DEVELOPMENT OF SUSTAINABLE MATERIAL FOR HYBRID WALL SYSTEM TO IMPROVE INDOOR THERMAL PERFORMANCE

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To my lovely mother and amazing father. I couldn’t have done this without you. I believe that this achievement will complete your dream that you had for me all these many years ago when you chose to give me the best education you could.
ACKNOWLEDGEMENT

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ABSTRACT

Thermal performance of building envelope has been of great importance in determining the indoor thermal environment mainly due to the impact of existing global warming issues. Due to the hot and humid climate of Malaysia, and poor thermal design of building envelope, mechanical cooling of buildings is becoming almost a necessity. This necessity in the case of low-income home owners is an added burden. Thus there is a need to provide wall system with better thermal performance than conventional wall systems. Due to the emphasis on developing sustainable built environments, researchers are striving for waste incorporation in building wall material. However, the waste incorporated within the building wall system, especially in bricks still lacks practical applicability when it comes to the overall performance of the system in terms of mechanical, thermal and physical properties. The focus of the research is to tackle the twin issues of sustainability and thermal performance of building wall systems for affordable homes using a Design Science methodology. A cost-effective sustainable alternative building wall system with better thermal performance than conventional material is proposed by utilizing locally available waste materials such as waste glass and oil palm industry byproducts. The enhancement of thermal performance of wall materials was done by the introduction of cellular porous palm oil fibers to lower the heat transfer. Fiber reinforced mortar (FRM) and thermally enhanced sustainable hybrid (TESH) bricks were developed by optimizing the mix design using Glass Powder, Palm Oil Fly Ash and Oil Palm Fibers based on Taguchi’s Process Parameter approach. Both the FRM and TESH bricks, which constitute the thermally enhanced sustainable hybrid (TESH) wall system, were analyzed for physical, mechanical and thermal performance and they comply with the various codes of practice for building materials. ANSYS WORKBENCH software was used to determine the thermal performance of the newly developed TESH. The temperature distribution and rate of heat transfer through the wall system was found to be significantly lower than conventional wall systems. Also, comparative energy analysis established that the energy consumption is 10.6% lower for TESH. Due to the lower electricity consumption, the total energy costing for the building
was also reduced by 10.2%. Thus, TESH proves to be more sustainable and cost effective within the operational phase of the building. TESH is a sustainable alternative for low-cost housing units due to its proven low embodied energy as it comprises mainly of locally available waste materials for its production.
ABSTRAK

mengurangkan suhu ruang dalam rumah berbanding sistem dinding biasa dan terbukti adalah lebih mampu berdasarkan analisis yang dilakukan pada fasa operasi bangunan. Tenaga yang digunakan oleh sistem dinding TESH adalah 10.6% lebih rendah dan kos tenaga kurang sebanyak 10.2%; maka ia terbukti boleh menjadi alternatif yang mampu untuk mencapai keselesaan terma untuk unit rumah kos rendah secara lebih berkos efektif.
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<tr>
<td>Al₂O₃</td>
<td>Aluminium oxide</td>
</tr>
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<td>ANOVA</td>
<td>Analysis of variance</td>
</tr>
<tr>
<td>ASHRAE</td>
<td>American Society of Heating, Refrigerating and</td>
</tr>
<tr>
<td></td>
<td>Air-Conditioning Engineers</td>
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<tr>
<td>BEM</td>
<td>Boundary element method</td>
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<td>CaCO₃</td>
<td>Calcium Carbonate (Calcite)</td>
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<td>CaO</td>
<td>Calcium Oxide</td>
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<tr>
<td>CAS</td>
<td>Calcium alumina silicates</td>
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<tr>
<td>C-A-S-H</td>
<td>Calcium alumino silicate hydrate</td>
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<td>Cl</td>
<td>Chlorine</td>
</tr>
<tr>
<td>CO₂</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CO₂e</td>
<td>Carbon dioxide equivalent</td>
</tr>
<tr>
<td>Cp</td>
<td>Heat Capacity (J/g.°C)</td>
</tr>
<tr>
<td>Cₚw</td>
<td>Heat capacity of water (J/g.°C)</td>
</tr>
<tr>
<td>Cr₂O₃</td>
<td>Chromium oxide</td>
</tr>
<tr>
<td>C-S-H</td>
<td>Calcium silicate hydrate</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Scientific and Industrial Research Organization</td>
</tr>
<tr>
<td>D</td>
<td>Diameter (m)</td>
</tr>
<tr>
<td>DOF</td>
<td>Degree of Freedom</td>
</tr>
<tr>
<td>DSR</td>
<td>Design Science Research</td>
</tr>
<tr>
<td>e</td>
<td>Thermal Effusivity (WK⁻¹m² s¹/²)</td>
</tr>
<tr>
<td>EE</td>
<td>Embodied energy</td>
</tr>
<tr>
<td>EFB</td>
<td>Empty fruit brunch</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>FDM</td>
<td>Finite difference method</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>Iron oxide or Ferric oxide</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite element analysis</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
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</table>


