INVESTIGATIONS ON HYGROTHERMAL PERFORMANCE OF COCONUT COIR CEMENT BOARDS UNDER THAI CLIMATE AS DETERMINED BY FIELD TEST AND SIMULATION

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Abstract

This research presents result on heat and moisture transport in coconut cement boards as determined by field test and simulation. Coconut coir cement boards are composed of cement, sand and coconut coir. Coir had been pretreated by boiling and washing before mixing. Cement: fiber: water mixture ratio by weight was 2: 1: 2. Field heat and moisture performance of coconut coir cement board wall were compared to commercial wall boards. The study was conducted under Bangkok climatic conditions by using two small houses. The dimensions of each were 1.5 m x 1.5 m x 2.1 m. In addition, the performance of the composite was simulated by using a computational tool. The software (WUFI 2D) was used to calculate heat and moisture transfer through coconut coir cement boards. The materials were exposed to a climate condition similar to the one in Bangkok and the hygrothermal characteristics of the materials were investigated.

1. Introduction

Knowledge of natural fiber use in cement composites, mechanisms of mechanical behavior, insulating behavior, etc. has increased substantially. The literature is rich and various textbooks and research papers are already available. Many literatures indicated various advantages in the use of natural fibers in cement composites, along with the following: increased flexural strength, post-crack load bearing capacity, increased impact toughness and improved strength [1]. Natural fibers exhibit many advantageous properties as reinforcement for composites [2]. By far the best advantage of using natural fibers is that they offer significant cost reduction and benefits associated with processing, as compared to synthetic fibers. That's why they are currently getting a lot of attention for replacing synthetic fibers [3].

At the present time, due to simultaneous awareness increase on environment and energy, increasing attention should be focus on natural fibers with a mean to conserving energy and protecting the environment. [4] reported that the addition of natural fiber reduced the thermal conductivity of the composite specimens and yielded a lightweight product. Development of composite materials [5] for buildings using natural fiber such as coconut coir and durian fiber with low thermal conductivity is an interesting alternative, which would solve environment and energy concern.

In Thailand, a large amount of agriculture products are produced annually. On the other hand, Thailand located in the tropical zone produces a huge amount of coconut *(Cocos nucifera)*. It is the most interesting product as it has the lowest thermal conductivity.

In this study, the idea was to use Coconut coir to produce Coconut coir lightweight cement Boards (CCB) with low thermal conductivity. Actually, coir is the name given to the fiber that constitutes the thick mesocarp or husk of the coconut (*Cocos nucifera*). Coir is extracted by beating it manually using a mechanical extractor machine. It is the most interesting raw material for producing CCB as it has the advantage of being abundantly available, renewable, cheap and exhibited good mechanical properties [6]. Research reported in [7] indicated that the composites made with short coconut coir fibers and ordinary Portland cement matrix presented a significant increase in toughness [8].

In this study, field heat and moisture performance of coconut coir cement board wall were compared to commercial wall boards. The study was conducted under Bangkok climatic conditions by using two small houses. The dimensions of each were 1.5 m x 1.5 m x 2.1 m. In addition, the performance of the composite was simulated by using a computational tool. The software (WUFI 2D) was used to calculate heat and moisture transfer through coconut coir cement boards. The materials were exposed to a climate condition similar to the one in Bangkok and the hygrothermal characteristics of the materials were investigated.

2 Raw Materials [9]

Comparison of the physical, mechanical and thermal properties of the manufactured CCBs to the commercial boards is shown in Table 1. It can be seen that the properties of the prepared coconut coir cement boards were within the range of properties of commercialized boards. Coconut coir fiber based cement boards have the advantage of being light in weight and possess good thermal insulation property. These are very interesting advantages which would help to develop market penetration.

The purpose of this study is to investigate the field performance of our coconut coir-based lightweight cement board walls (CCB walls) and compare their performance to commercial flake board walls.

Two small houses were built by using two different wall materials. The first house used commercial flake board available in the local market whereas the second house used our CCB. The well-insulated roofs were built with autoclave aerated concrete block without ceiling. Each house had a volume of about 7 m^3. The dimensions of each were 1.5 m x 1.5 m x 2.1 as schematically shown in Fig.1. The walls of houses were built without paint in both internal and external wall sides. The inclination of the roof was 30 ° to the horizontal plane. The spaces between all boards, structure roof and windows (Not openable) were well sealed using silicone to prevent from moisture penetration.

