m^2K/W), l = the thickness of the material in metres and λ = the thermal conductivity in W/m.K. The thermal transmittance is denoted by U value and it is the inverse of the total thermal resistance of the element. The acrylic polymer modified bamboo reinforced cement bonded composites (APMBRCBC) samples were oven dried at 150 °C for 24 h (Fig. 2) until the 2 successive weights remained constant and the moisture content of 0.1% wet basis was obtained for all tested samples using AND1 moisture analyzer. Thereafter, the samples were completely immersed in a plastic bucket filled with tap water at 24 °C for 15 h until the weight difference remained constant and the moisture content on wet basis was determined using the moisture analyzer. A moisture content of 11% wet basis was used for all the tested samples.

Results and discussions

Thermal performance

Thermal conductivity of AEPMBRCBC

Thermal conductivity of the samples as seen in Fig. 3 shows that sample C with 10% polymer content with no fibre had the highest conductivity at 109.37×10^{-5} W/mK, this was closely followed by N sample with 104.9937×10^{-5} W/mK at 15% polymer content with no fibre as well and followed by Y at 15% polymer and 1.5% fibre inclusion. Sample B had the least thermal conductivity, this showed that it is a good conductor and therefore this thermal trait is undesirable. This situation was observed because the materials became closely packed

Fig. 2 Samples in Memmert oven

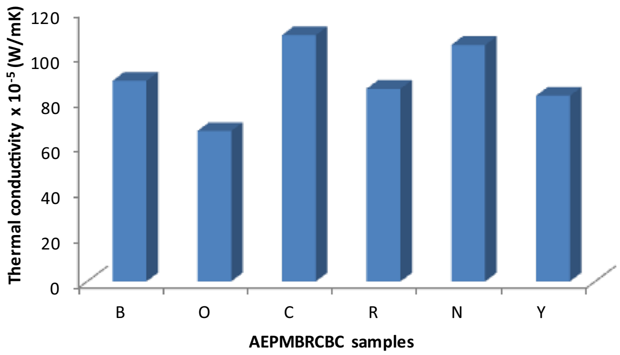

Fig. 3 Thermal conductivity of samples

together during the hydration and film formation stage thereby eliminating the presence of voids and making the material to possess low porosity. The heat is mostly transferred in the composite material at low temperature of about 25 °C through conduction. The sudden increase in thermal conductivity from sample B to C was caused by the increase in latex content from 5 to 10% which ultimately translates to more moisture within the samples, hence more conduction. However, when the temperature rose close to 60 °C, evaporation of water vapour took place which reduced the volume of moisture within the sample. This condition led to a slight decline in thermal conductivity at N. Inclusion of bamboo fibres into the mix resulted into 33% reduction in heat conduction at sample O when compared with B, 28% reduction at R compared with C and finally 27% reduction in heat conduction at Y when compared with N. Bamboo fibres inclusion into the composite cement material produced an overwhelming reduction in the thermal conductivity which therefore makes it to be a potential thermal insulator if introduced in real life structural applications. This phenomenon is related to insulating property of the fibres which could be likened to wood shavings that has low thermal conductivity. Hence the heat conduction property of this material depends on the constituents used during the mixing phase. It could therefore be stated that the lower the thermal conductivity of inclusions, the more the material is insulating. Furthermore, the increase in porosity led to decreased density of the material and ultimately the reduction in thermal conductivity (Driss et al. 2013). A similar result was obtained by Cristel et al. (2010) who worked on thermal properties of bagasse fibre concrete with low thermal conductivity figures recorded for samples with higher bagasse fibres. Mounika et al. (2012) also reported that the thermal conductivity of bamboo fibre reinforced polyester composite decreases with increase in fibre content which gives credence to the result of this research.