<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>FRM</td>
<td>Fibre reinforced mortar</td>
</tr>
<tr>
<td>GBS</td>
<td>Green building studio</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse gas</td>
</tr>
<tr>
<td>GP</td>
<td>Glass Powder</td>
</tr>
<tr>
<td>HVAC</td>
<td>Heating Ventilation and Air Conditioning</td>
</tr>
<tr>
<td>IAQ</td>
<td>Indoor Air Quality</td>
</tr>
<tr>
<td>IEA</td>
<td>International Energy Agency</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>IRA</td>
<td>Initial rate of absorption</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>Potassium oxide</td>
</tr>
<tr>
<td>k-value</td>
<td>Thermal Conductivity (W/m.K)</td>
</tr>
<tr>
<td>L</td>
<td>Length (m)</td>
</tr>
<tr>
<td>LCH</td>
<td>Low Cost Housing</td>
</tr>
<tr>
<td>LCTH</td>
<td>Low Cost Terrace Housing</td>
</tr>
<tr>
<td>LOI</td>
<td>Loss of Ignition</td>
</tr>
<tr>
<td>M</td>
<td>Rate of flow of water (kg/s)</td>
</tr>
<tr>
<td>MgO</td>
<td>Magnesium oxide</td>
</tr>
<tr>
<td>Mn$_2$O$_3$</td>
<td>Magnesium oxide</td>
</tr>
<tr>
<td>MSW</td>
<td>Municipal solid waste</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>Sodium oxide</td>
</tr>
<tr>
<td>NaOH</td>
<td>Sodium hydroxide</td>
</tr>
<tr>
<td>OPC</td>
<td>Ordinary Portland Cement</td>
</tr>
<tr>
<td>OPF</td>
<td>Oil Palm Fibers</td>
</tr>
<tr>
<td>OPS</td>
<td>Oil palm shell</td>
</tr>
<tr>
<td>P$_2$O$_5$</td>
<td>Phosphorous pentoxide</td>
</tr>
<tr>
<td>POFA</td>
<td>Palm oil fly ash</td>
</tr>
<tr>
<td>q</td>
<td>Amount of heat transfer per unit area</td>
</tr>
<tr>
<td>Q</td>
<td>Amount of heat transfer</td>
</tr>
<tr>
<td>R-Value</td>
<td>Thermal Resistance</td>
</tr>
<tr>
<td>S/N</td>
<td>Signal to noise ratio</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscopy</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Bulk Density (kg/m$^3$)</td>
</tr>
<tr>
<td>SHGC</td>
<td>Solar Heat Gain Coefficient</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>Silicon dioxide (Silica)</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------</td>
</tr>
<tr>
<td>SO$_3$</td>
<td>Sulphur trioxide</td>
</tr>
<tr>
<td>SrO</td>
<td>Strontium oxide</td>
</tr>
<tr>
<td>SS</td>
<td>Sum of square</td>
</tr>
<tr>
<td>$T_{1-6}$</td>
<td>Temperature reading by sensors 1-6</td>
</tr>
<tr>
<td>TESH</td>
<td>Thermally Enhanced Sustainable Hybrid</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>Titanium dioxide</td>
</tr>
<tr>
<td>UTHM</td>
<td>Universiti Tun Hussein Onn Malaysia</td>
</tr>
<tr>
<td>U-value</td>
<td>Thermal transmittance</td>
</tr>
<tr>
<td>V</td>
<td>Variance</td>
</tr>
<tr>
<td>XRD</td>
<td>X-ray Diffraction</td>
</tr>
<tr>
<td>XRF</td>
<td>X-ray Fluorescence</td>
</tr>
<tr>
<td>ZnO</td>
<td>Zinc oxide</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Thermal Diffusivity (m$^2$/s)</td>
</tr>
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1.1 Research Background

In designing comfortable room conditions, there are various factors that need to be kept in mind. The factors that affect the indoor thermal quality include radiant temperature, humidity, air movement, air temperatures, and human physiological aspects like body metabolic rate, level of activity and clothing of the occupants which affect the microclimatic condition within the indoor environment. A good indoor thermal condition is essential for providing comfortable (primarily without heat stress or thermal strain for the occupants) and healthy environmental conditions to sustain occupants’ living quality. It is important to distinguish between thermal condition of the indoor environment, which refers to the indoor air temperature and thermal comfort which is a broader physiological state.

The optimal temperature of human body temperature based on human physiological needs is at 37±0.5°C (97.7–99.5 °F), regardless of environmental conditions. Thus, it is important to maintain the indoor temperature conditions in buildings that meet the thermal comfort levels for better human productivity and performance. Department of Standards Malaysia (2007) provides a guideline for standard indoor environment design for Malaysian climatic conditions which recommends the indoor temperature levels to be in the range of 23 – 26 °C. The indoor thermal environmental condition is very much affected by local climate, and air movement through the buildings is necessary to decrease indoor discomfort due to overheating conditions in tropical climatic conditions (Rajapaksha et al., 2002). To be more specific, environmental factors such as air temperature, air movement,
humidity and radiation influence the indoor thermal environment. It is noted by Kubota and Ahmad (2006) that in warm and humid climates, external air movement assists in controlling the indoor environment. In recent years, researchers have put much emphasis on the rising concerns over low indoor thermal conditions of the indoor air space. The indoor thermal conditions can adversely affect the well-being of people as they generally tend to spend more than 70 - 90 % of their time indoors (Sharpe, 2004; Triantafyllou et al., 2008).

In this modern era, occupants tend to use air conditioning systems for achieving better indoor thermal conditions, especially in tropical climatic conditions. One of the main drawbacks of dependency on a mechanical system to maintain suitable indoor thermal conditions is an increase in the energy consumption in residential buildings (Uno et al., 2012). It is noted by Bostancioglu and Telatar (2013) that the building sector consumes the largest amount of energy during the utilization phase of the building for heating and cooling purposes. Thus, it is important to design the building in such a way that the consumption of energy during the operational stage of the building can be kept at a minimal level (Jamaludin et al., 2014).