Table 1 Comparison of the physical, mechanical and thermal properties of tested cement boards to commercial board [9]

Properties	Board Type	
	Coconut coir cement board	Commercial flake board (Viva board)
Density (kg/m^3)	1,040	1,400
MC (%)	9.13	9.50
TS (%)	3.64	10.55
WA (%)	19.63	10.02
IB (MPa)	0.73	0.59
MOR (MPa)	19.94	11.80
MOE (MPa)	5,315	5,996
Thermal conductivity (W/m K)	0.40	0.36

*C:CF:W = 2:1:2, 1-6 cm, boiled and washed coir
Note: C= Cement, CF = Coconut coir fiber TS = Thickness swelling, WA = Water absorption, MOR = Modulus of rupture, MOE = Modulus of elasticity, IB = Internal bond

Part I Field test

3 Experimental method and instrument

Fig. 1 shows the measuring points and dimensions of the test houses. Type K thermocouples were used to measure the temperature at middle, inner and outer surfaces of east and west walls of commercial wall and CCB wall (Points, T_{o1}, T_{i1}, T_{o2}, T_{i2}), the error of those is ± 0.5 ºC. Five testo-loggers (Model, Testo 175-H_2) were used to measure the temperature and humidity at the attic and middle room of these walls and ambient (Point, Tr_1, RHr_1, Tr_2, RHr_2). Three Hioki-loggers (Model, 3641-20) were used to measure the interior temperature and humidity in these walls at a depth of 4 mm (Points, Twi_1, $RHwi_1$, Twi_2, $RHwi_2$). Data were collected on hourly basis from 25 February 2006 to 12 May 2006.:

The moisture content (W) was calculated from the experimental data by using psychromatric property equation [Devers, 1994], given by

$$W = 0.62198 (p_w/P-p_w) \qquad (1)$$

Where p_w is partial pressure of water in humid measured relative humidity (Φ), the partial pressure of water vapor can be calculated from equation below

$$P_w = \Phi . p_{ws} \qquad (2)$$

Where Φ is relative humidity and p_{ws} is pressure of saturated pure water which could be calculated from equation below air and P is atmospheric pressure. Using the

$$p_{ws} = 1000.\exp(\alpha) \qquad (3)$$

with

$$\alpha = A.T^2 + B.T + C + D.T^{-1} \qquad (4)$$

Where T is the dry bulb temperature of air and A, B, C and D are constant values.

A = $+ 0.1255001965 \times 10^{-4}$
B = $- 0.1923595289 \times 10^{-1}$
C = $+ 0.2705101899 \times 10^{+2}$
D = $- 0.6344011577 \times 10^{+4}$