Thermal resistance of AEPMBRCBC

The R-value is a measure of resistance to heat flow through a given thickness of material. So the higher the R-value, the more thermal resistance the material has and therefore the better its insulating properties. The R-value is therefore a relatively simple way to compare two insulating materials if the thermal conductivity for each material is known. Samples with polymer inclusions only had the highest resistance to heat flow at B with 7903 m^2K/W, this was closely matched by N at 7540 m^2K/W and the least at C with 6961.5 m^2K/W as shown in Fig. 4. This implies that further inclusion of polymer emulsions from 5 to 10 and 15% respectively led to 14 and 5% reduction in heat resistance. This could mean that any further increase in polymer addition could lead to more reduction but if a lower volume of acrylic polymer were to be used an higher resistance could be obtained for the composite materials. The ability of the composites to resist heat is more related to the quantity of fibres included than the quantity of polymers added to it. This could be seen at sample O which had 37% more resistance than B, 33.4% higher resistance value at R than C and lastly 7.5% higher resistance at Y than N. Overall performance depends on material type, thickness and mass density of each sample. Generally, the best thermal resistance was obtained at sample O with 10,831.09 m^2K/W. Thermal resistance also helps to see the impact of adding thicker layers of the same insulating material. Therefore by using constituent materials used for the production of sample O to produce several layers, the best resistance ever for this type of composite materials could be obtained. In real buildings a wall is made up of many different material layers. The total thermal resistance of the entire wall is calculated by adding the thermal resistance of each separate layer. Unfortunately heat moves in and out of the building envelope in several different ways and R-values only take into account conduction. It does not include either convection or radiation, therefore, the U-value is the best choice when compared with the

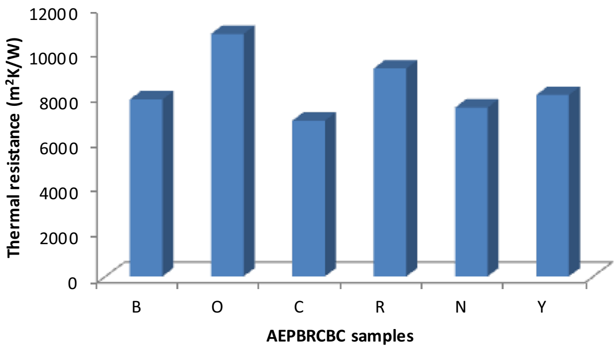

Fig. 4 Thermal resistance of samples

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resistance because it takes into account all the different mechanisms of heat loss. By comparing this result with the thermal conductivity values, the resistance is quite higher than the conductivity and it confirms the fact as reported by Luca et al. (2015) that the higher the thermal resistance values obtained, the lower the thermal conductivity values that will be recorded.

Thermal transmittance of AEPMBRCBC

The thermal transmittance (U-value) is the measure of how much heat is lost through a given thickness of the composite materials, and it includes the three major ways in which heat loss occurs therefore it is the most accurate way to judge a material's insulating ability because it takes into account all the different ways in which heat loss occurs. The environmental temperatures inside and outside a test location played an important role when calculating the U-value of an element therefore a completely sealed enclosure was used during the test. As seen in Fig. 5, samples with acrylic polymer inclusions only such as B had 12.66×10^{-5} W/m^{2}K, C had 11.49×10^{-5} W/m^{2}K and N had 13.27×10^{-5} W/m^{2}K, the least value was gotten at C, B and N respectively in that order. This implies that 10% acrylic polymer content gave the best compact and condensed particle arrangement within the internal structure of the composites which led to the least transmittance. It is also possible that an higher increase in the polymer led to a higher transmittance of the samples while a lower polymer content at 5% provided an insufficient dense substance due to lower rate of film formation within the structure. Samples with bamboo fibres inclusion had a far lower transmittance than samples with polymer inclusions which gives them an edge. Sample O had 37% lower transmittance than B, R is 6.7% lower C and Y is 7.1% lower transmittance than N. This implies that implies that the inclusion of bamboo fibre in the acrylic emulsion polymer modified mortars has improved the insulating property of the composite. The lower the U-value is, the better the material is as a heat insulator. In addition to this, when the material is used as structural material in buildings it would save energy because of its insulating capacity through its lower thermal transmittance values (Francesco et al. 2014).