Commercial buildings and several residential buildings in the hot-humid climate are often equipped with air conditioning and mechanical ventilation systems to sustain and enhance indoor thermal conditions. Besides this being an unsustainable option, due to their financial limitations low cost house owners are overly burdened in having to use the artificial means of HVAC. Thus, alternative solutions that can provide the occupants of low cost houses with cost-effective options to manage indoor thermal environment without burdening them with costly technologies or building designs is an important consideration, and also can be a more sustainable one.

In Malaysia as in other developing countries, the migration of residents, rapid industrialization, and economic growth is one of the main reasons behind the increase in high demand for housing and infrastructure projects. The construction industry in Malaysia grew by 8.1 % year on year basis to record RM 32.6 billion in the fourth quarter of the year 2016 (Department of Statistics Malaysia, 2017). The Malaysian government together with the private sector has been funding a big portion of the infrastructure construction and many housing schemes. However, notably the housing projects financed by the government that aim to cater for the
lower income sector has some major drawbacks e.g. building technical failures, safety and quality issues (Husin et. al., 2011), poor thermal design (Tinker et. al., 2004). The affordable housing, primarily that of low-cost houses (sometimes referred to as low-income housing) as designed and built before 2017, have been found to be lacking in the provision of the basic level of thermal comfort for the occupants. Previous studies by Ibrahim (2014) have indicated that the thermal design of low-income housing is rather ineffective, resulting in the majority of the occupants not being satisfied with the thermal comfort levels provided. It is noted by Tinker et al. (2004), that the inappropriate design for maintaining thermal comfort is responsible for overheating of the indoor environment during the day time. The extent to which this phenomenon is evident and reported in Malaysia is regarding the estimation made by a local Non-governmental Organization in the year 2000 that two million houses may overheat (Tinker et. al., 2004) and that the occupants prefer to spend their time outside the house during the day rather than inside.

There has been various research conducted within the past decade on indoor environment of residential houses in Malaysia. Malaysia has humid tropical climatic conditions, where urban houses are found to overheat by about 3°C throughout the day (Davis et al., 2000). Based on the research done by Wahab & Ismail (2012), high indoor temperature is attributed to the hot and humid air mostly trapped indoors causing discomfort to the occupants. Generally, the thermal condition within the indoor spaces worsens when there is no active air movement. Within the compact layout of urban houses nowadays, even the 10% opening size with respect to the floor area requirement under the Malaysian Uniform Building By Law 1984 Part III does not seem to help much. In warm humid climate, the predominance of high humidity necessitates steady, continuous air movement over the body to increase the efficiency of sweat evaporation and to avoid any discomfort caused by moisture forming on the skin and clothes (Ibrahim et al., 2014). Additionally, much research (Al-Hammad et al. 1993, Budaiwi et al., 2002, Saleh, 2006) has also been undertaken to improve wall insulation of buildings as the wall is one of the primary areas through which heat is transferred (conducted) from external to internal and vice versa.

In Hong Kong, research shows that architects and designers have to vary the building height in order to maximize the ventilation. However, despite all the research being undertaken and improvements in building technology, Al-Obaidi et
al. (2014) notes that about 75% of Malaysians depend on the mechanical cooling systems to maintain suitable indoor temperatures. Thus, in the residential buildings, occupants tend to consume more energy to power the mechanical cooling system, which would increase as an added expense for operation and maintenance. The excessive demand for energy consumption arises because of emphasis on modern comfort standards, social customs, and design practices, which has made mechanical cooling one of the important factors in daily life (Abdul Rahman et al., 2013).

1.2 Indoor Thermal Environment for Malaysian Climate

Malaysia is a tropical country located within the Equatorial Zone and therefore its climatic conditions are stable, normally temperature ranges within 27°C and 32°C during the day and 21°C and 27°C during the night (Jabatan Meteorologi Malaysia, 2016). The mean monthly temperature data map of Malaysia is shown in Figure 1.1. Climatic conditions are such that this region encounters large variations in rainfall according to the season; and the relative humidity is high throughout the year at about 75%. The wind has a low but variable speed, predominantly from southerly direction. The country has abundant sunshine and associated radiation for up to 6 hours each day. The solar radiation reaching the earth’s surface mostly gets diffused due to the characteristic cloud cover.

Figure 1.1: Mean monthly temperature of Malaysia (Sept 2014)
Source: www.metgov.my
For maintaining a thermally comfortable environment within the available spaces for building occupants, four environmental parameters such as air velocity, mean radiant temperature, air temperature and relative humidity need to be present in adequate proportions. Thermal performance of a building is affected by parameters which can be grouped in two types: i) unsteady climatic excitation and ii) design variables of building. The thermal performances of buildings are affected by unsteady climatic excitation that occurs due to air temperature, solar radiation, relative humidity and wind speed and direction. The building envelope design variables are controlled by architects during design phase of buildings. The design parameters of building envelope which determine the envelope’s thermal performance with respect to the climatic conditions include the following as noted by Yasa et al. (2014):

- General layout and sitting.
- The thermo physical properties of the building materials.
- Location of windows and their sizes.
- Shading of windows and envelope.
- Insulation properties and thickness.
- Surface treatment of the enclosing envelope.
- Mass and surface area of partitions.