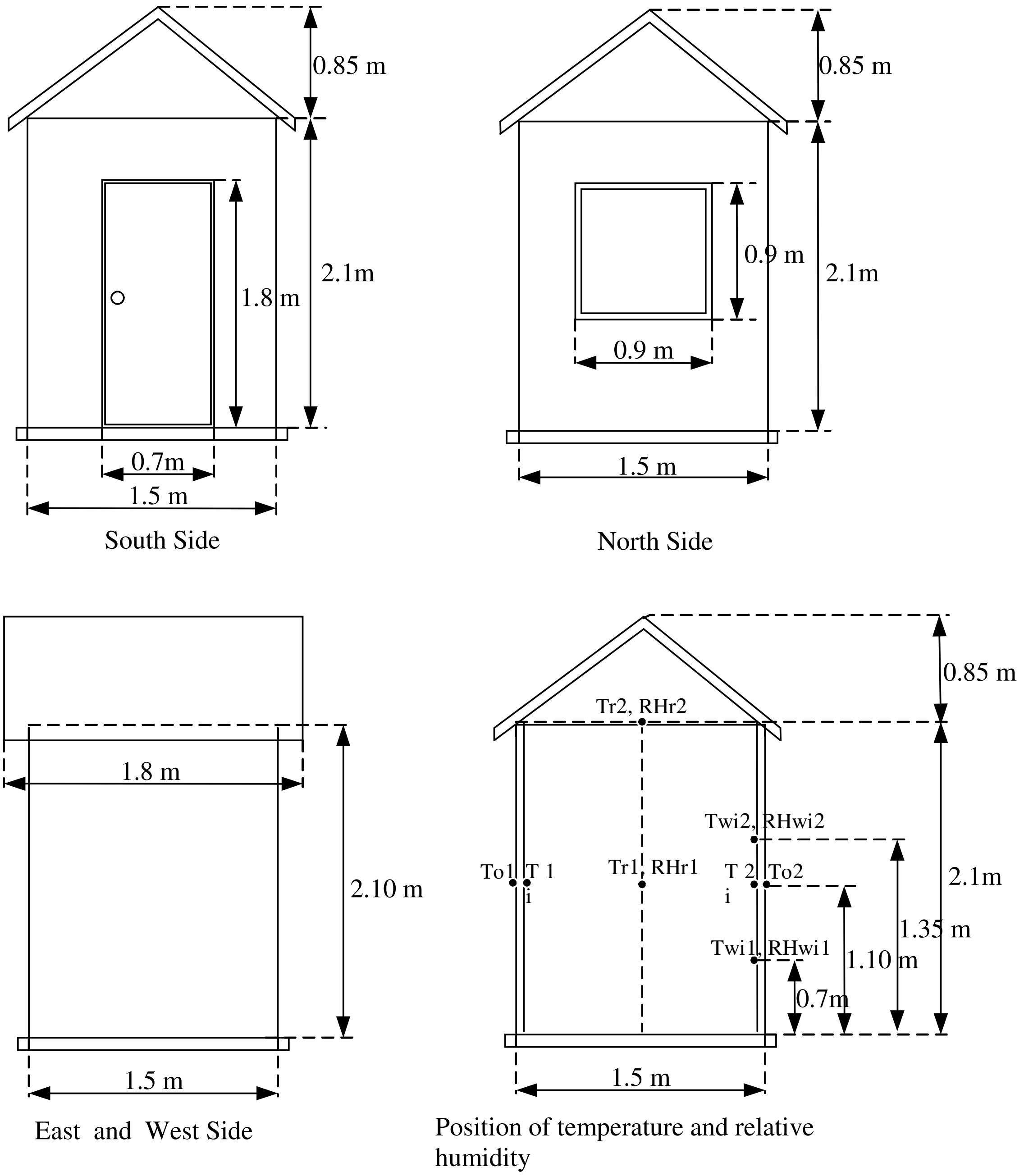

Fig. 1 Dimensions of the test houses and positions of temperature and relative humidity measurement[9]

3.1 Experimental Results

In this section, data collected during the field testing through various representative days (26-29 April 2006) are presented and discussed. As a result, Thailand located in the tropical zone and April is the hottest month in the year. They concern temperature of air and wall at different positions and moisture content at different positions of the two houses (Commercial flake board house and CCB house).

3.3.1 Temperature profiles [9]

Fig. 2 and Fig. 3 show the hourly variations of measured temperatures at different positions in commercial flake board house and CCB (26-29 April 2006) respectively. The explanation of symbols used is given are as follows

Ti3 = Temperature : Hourly variation of temperature at different position of commercial flake board house at the middle of inner west surface of CCB house

To4 = Temperature at middle of outer east surface of CCB house

Ti4 = Temperature at the middle of inner east surface of CCB house

Tr3 = Temperature at the middle room of CCB house

It can be observed that at each surface and level temperatures were nearly close which is due to the small thickness of wall materials (0.8 cm). Obviously east wall temperatures are higher in the morning than those at the west facade. In addition as expected no significant differences are observed between the two houses. In fact the CCB and commercial flake boards have close mechanical and thermal properties. That explained why the measured temperatures of CCB and commercial flake board houses were practically the same.

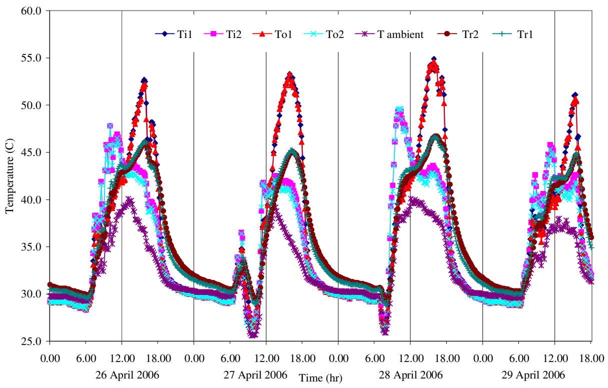

Fig. 2 Hourly variation of temperature at different position of commercial flake board house

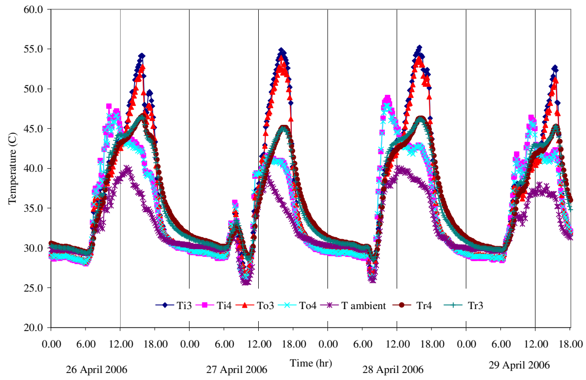

Fig. 3 Hourly variation of temperature at different position of CCB house

Comparison between the hourly variation of measured temperatures at the middle of inner and outer west surfaces of commercial flake board house and CCB houses are shown in Fig 4. As seen in the figures measured temperatures at the different positions are the same as a result of the board's close physical and mechanical properties. A slightly higher temperature of the inner west surface of was observed due to the relatively higher CCB thermal conductivity compared to that of commercial flake board, (Table 1)

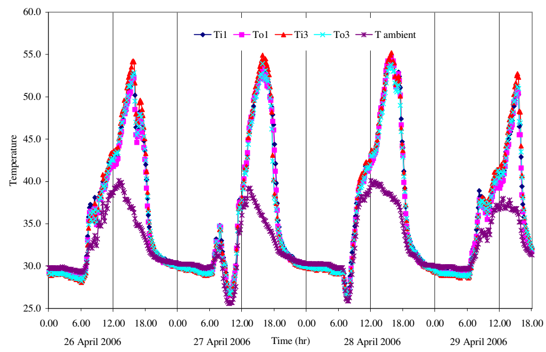

Fig. 4 Comparison of hourly variation of measured temperature at middle of inner and outer west surface of commercial flake board and CCB houses (26-29 April 2006)

Fig. 5 show comparison of hourly variation of measured temperature at the middle of inner and outer east surface of commercial flake board house and CCB house at the various time periods. It can be seen that (Fig. 5), the temperature at the middle of inner east surface of CCB house is higher than that at the same position of commercial flake board house, which is also due to the higher thermal conductivity of CCB.