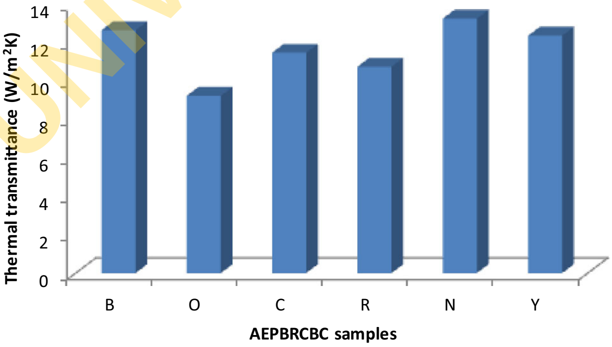

Fig. 5 Thermal transmittance of samples

Effect of moisture on thermal performance

1. Effect on thermal conductivity: Fig. 6 showed that there was a general increase in the thermal conductivity for all the samples when compared with earlier results. R sample had the best performance with 7% decrease in thermal conductivity, the rest had major increment in their values in the following orders of performance: Y had 3% increase, C had 4.5% increase, R and B had close values of 7% and 7.7% increment for the former and latter, and N at 38.6% increase and the worst value was recorded at O with 44% increase. This trend was also observed by Bouguerra (1999) who worked on the thermal conductivity of wood aggregate–clay–cement composites and the result showed that the thermal conductivity values is very dependent upon both moisture content and temperature. A similar result was observed by Driss et al. (2013) with an increase in thermal conductivity of wood–concrete composite on immersion in water.
2. Effect on thermal resistance: Fig. 7 showed that moisture content has negative influence on the composite samples by reducing their ability to resist the heat flow into them because a higher thermal resistance values gives a better insulating performance. The best performance was recorded for R at 2.1% reduction in thermal resistance value when compared with earlier values without moisture influence, the rest are in this order: C at 5.4% reduction, B at 6.6% reduction, Y at 12.4% reduction, N at 28.2% reduction and lastly O at 29.1% reduction. The top performer showed that by combining the advantages of acrylic emulsion property

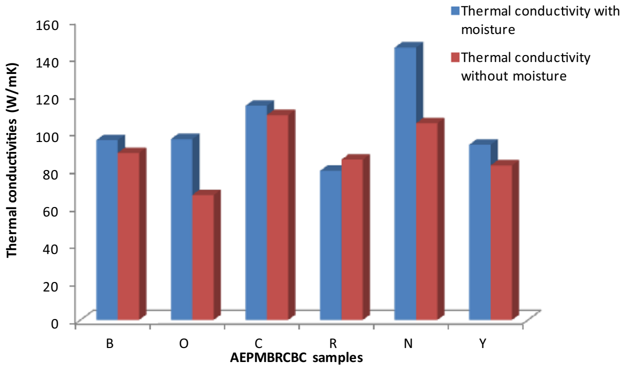

Fig. 6 Comparison between thermal conductivities with and without moisture influence

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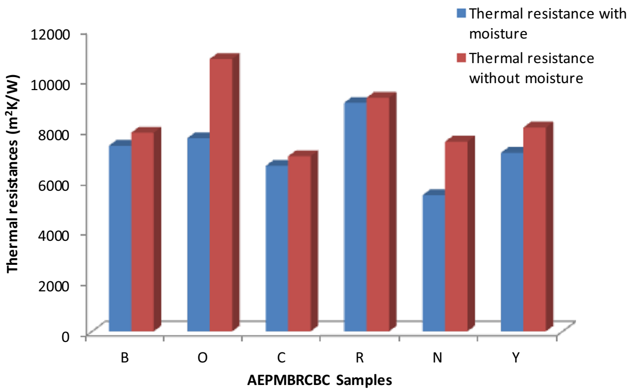

Fig. 7 Comparison between thermal resistance with and without moisture influence

with the improved and durable fibre through chemical modification, a better thermal resistance material with great potential could be developed for structural use.

3. Effect on thermal transmittance: Fig. 8 showed the thermal transmittance increased substantially for majority of the samples with few exceptions. The implication of this is that the lower the transmittance, the less the conduction and a better insulator is produced. However, some samples performed better than the rest, this are arranged in order of their performance: the least value was recorded at R with 2.3% increase, B at 7.1% increase, Y at 13.8% increase, C at 32% increase, N at 39.3% increase and lastly O at 41% increase in the thermal transmittance value when compared with the initial values recorded with moisture influence.

Conclusion

In this study treated bamboo fibres (soaked in 10% weight of NaOH solution for 24 h at 23 °C) were used as a reinforcement in acrylic emulsion polymer modified cement bonded composites. Thermal conductivity, thermal resistance and thermal transmittance were carried out at 0.1% moisture content (wet basis) thereafter the effects of moisture penetration at 11% moisture content (wet basis) were conducted. The results showed that poor thermal conductivity performance was observed for samples with polymer emulsion only but the inclusion of fibres greatly improved this property at 5% polymer and 1.5% fibre inclusion. A similar result was gotten for thermal resistance with 5% polymer and 1.5% fibre inclusion this showed that this ability has more to do with fibre than polymer addition. The lower the thermal transmittance, the better it is as an insulator. The least value of 5% polymer and 1.5% fibre inclusion was obtained for this property. Therefore, O sample gave the optimum desired performance. Moisture penetration generally had negative influence on all the thermal properties considered except for R which had 7% decrease in thermal conductivity while the rest recorded increment in values, least thermal resistance value of 2.1% reduction was also obtained for R and finally 2.3% increase in thermal transmittance was also recorded for R.