1.3 Building Envelope

Building envelope or building enclosure is defined as that part of any building that physically separates the exterior environment from the interior environment(s). The main function of the envelope is to isolate the interior environment from the exposed exterior environment. Physically, the typical building enclosure usually consists of the following components:

- the roof system(s),
- the above-grade wall system(s) including windows (fenestration) and doors,
- the below-grade wall system(s) and
- the base floor system(s).

Walls, roof, and foundation consists of building envelope which acts as an interface between indoor and outdoor environments. By acting as a thermal barrier,
the building envelope plays a crucial role in maintaining interior temperature conditions and helps determine the quantity of energy necessary to maintain thermally comfortable conditions. Restricting the heat transfer to minimum level through the building envelope is important for reducing the need for heating and cooling of interior space. In cold/hot climates, by lowering the heat transfer through the building envelope, it is possible to reduce the amount of energy required for heating/cooling.

The process of heat transfer through the building envelope’s components are complex and dynamic. The direction and level of heat flow depends upon outdoor temperature, solar gains from the sun, indoor space temperature, and exposed surface area. A block diagram showing various factors affecting the heat balance of a building is shown in Figure 1.2. Building envelope components have three major characteristics that influence the building envelopes thermal performance (Kosny et al., 2014):

- U-factor or Thermal resistance of material (depends on thermal conductivity of material).
- Thermal mass (depends on heat capacity of material).
- Exterior surface conditions/finishes.
1.4 Insulation through Wall Materials

It is without doubt that modern buildings are less able to control the indoor thermal environmental conditions without mechanical air conditioning. The passive technique used for reducing the dependency on mechanical air conditioning is mainly through the application of thermal insulation in roofs and walls. Various other techniques are looked towards for enhancing indoor thermal environment levels such as architectural shading, very low SHGC windows, insulated and reflective walls & roofs, optimized natural/mechanical ventilation. As this research aims to deal with the issue of low cost housing, the insulation needs of building envelopes should not have adverse impact on costing. The exterior wall covers majority of the building envelope surface area, and in the case of low cost housing, the cost of the masonry
wall products will have to be kept to a minimum. However, not much research has been done to find out surrogate wall materials that are particularly lower in cost.

Most heat gain from buildings in tropical climatic conditions is through walls and roofs which represent the largest external area of low cost houses. Wall is one of the significant components of a building envelope. In most of the buildings, walls are designed as non-load bearing structural components. Mainly its function is to act as a barrier between spaces inside the building and to act as a protection against environmental exposures. The construction of buildings based on opaque materials such as bricks, concrete and several types of finishes does affect the thermal comfort inside the building. Therefore it is necessary to add some sort of insulation type components for insulating the wall. Figure 1.3 represents the conceptual framework to enhance the performance of wall systems. In this research, the focus was to improve the thermal resistivity of wall system by tackling particular independent variables as shown in Figure 1.3.

![Theoretical framework for enhancing thermal performance of wall](image)

**Figure 1.3: Theoretical framework for enhancing thermal performance of wall**

Thermal performance of wall frame assemblies can be increased by either: (i) improving thermal resistance of insulation materials; (ii) providing thicker and wider insulation space in wall cavity; (iii) installing insulating sheathing; (iv) reducing or
eliminating thermal bridging; or (v) providing airtight construction. Combination of these methods is normally applied in practice to reach high $R$-values and sometimes to improve other performance aspects such as constructability, durability, and costs. European standard BS EN ISO 13790 (2008) states that, depending on the location and climate, walls should be constructed by using material with a heat transfer coefficient of 0.4–0.7 W/m$^2$ K, the lower the better.

1.5 Affordable Housing

According to United Nations Human Settlements Program’s global report on Human Settlements (UNHS, 2003) in 2001, it was estimated that about 924 million people or 31.6% of the world’s urban population lived in slums. The majority of them are in developing areas across the globe and in fact, 60% of the global slum dwellers live in Asia. It is estimated that the number of people living in slums can go beyond 2 billion in the next 30 years. However, economic liberalization process during the 1990’s forced many governments around the world to move towards market economy and retreat from direct housing provision as promoted by international agencies (Syafiee Shuid, 2010), increasing the ability to meet the requirements of affordable housing through private sector participation.

In the Tenth Malaysia Plan it is stated that, continuous efforts will be put into ensuring citizens of Malaysia of all income groups can have the opportunity to acquire houses that are normally referred to as “adequate, affordable and good quality”. Since the issue of housing is more crucial in urban areas, greater emphasis is placed on the low-income group for better urban services and healthy living (Government of Malaysia, 2010). The Malaysian government has a requirement that for all private development, 30% of housing units should be of the low cost housing type. Otherwise, the developer will have to pay the government the cost of building those units, if so agreed. Studies based on all Malaysian Plans have shown that the government encourages the private sector to develop more low-cost houses and low-medium-cost houses. Hence, there is a huge demand and provision of low income housing in Malaysia, which is being satisfied mainly by government policy.

Universal Declaration of Human Rights has declared that: “Everyone has the right to a standard of living adequate for health and wellbeing of himself and his
family, including food, clothing, housing and medical care and necessary social services” (UN-HABITAT, 2002).

The Malaysian housing policy does focus on the objective to ensure access to affordable and adequate shelter and related housing facilities for the lower income groups (MHLG, 1999). Also, the Tenth Malaysia Plan focuses on lower income groups residing in rural as well as urban areas; one of its longstanding objectives is to emphasize on the provision of affordable housing for Malaysians.