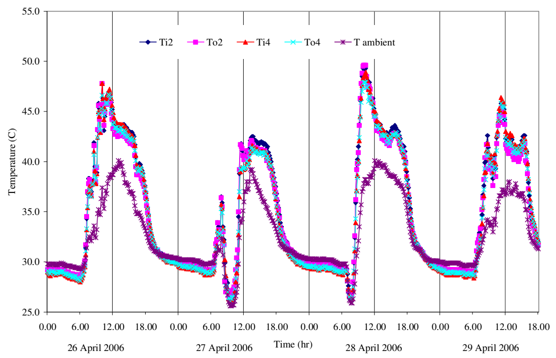

Fig. 5 Comparison of hourly variation of measured temperature at middle of inner and outer east surface of commercial flake board and CCB houses (26-29 April 2006)

The attic and room temperatures of viva house are compared to those of CCB house in Fig. 6. It can be seen that no significant differences are observed due to the explanation given earlier; i.e., thin walls and close boards properties. Therefore, it can be concluded that our CCBs will perform in the same way as that of commercial board. Consequently, they can be used to construct houses and buildings.

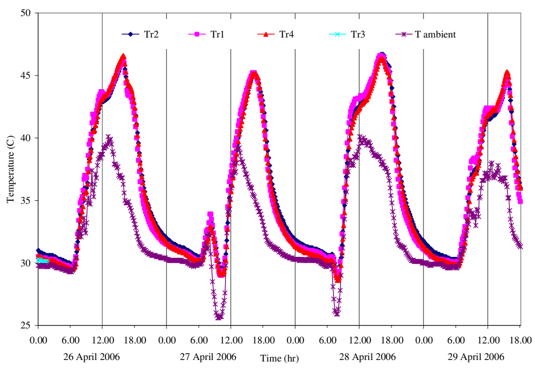

Fig. 6 Comparison of hourly variation of attic and room temperatures of commercial flake board and CCB houses (26-29 April 2006)

Fig. 7 and 8 show comparison of hourly variation of temperatures measured at middle of inner and outer east surface and at a 4 mm depth at low and high positions of the commercial flake board and CCB boards. Here too similar profiles are obtained. In addition, due to thermal stratifications, higher temperatures are observed at the higher level.

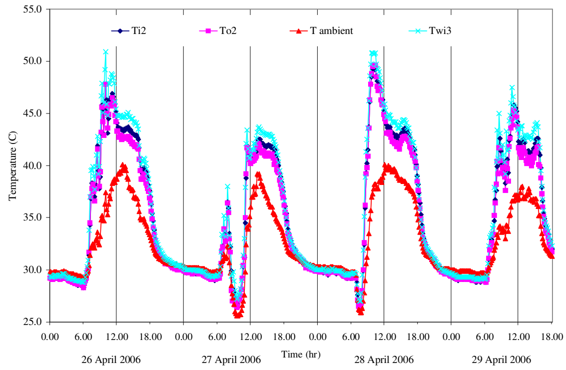

Fig. 7 Comparison of hourly variation of measured temperature at middle of inner and outer east surface and at 4 mm. depth of commercial flake board house, high position (26-29 April 2006)

The measured temperature at 4 mm depth of east wall of commercial flake board and CCB houses, at both low and high positions are compared in Fig. 9. It can be seen that the temperature profiles of commercial flake board and CCB boards were relatively similar that confirmed that the measured the physical and mechanical properties of boards and the accuracy of our results.

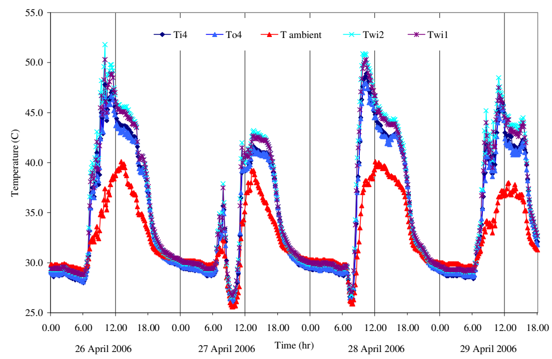

Fig. 8 Comparison of hourly variation of measured temperature at middle of inner and outer east surface and at 4 mm. depth of CCB house, low and high position (26-29 April 2006)