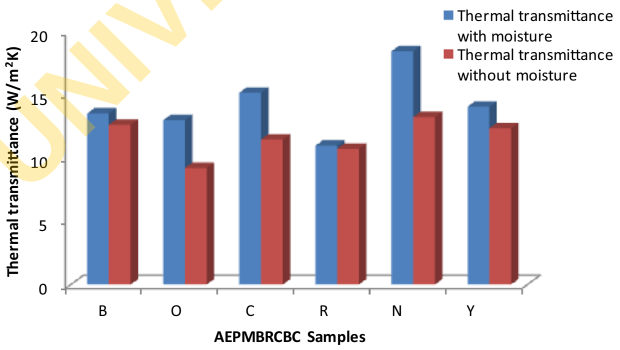

Fig. 8 Comparison between thermal transmittance with and without moisture

References

ACI 548 (2003) 3R-03-American Concrete Institute, Polymer modified concrete

Akinyemi BA, Omoniyi TE (2017) Engineering properties of acrylic emulsion polymer modified bamboo reinforced cement bonded composites. Eng Struct Technol 9(3):126–132

Al Rim K, Ledhem A, Douzane O, Dheilly RM, Queneudec M (1999) Influence of the proportion of wood on the thermal and mechanical performances of clay-cement-wood composites. Cement Concr Compos 21(4):269–276

Benfratello S, Capitano C, Peri G, Rizzo G, Scaccianoce G, Sorrentino G (2013) Thermal and structural properties of a hemp–lime biocomposite. Constr Build Mater 48:745–754

Benmansour N, Agoudjil B, Gherabli A, Kareche A, Boudenne A (2014) Thermal and mechanical performance of natural mortar reinforced with date palm fibers for use as insulating materials in building. Energy Build 81:98–104

Blankenhorn PR, Michael RS, Brad DB, Maria D, Kevin K (1999) Temperature and moisture effects on selected properties of wood fiber-cement composites. Cem Concr Res 29:737–741

Bouguerra A (1999) Temperature and moisture dependence on the thermal conductivity of wood-cement-based composite: experimental and theoretical analysis. J Phys D Appl Phys 32(21):2797

Cristel O, Nady P, Fernando T, Silvio D, Marie-Ange A (2010) Sugar cane bagasse fibres reinforced cement composites: thermal considerations. Compos A 41:549–556

Driss T, Abdelmajid E, Friedrich S, Abdelaziz M, Hassan E, Taib A (2013) Moisture content influence on the thermal conductivity and diffusivity of wood–concrete composite. Constr Build Mater 48:104–155

Francesco A, Francesco D, Giorgio B, Francesco B (2014) Evaluating in situ thermal transmittance of green buildings masonries—a case study. Case Stud Constr Mater 1:53–59

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Huijun W, Jing Z, Zhongchang W (2013) Study on micro-structure and durability of fiber concrete. Res J Appl Sci Eng Technol 5(2):659–664

Khedari J, Suttisonk B, Pratinthong N, Hirunlabh J (2001) New lightweight composite construction materials with low thermal conductivity. Cement Concr Compos 23(1):65–70

Khedari J, Watsanasathaporn P, Hirunlabh J (2005) Development of fibre-based soil–cement block with low thermal conductivity. Cement Concr Compos 27(1):111–116

Lagerblad B, Vogt C (2003) Ultrafine particles to save cement and improve concrete properties. Draft report, CBI. Stockholm, Sweden

Luca E, Claudia G, Paola G, Roberto DLV (2015) *In Situ* thermal transmittance measurements for investigating differences between wall models and actual building performance. Sustainability 7:10388–10398. https://doi.org/10.3390/su70810388

Mounika M, Ramaniah K, Ratna Prasad AV, Mohana Rao K, Hema Chandra Reddy K (2012) Thermal conductivity characterization of bamboo fiber reinforced polyester composite. J Mater Environ Sci 3(6):1109–11162

Ramirez RA, Castillo FC, Dominguez VJM, Guzman MO (2012) Thermal conductivity of coconut fibre filled ferrocement sandwich panels. Constr Build Mater 37:425–431

Scott HPE, Nathaniel CEIT (2013) Design and evaluation of thin-shell latex-modified concrete barrel roof units. Research Publication of University of Alaska Anchorage

Taoukil D, Sick F, Mimet A, Ezbakhe H, Ajzoul T (2013) Moisture content influence on the thermal conductivity and diffusivity of wood–concrete composite. Constr Build Mater 48:104–115

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