According to the statistical records, as of 25th July 2011, it is estimated that the population of Malaysia is approximately 28.59 million (Department of Statistics, Malaysia, 2011), which consists of different religion, race and ethnicity. The Malaysian government’s policy on low-cost housing scheme is focused on providing essential needs to lower income group of the population, particularly in terms of house ownership (Ministry of Housing and Local Government, 1968a). One of the main focus areas in the Tenth Malaysian Plan is to ensure access to “quality and affordable housing”. Thus, aiming to meet the needs of the lower income group by providing affordable housing along with promoting an efficient and sustainable housing industry (Malaysian Government, 2010). Incentives towards house ownership for the lower income group includes subsidized cost of housing, packages such as exemption on full stamp duty on all instruments, including loan agreement on purchase on low cost houses have been provided (Malaysian Government, 2006).

The commitment of the government in housing provision for the lower income group is clearly evident. National Housing Department was allocated by the central government with RM 330 million to complete 6,500 units to be rented out or owned under the People’s Housing Program in 2009. The National Housing Department further planned to develop and provide 33,000 houses for low income population.

For providing the affordable houses to low income groups, the Ministry of Housing and Local Government has categorized the housing prices based on the target income group. Table 1.1 presents the Malaysian low-cost housing selling prices based on the location and target income group. Whilst, Table 1.2 presents the price structure and target income groups for the state of Johor. The house prices are subsidized and purchase price maintained so as to be affordable to the major lower-income groups in Malaysia based on federal and state categorizations of target groups.
Table 1.1: Low cost housing price structure based on location and target groups

<table>
<thead>
<tr>
<th>Housing price per unit</th>
<th>Location (Land price per square meter)</th>
<th>Monthly income of target groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM 42,000</td>
<td>City center and urban (RM 45 and above)</td>
<td>RM 1,200 - RM1,500</td>
</tr>
<tr>
<td>RM 35,000</td>
<td>Urban and sub-urban (RM 15 – RM 44)</td>
<td>RM 1,000 - RM1,350</td>
</tr>
<tr>
<td>RM 30,000</td>
<td>Small Township &amp; Sub-rural (RM10 - RM14)</td>
<td>RM 850 - RM 1,200</td>
</tr>
<tr>
<td>RM 25,000</td>
<td>Rural (below RM10)</td>
<td>RM 750 – RM 1,000</td>
</tr>
</tbody>
</table>

Source: Ministry Of Housing and Local Government (MHLG), 2002

Table 1.2: Low cost housing price structure for Johor State

<table>
<thead>
<tr>
<th>Category</th>
<th>House price per unit</th>
<th>Target groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Cost</td>
<td>RM 25 000</td>
<td>Below RM 2,500 per month</td>
</tr>
<tr>
<td>Low Medium Cost</td>
<td>RM50 000</td>
<td>RM 2,500 - RM 3,000 per month</td>
</tr>
<tr>
<td>Low Medium Cost</td>
<td>RM80 000/RM 90 000</td>
<td>RM 3,000 - RM 4,500 per month</td>
</tr>
</tbody>
</table>

Source: SUK Johor State, 2008

Even though the Malaysian government’s commitment is said to be the provision of quality and affordable housing, however the aspect of control over the thermal environment indoors is noted to be unsatisfactory (Abdulazeez and Gomez, 2016). Low cost housing (LCH) is perceived to have a lower standard of housing, and in trying to provide affordable housing Abdulazeez and Gomez (2016) argue that the quality of houses are always being compromised. The aim of providing suitable indoor thermal conditions based on passive strategies are in line with the sustainability agenda of minimizing energy utilization. It cannot be denied that there are certain barriers in establishing sustainability agenda in low cost housing sector, which are akin to that of issues related to green buildings as identified by Samari et al. (2013), this is presented in Table 1.3.
Table 1.3: Barriers in promoting green building in Malaysia (Samari et al., 2013)

<table>
<thead>
<tr>
<th>Lack of building codes and regulation</th>
<th>Lack of incentives</th>
<th>Higher investment cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk of investment</td>
<td>Higher final price</td>
<td>Lack of credit resources to cover up front cost</td>
</tr>
<tr>
<td>Lack of Public awareness</td>
<td>Lack of demand</td>
<td>Lack of strategy to promote green building</td>
</tr>
<tr>
<td>Lack of design and construction team</td>
<td>Lack of expertise</td>
<td>Lack of professional knowledge</td>
</tr>
<tr>
<td>Lack of database and information (case study)</td>
<td>Lack of technology</td>
<td>Lack of government support</td>
</tr>
</tbody>
</table>

1.6 Problem Statement

Previous studies (Ibrahim, 2014) have indicated that the thermal design of low-income housing could be ineffective and, resulting from this, the majority of their occupants are not satisfied with the indoor thermal environment levels provided. Abdulazeez and Gomez (2016), note the dissatisfaction of home owners of low cost housing in Malaysia in terms of poor spatial and functional attributes and their desire for undertaking renovations to improve their thermal indoor environment levels. Ibrahim et al. (2014) confirmed that the low income houses in Malaysia are thermally uncomfortable under normal climatic and living conditions.