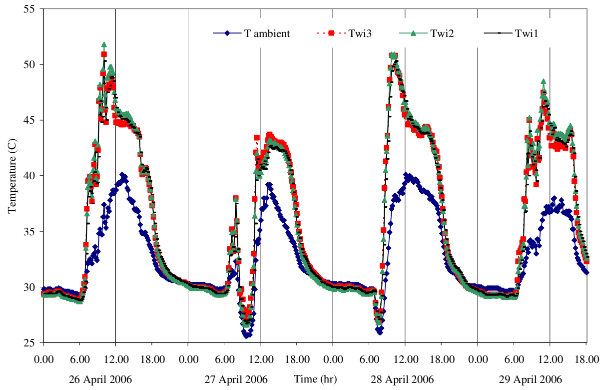

Fig. 9 Comparison of hourly variation of measured temperature at 4 mm. depth of east wall of commercial flake board and CCB house at low and high position (26-29 April 2006)

3.3..2 Moisture content ratio

The hourly variation of moisture content (ratio) of attic, middle room and at 4 mm depth of east wall of commercial flake board house measured at the high position at various times are shown in Fig. 10. As seen in the Fig., the moisture content at 4 mm depth of east wall of commercial flake board house is the highest during daytime and the lowest at night. These variations are caused by the incident solar radiation on the wall panel in the morning. That heat up the wall leading to natural evaporation of the water contained in the wall material. In the afternoon, the measured moisture content decreased rapidly as no more solar radiation received by the east wall. After sunset and till sunrise the moisture content is noticeably constant as wall temperature remained low with no heat migration. The moisture content of the attic and middle room of commercial flake board are almost the same as there is no ceiling.

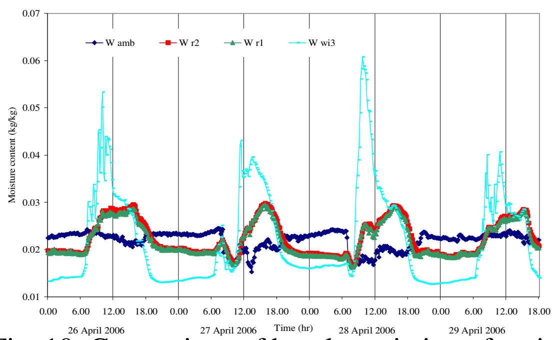

Fig. 10: Comparison of hourly variation of moisture content of attic, middle room and at 4 mm depth of commercial flake board house east wall measured at the high position (26-29 April 2006)

Fig. 11 show the same variations for the house with CCB. The same observations made for the commercial flake board house is still valid. In addition, it can be observed that the moisture content at 4 mm depth of east wall, high position, is higher than that at the low position. This is due to the thermal stratification and the associated heat and moisture transfers occurring at each position.

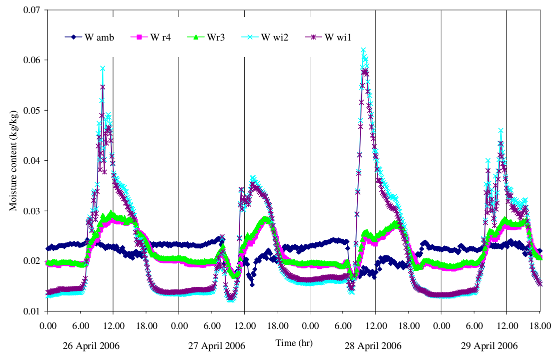

Fig. 11**:** Comparison of hourly variation of moisture content of attic, middle room and at 4 mm depth of CCB house east wall measured at the low and high positions (26-29 April 2006)

A comparison between the hourly variation of moisture content of attic of commercial flake board and CCB houses is shown in Fig. 12. It can be seen that the moisture content of commercial flake board and CCB house are quite similar. The significant differences are observed in the afternoon. This can be attributed to the effect of incident solar radiation that enhances daily heat and moisture transfers leading to high indoor moisture ratio.

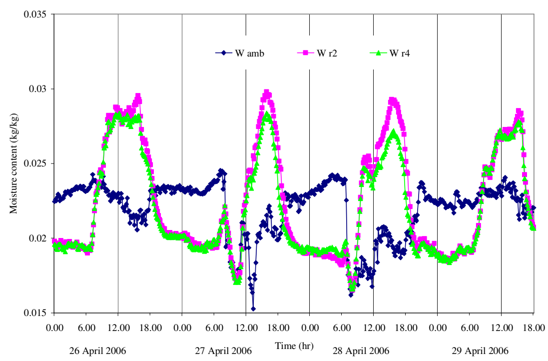

Fig.12Comparison of hourly variation of moisture content of attic commercial flake board and CCB house (26-29 April 2006)

Figure 13 show comparison of hourly variation of moisture content at the middle room of commercial flake board and CCB houses. It can be seen that moisture at the middle room of commercial flake board is close to that of CCB house. The observed difference is probably due to a variety of reasons such house position, driving rain/ wind, rain exposition etc. Despite this, it can be confirmed that the accuracy of measurement, which indicated that the physical and mechanical properties of commercial flake board and CCB were closely. Therefore, field measurement of indoor conditions showed similar profiles.