Al-Obaidi and Woods (2006) and Nugroho et al., (2007) confirmed that there is an issue of poor thermal conditions in Malaysian terraced house design. According to Tinker et al. (2004), the building envelope often fails to provide basic levels of thermal comfort in low cost houses because of inferior standards of houses provided at affordable rates. However, in their research undertaken in comparing the traditional Malay house and Modern Low income house in Malaysia, they attribute this problem of the building envelope from the perspective of improving building ventilation. In their research undertaken in 2004, Tinker et al. (2004), reported that two million houses may overheat because of inferior standard of housing. Al Yacouby et al. (2011) indicated that about 75% of Malaysians depend on the air-
conditioning system to maintain the indoor temperature within comfort levels. Thus, thermal conditions in low cost terrace housing has been identified to be at an undesirable level.

Whilst the issue of improving control over indoor thermal environment levels is being given much consideration, there is a growing concern of trying to ensure that such efforts are not done at the expense of being unsustainable. Reddy & Jagdish (2003) note that conventional wall materials have negative environmental effects because of their high embodied energy (clay bricks: 2.0 KWh per brick; cement bricks: 1.5 KWh per brick). Also these conventional wall materials have been overused in construction industry, in the sense of not being superseded by more technologically advanced and sustainable alternatives. Foreseeing this problem, many researchers have studied the utilization of waste materials to produce bricks. Most researchers striving for this characteristic in wall materials however overlook other crucial criteria such as mechanical performance in trying to select raw materials and design mix proportions for achieving lower thermal conductivity. The majority of such newly developed waste incorporated bricks still lack practical applicability when it comes to overall performance as sustainable wall materials. Thus, while tackling the issue of thermal performance, sufficient emphasis needs to be given to the performance characteristics of the newly developed wall component.

Research on better thermal performance wall materials (low thermal conductivity), which also have additional sustainable characteristics, seems to be compromised on retaining the physical, and mechanical properties as required according to international standards. Thus, this research is undertaken to tackle the twin issue of providing better thermal performance building envelopes (low thermal conductivity) that are sustainable at the same time having the required desired physical and mechanical properties. The critical component of the building envelope that contributes to high building thermal performance (low thermal conductivity) is that of the building wall material. It is without doubt that a multitude of factors contribute to indoor thermal environment as is explained in Chapter 2. However, this research focuses on discerning the suitable building wall composition that has low thermal conductivity in terms of its thermal transmittivity (U-value) which primarily depends on thermal conductivity and thickness of wall.
1.7 Aim & Objective

1.7.1 Aim

- To develop sustainable hybrid wall material for low cost terrace house (LCTH), to overcome undesirable thermal conditions faced by occupants.

1.7.2 Objectives

The objective of this research are as follows:

I. To determine the final mix design based on the analysis of thermal properties of trial mixes of thermally enhanced sustainable hybrid samples (brick + mortar).

II. To analyse the thermal, physical, mechanical, and microstructural characteristics of trials mixes of sustainable hybrid bricks and Fiber reinforced mortar (FRM).

III. To verify and compare the thermal, physical and mechanical properties of final optimal mix of thermally enhanced thermally enhanced sustainable hybrid sample (TESH brick + FRM) with Conventional wall material.

IV. To analyse the heat transfer behaviour of final optimal mix of TESH wall system using ANSYS simulation software in terms of Finite Element Analysis (FEA).

V. To perform the comparative building energy analysis for TESH wall system and Conventional wall system to understand the performance of TESH wall system during building’s operational stage.

VI. To verify the sustainability aspect of developed TESH brick using embodied energy analysis.
1.8 Scope of Research

This study is focused on utilization of industrial and municipal waste in a hybridized form to be incorporated into building wall construction as a potential for increasing control over indoor thermal environment levels of low-cost terrace housing. The chosen industrial and municipal waste used is sourced locally as the materials are available abundantly in Malaysia (focused on natural fibers, waste glass, natural pozzolanic materials and oil palm waste). The laboratory work for this study has been accomplished by conducting significant testing on the newly developed sample of bricks and mortar. These included the testing of the physical, mechanical and thermal properties and their influence on the performance of the wall system (bricks and mortar). The analysis on the results to achieve the objectives included investigation of the heat transfer properties of the wall system and its energy and sustainability performance on the building. This research is primarily focused on developing a cost-effective hybrid wall system that can provide greater potential for control over indoor thermal environment. The focus is on tackling the thermal performance in terms of thermal transmittance value (U-value) of wall system.

1.9 Significance of Research

The building sector is one of the largest consumers of resources causing high carbon emissions. In the backdrop of environmental issues, many countries are adopting sustainable technologies and materials. Therefore, it is crucial to find suitable surrogate materials which have sustainable features. One way to overcome this situation is to adopt natural renewable sources or non-hazardous waste materials. Implementation of sustainability features in the manufacture of energy efficient products would certainly benefit the environment. Also, the amount of raw materials consumed by the construction industry is approximately 24% of the global raw material resource (Bribián et al., 2011). Thus, for achieving the goal of sustainable development in the construction industry, the selection of building material plays a pivotal role. There have been continuous efforts to research on the viability of reusable waste materials as alternative building materials. Efforts have been ongoing to utilize demolition waste, municipal solid waste, agricultural waste and industrial
waste in building materials (Rao et al., 2007; Lin, 2006; Raut et al., 2013; Shih et al., 2004). However, most of the studies while studying the incorporation of waste materials have failed to address the twin objectives of addressing the thermal insulation characteristics of such material for improving energy efficiency needs and their overall mechanical performance. Thus, this research focuses on utilizing the locally available waste materials as alternative constituent materials for bricks and mortar, keeping in view their final intrinsic physical properties after being incorporated within the hybrid mix of the wall components.