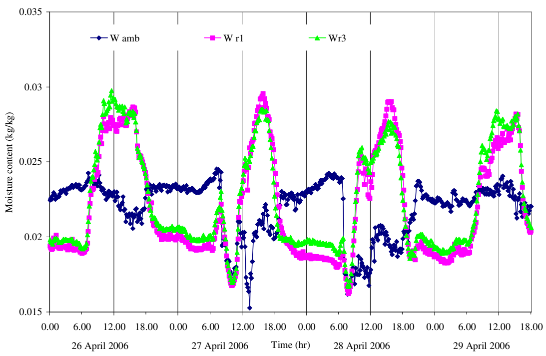

Fig.13 Comparison of hourly variation of moisture content of middle room commercial flake board and CCB house (26-29 April 2006)

The measured hourly variation of moisture content at 4 mm depth of east wall of commercial flake board house (high position) and CCB house (low and high position) are shown in Fig. 14. The profiles are practically not different. During 27 April 2005, the moisture at the high position of commercial flake board wall is higher than that at the high position of CCB house. In fact, there was raining during these days; therefore, moisture has accumulated on commercial flake board wall.

Field heat and moisture performance of our CCBs wall were compared to commercial wall boards. The study was conducted under Bangkok climatic conditions using two small houses. The dimensions of each were 1.5 m x 1.5 m x 2.1 m. Houses were built without any paint at both internal and external wall surfaces. The well-insulated roof was built with autoclave aerated concrete block without ceiling. The inclination of the roof was 30° to the horizontal plane. Tests were conducted with closed windows and doors. Experimental observation demonstrated that measured temperature profiles were comparable but humidity profiles were different among the two houses. The CCB wall had higher moisture level than the commercial wall. This difference is less important during normal weather condition. Whereas under high humid condition (rain), tests indicated good moisture prevention was observed at the commercial house. This is most probably due to the manufacturing process as our CCBs are laboratory manufactured. Regarding heat gain reduction into building, the two commercial and CCB walls performed quite similarly as indoor temperature was relatively comparable

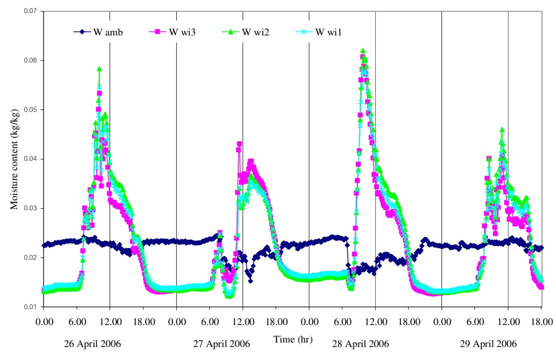

Fig.14 Comparison of hourly variation of moisture content at 4 mm depth of commercial flake board east wall of (high position) and CCB wall (low and high positions (26-29 April 2006)

Part II Simulation

In this part, heat and moisture transport in the coconut coir fiber based lightweight construction materials was simulated by a commercial software

(WUFI 2D) program and the results were presented. The simulated temperature and water content of the composite were compared to those of a common local material. As it will be seen, results so far achieved were very encouraging and necessitate further systematic research in predicting performance and durability of the composite material.

4.1 Hygrothermal simulation tool (WUFI)

As mentioned in the introduction, the research hygrothermal software (WUFI 2D) was used to calculate coupled heat and moisture transfer through composites. WUFI® (Wärme und Feuchte instationär) is a menu-driven PC program which allows realistic calculation of the transient-coupled two dimensional heat and moisture transport in multi-layer building components exposed to natural weather (www. wufi.de, Künzel, 1995). In addition, it can use weather data --including driving rain and solar radiation-- as boundary conditions, thus allowing realistic investigations on the behavior of the component under exposure to natural weather.

It requires only properties of standard material and easy-to-determine moisture storage and liquid transport functions. The program can be used for assessing the danger of interstitial condensation or the influence of driving rain on exterior building components. It can help to analyze the effect of repair and retrofit measures or the hygrothermal performance of wall assemblies under unanticipated use or in different climate zones.

4.2 Determination of material properties

The minimum material properties required for the simulation are Bulk density, Porosity, Heat, Heat conductivity (dry) and Diffusion resistance factor (dry).