This research is anticipated to enhance the indoor thermal environment levels by providing an alternative wall system which provides better thermal insulation compared to the conventional wall system, especially for low cost housing in Malaysia. Over the years, the issue of providing better indoor thermal environment has not received sufficient attention. This research provides a solution to the current existing issue of inefficient indoor thermal environment in low cost houses. The research also contributes towards promoting sustainable built environment by reducing the dependency on mechanical cooling systems, thus lowering the energy needs of the building. The reduction of energy consumption by using such a passive strategy will eventually be beneficial for occupants as well as it will promote sustainability.

Previous attempts to achieve better thermal performance of wall systems have failed to undertake thorough analysis of brick and mortar as well as to provide complete analysis of required key parameters. Thus, by undertaking a more systemic design science approach, the researcher has been able to provide a “prototype” (Thermally Enhanced Sustainable Hybrid wall system), which has direct applicability that can provide better thermal environment within indoor spaces. Thus, this research is able to tackle the twin issues of sustainability and enhance the indoor thermal environment by promoting the usage of locally available waste material to develop a thermally enhanced sustainable hybrid wall system.

1.10 Proposed Thesis Outline

This thesis presents the research undertaken for the purpose of developing alternative building wall material that provides better thermal indoor environment based on
utilizing agro-waste (industrial waste) and municipal waste for design and development of sustainable building bricks/blocks. To achieve the above aims the thesis is organised according to the following eight chapters.

**Chapter 1:** This chapter includes an overview of low cost housing in Malaysia. It also presents brief descriptions on current conditions of quality in terms of functionality (particularly that of indoor thermal performance that is influenced by the building envelope) of Low cost housing. It also focuses on the need of sustainable insulating material for improvement of indoor thermal environment specifically that of providing better thermally performance of enclosed building spaces of which a key attribute is that of indoor air temperature and thermal performance of components of building envelope.

**Chapter 2:** This chapter focuses on the detailed literature review of sustainable insulating materials aimed at contributing towards enhancing indoor thermal environment levels by having high building thermal performance, equivalent to the building material having low thermal conductivity. Also, the potential use of various agricultural industrial waste materials for developing wall material is discussed. This chapter also discusses the brief literature review of locally available waste materials (i.e. oil palm waste and waste glass). Finally, it discusses the concept of hybrid material and its various definitions provided by researchers.

**Chapter 3:** Chapter 3 discusses the methodology adopted for designing and developing sustainable hybrid material for various waste materials. It also discusses the various testing and its analysis conducted on identified raw materials for development of Thermally Enhanced Sustainable Hybrid (TESH) Wall System.

**Chapter 4:** Chapter 4 outlines the detailed procedure undertaken for designing and developing thermally enhanced sustainable hybrid wall material.

**Chapter 5:** This chapter includes the evaluation of performance analysis of developed hybrid wall material by conducting Physico-Mechanical & Thermal testing.
Chapter 6: Chapter 6 presents the simulation of heat transfer through thermally enhanced sustainable hybrid (TESH) wall system by using Finite Element Modelling (FEM) method. Also, this chapter presents the comparative energy analysis for TESH and conventional wall system. The embodied energy analysis is also performed for TESH bricks to validate it as a sustainable product.

Chapter 7: This chapter outlines the conclusion drawn from the work described in chapters 4-6.
CHAPTER 2

LITERATURE REVIEW

This chapter briefly discusses the developmental necessities of sustainable building environment against the backdrop of unprecedented degradation of urban climate and ecological imbalance. A review is provided of the basic concept of thermal conductivity, various potential thermal insulating materials which can be developed as alternative hybrid wall material that also serves as a sustainable solution. A brief overview of the concept of hybrid material as put forward by previous researchers is also presented.

2.1 Sustainable Building Environment

Buildings are an inseparable part of society; they are the places where we live, play, learn and work. The time spent indoors varies according to the socio-economic commitments and adaptive practices. In developed countries such as United States, people tend to spend 90% of time indoors (Hoppe, 2002). As centers of our social and economic lives, buildings also have significant environmental impact due to consumption of energy and resources. The International Energy Agency (IEA) (2009) has estimated that building sector contributes to nearly 60% of the global electricity demand. However, the energy demand varies depending on the geographical location, climatic conditions, and socio-economic practices. This consumption can explain why the Intergovernmental Panel on Climate Change (IPCC) estimates that by 2030, Greenhouse gas (GHG) emissions due to residential and commercial buildings will account for over one-third of total emissions (Levine, et al., 2007).
The building sector is one of the most important industries in the world and has a substantial impact on the living environment and the ecosystem. From a sustainable building perspective, the environmental concerns associated with building design becomes of utmost importance. With respect to sustainable design strategies of buildings, thermal performance of building plays a vital role in attaining a sustainable built environment. A sustainable building is one which is designed:

I. To minimize consumption of energy and resources by utilizing recycle materials and minimize the emission of greenhouse gases throughout its life cycle.

II. To harmonize with the local climate, traditions, culture and the immediate environment,

III. To sustain and improve the quality of human life and maintaining the capacity of the ecosystem at the local and global levels.