The measured properties of CCBs and Viva boards are listed here after:

- Measured properties of coconut coir fiber based lightweight cement board

Bulk density [kg/m^3] 1040
ASTM C 134-94

Porosity [m^3/m^3] 0.19
ASTM C20-00

Heat capacity [J/kg K] 1309.30
ASTME1296-01

Heat conductivity [W/m K] 0.40
JIS R 2618

Diffusion resistance factor dry [-] 31.16
ASTM E 96-00

- Measured properties of viva cement board material

Bulk density [kg/m^3] 1400
ASTM C 134-94

Porosity [m^3/m^3] 0.129
ASTM C20-00

Heat capacity [J/kg K] 1367.60
ASTME1296-01

Heat conductivity [W/m K] 0.36
JIS R 2618

Diffusion resistance factor [-] 21.83
ASTM E 96-00

4.3 The geometry and composition of the building component

The dimensions of the coconut coir cement board and viva cement board samples are 0.8 x 30 x 30 cm^3. The monitor positions of material are as follow;

Monitor 1 at the board's surface closes to indoor climate

Monitor 2 at the board's middle point in the sample (4mm depth)

Monitor 3 at the board's surface closes to outdoor climate (8 mm depth)

WUFI 2D was designed to calculate the behavior of building components exposed to the weather. It is natural to describe the conditions of the surrounding air in terms of meteorological parameters such as temperature, relative humidity, solar radiation and driving rain. Hourly weather data used in the analysis are based on climate conditions in Bangkok weather, using a Typical Meteorological Year (TMY). Data of TMY are averaged from a period of 10 years (1990 – 1999). Fig. 16 to Fig. 19 showed typical hourly weather data in Bangkok as temperature, relative humidity, solar radiation and driving rain, respectively.

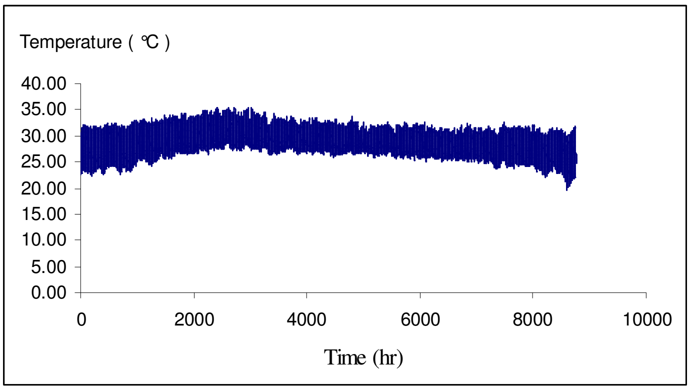

Fig. 16 Hourly outdoor air temperature variations at Bangkok, Thailand [10]

4.4 Indoor climate

Thermal comfort of room condition for Thai people is 26 °C for temperature and a relative humidity of 60 % [10]. Those conditions are used as input data for indoor climate in WUFI 2D.

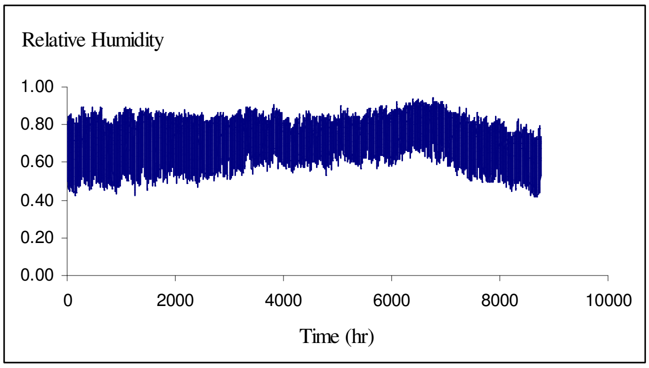

Fig. 17 Hourly outdoor relative humidity variations in Bangkok, Thailand [10]

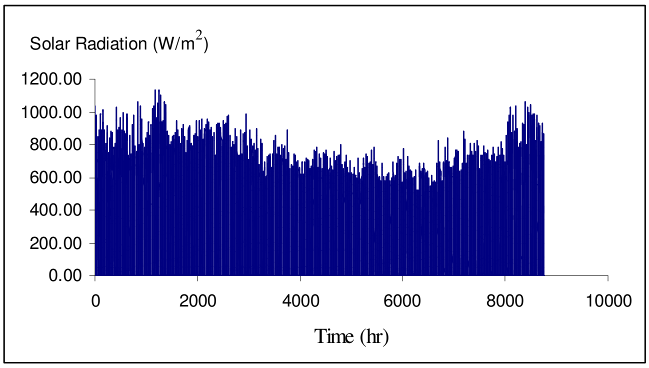

Fig. 18 Hourly solar radiation variations at Bangkok, Thailand [10]

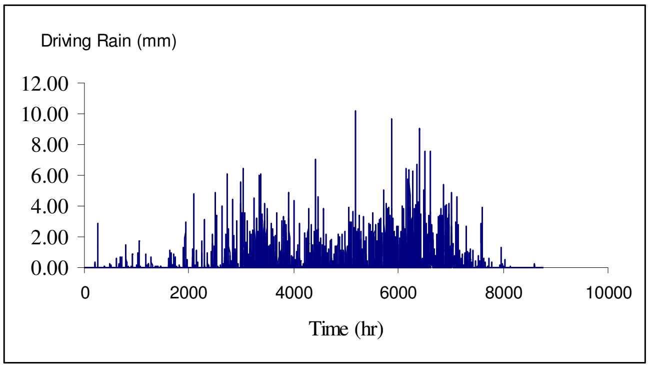

Fig. 19 Hourly driving rain variations at Bangkok, Thailand [10]