According to the Environmental Protection Agency (EPA), “Sustainability is the ability to provide for future generation needs without compromising present necessities for the continuity of the human and natural environment”. Nowadays, there is more focus on sustainable development, resulting in the environmental assessment of building performance and the certification as a green building. In this assessment one of the main objectives is to provide a healthy living indoor environment for occupants, meanwhile keeping the usage of natural resources to its minimum level, thus lowering overall negative impact to the natural environment (Byrd and Ramli, 2012).

Achieving enhanced levels of indoor thermal environment in a sustainable manner is key to addressing the issue of producing a healthy living indoor environment. Much research has been done to tackle indoor thermal environment issues within the global green rating building context. But not much emphasis has been put to address wider sustainable built environment issues in terms of consideration of provisions for sustainable building wall material. Hence, greater emphasis needs to be placed on the properties of materials used in constructing a building that can contribute towards better indoor thermal environment.
2.2 Basic Concept of Thermal Conductivity

Thermal conductivity is one of the key properties for analyzing the thermal insulation of a material. Thermally insulated buildings must possess lower values of thermal conductivity. Thermal conductivity of material is defined as the property of a material to conduct heat. The category of thermal insulation materials refers to materials that have a low rate of heat transfer through it. Hence, these materials have a low thermal conductivity (W/(mK)) which allows the use of relatively thin building envelopes. In other words, the building envelopes utilizing such material have a high thermal resistance (m²K/W) and an overall low thermal transmittance U-value (W/(m²K)). The Thermal Conductivity \( k \) of a material is defined as the rate of heat flow through a given cross sectional area (given in Equation 2.1).

\[
q = -k \cdot A \frac{dt}{dx}
\]  

- (2.1) 

Whereas, the total overall thermal conductivity \( k_{tot} \), i.e. the thickness of a material divided by its thermal resistance, is in principle made up from several contributions as outlined in Equation 2.2:

\[
k_{tot} = k_{solid} + k_{gas} + k_{rad} + k_{conv} + k_{coupling} + k_{leak}
\]  

- (2.2) 

Where, \( k_{tot} \) = Total overall thermal conductivity,  
\( k_{solid} \) = Solid state thermal conductivity,  
\( k_{gas} \) = Gas thermal conductivity,  
\( k_{rad} \) = Radiation thermal conductivity,  
\( k_{conv} \) = Convection thermal conductivity,  
\( k_{coupling} \) = Thermal conductivity term accounting for second order effects between the various thermal conductivities in Eq.(2.2),  
\( k_{leak} \) = Leakage thermal conductivity.

The solid state thermal conductivity, \( k_{solid} \) is caused due to lattice vibration between the atoms causing the transfer of heat, i.e. through chemical bonds between atoms. The gas thermal conductivity, \( k_{gas} \) is caused due to the collision of molecules with
each other in gaseous state thus enabling the transfer of thermal energy from one molecule to the other. The radiation thermal conductivity, $k_{rad}$ is caused due to electromagnetic radiation in the infrared (IR) wavelength region which is emitted from a material surface. The convection thermal conductivity, $k_{conv}$ is caused by the thermal mass transport or movement of air and moisture. The main factor resulting in transfer of thermal energy is the temperature difference between materials and its surrounding. The various thermal insulation materials and solutions utilize various strategies to keep these specific thermal conductivities as low as possible (Jelle, 2011). Figure 2.1(a) and Figure 2.1(b) illustrates the various forms of heat transfer through a material.

![Figure 2.1 (a): Heat Transfer through a wall system (Balaji, et al. 2014)](image-url)
2.3 Previous Studies on Thermal Properties of Building Materials

Most of the studies involving thermal performance of building materials are focused mainly on the thermal insulation of walls and its thickness by using various thermal conductivity measurement techniques (Al-Hammad et al. 1993, Budaiwi et al., 2002, Saleh, 2006). There has been much research solely focused on the thermal performance of building wall materials incorporating low thermal conductivity materials. The effectiveness of the insulation mainly depends on the low heat transfer rate of the material to prevent the heat gain within the indoor space through the wall materials. One way of enhancing the energy efficiency in buildings is to improve the heat insulation properties of the buildings. Insulating materials can be classified according to their chemical or their physical structure. The most widely used insulating materials can be classified as shown in Figure 2.2.
Figure 2.2: Different categories of insulating materials (Papadopolous, 2005)

Choi et al. (2007) analyzed composites for their insulating properties by varying the building wall thickness. The method adopted for measurement was steady state method using Lambda heat flow meter. Their research also addressed the issue of reliability of the performed quantitative analysis in terms of the measurement precision and uncertainty of the insulating composite materials. It was observed that with the increase of thickness by about four times, thermal resistance was also observed to vary from 3% to 4%, this was due to the heat loss from the sides. When the theoretical value and the actual value for three types of composite insulation were compared, then variation in the thermal values was found to be around 5%.

Abdelrahman et al. (1990) measured thermal conductivity of locally available bricks in Saudi Arabia by using hot guarded plate technique. The measurements were conducted at 40°C mean test temperature for establishing thermal performance of bricks. The results suggested that observed values for thermal conductivity was mostly on the higher side compared to those reported in handbooks (mainly at mean temperature of 24°C). In a more recent work, Al-Hazmy (2006) analyzed the heat transfer rate through common hollow building blocks. Experiments were performed considering the cavities filled with insulating material and gas filled conditions. Results concluded that the cellular movement of air within cavities of bricks


Malaysian Standard (1972). *Specifications for bricks and blocks of fired brickearth*