4.5 Boundary conditions

The heat and moisture exchange between a building component and its surroundings can be described by means of various boundary conditions. In WUFI 2D program, boundary conditions were divided into two parts; climate and surface transfer. Calculation of heat and moisture transfer through the material was simulated using the climate pattern of Bangkok, Thailand. Outdoor surface transfer conditions are as follows; total heat transfer coefficient of 17 W/m^2 K, short wave solar radiation absorptivity of 0.40, long wave radiation emissivity of 0.90 and water vapor transfer of 75 x 10^{-9} kg/m^{2}s Pa. For indoor surface transfer conditions, they are as follows; total heat transfer coefficient of 8 W/m^2 K and water vapor transfer of 25 x 10^{-9} kg/m^{2}s Pa.

4.6 Effect of temperature on composites

Fig. 20 displays the mean weekly variation of temperature in the coconut coir composite material. It can be observed that it does not exceed 30 °C. Normally, the temperature will affect the property of natural fiber based construction material when a temperature of about 75 °C or above is reached. Thus as the simulated temperature in the coconut coir fiber cement board construction material is not high; it is reasonable to conclude that, the long term durability of the composite is quite well. When compared to simulated weekly mean temperature profiles through viva board shown in Fig. 21, no significant difference at all.

Fig. 20 Weekly mean temperature variation at different positions of coconut coir fiber based construction material.

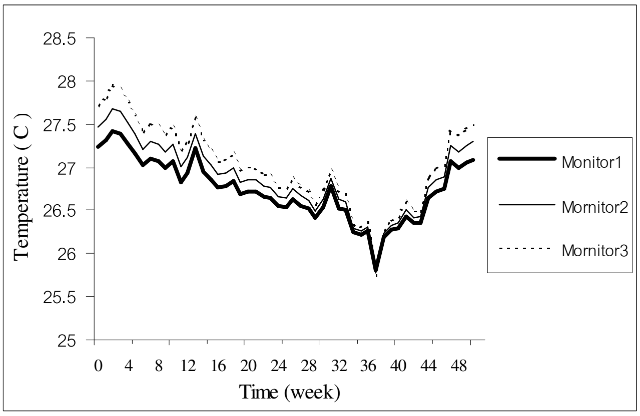

Fig. 21 Weekly mean temperature variation at different positions of viva cement board material

This demonstrated that our boards could be commercialized like another new product.

4.7 Effect of water content on composites

The water content in composites is shown in Fig. 22 and Fig. 23 for the CCBs and Viva boards respectively. Here too, it can be observed that the water content of coconut coir board is nearly close to that of the viva cement board. Therefore, our boards could be used in buildings, in the same way like any commercial product. The average calculated relative humidity of boards does not exceed 70 %. Therefore the chance of having mold growth is lower than 5%. In fact mold can grow only if the mean monthly relative humidity on the surface remains higher than 80% [10]

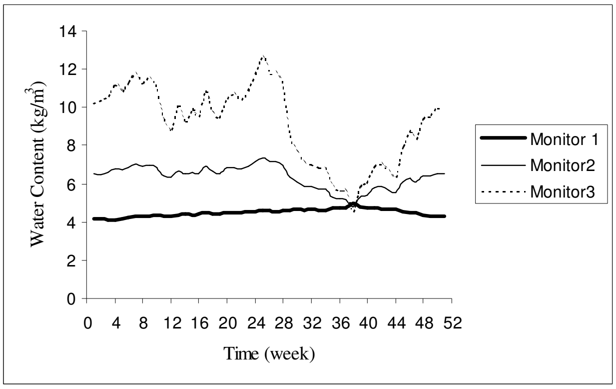

Fig. 22 Water content in coconut coir fiber cement board construction material

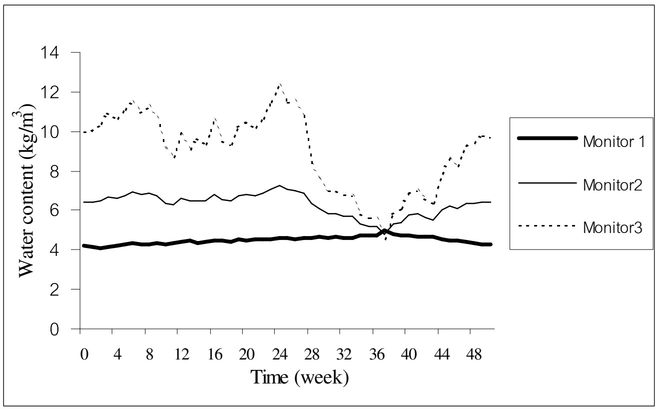

Fig. 23 Water content in viva cement board construction material

The results of field test and simulation are as similar. It confirmed that the manufactured composite satisfied the requirement of construction materials.

5 Acknowledgements

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