

AN EVALUATION OF MATERIAL CHARACTERISTICS AND
HYGROTHERMAL PERFORMANCE OF ECOLOGICAL THERMAL
INSULATION MATERIALS FOR USE IN TIMBER FRAME BUILDINGS

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INSULATION MATERIALS FOR USE IN TIMBER FRAME BUILDINGS**

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ABSTRACT

AN EVALUATION OF MATERIAL CHARACTERISTICS AND HYGROTHERMAL PERFORMANCE OF ECOLOGICAL THERMAL INSULATION MATERIALS FOR USE IN TIMBER FRAME BUILDINGS

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The effects of thermal insulation materials with toxic properties on users and on the ecosystem have led to the search for natural thermal insulation materials. The aim of this research was to study the properties of cork, coconut fiber, and cellulose-based ecological thermal insulation materials (ETIM) and to evaluate the hygrothermal behavior of the structure by using these materials in a sample timber framed structure.

The physical, thermal and hygric properties of the selected ecological thermal insulation materials (Corkoco, Expanded Corkboard, CelluBor) that were obtained from Amorim and CelluBor were determined in the laboratory at METU Materials Conservation Laboratory at the Faculty of Architecture; and data was gathered on their bulk density, apparent porosity, thermal conductivity, specific heat capacity, water vapor permeability, and capillary water absorption. Thereafter, WUFI Plus simulation software was used to compare the use of ETIMs in a timber frame structure in terms of their hygrothermal properties. Expanded Corkboard (EC1) was found to be the material showing the best material properties out of the four investigated samples. All the materials studied gave acceptable results in terms of energy consumption and thermal insulation according to the TS 825 standard. It has

been seen that the hygrothermal performance in the selected timber frame structure is also ideally achieved with EC1.

Keywords: Timber frame buildings, ecological thermal insulation materials, energy performance simulation, hygrothermal performance simulation



ÖZ

AHŞAP KARKAS YAPILARDA KULLANILAN EKOLOJİK ISI YALITIM MALZEMELERİNİN MALZEME ÖZELLİKLERİNİN VE ISIL-NEMSEL PERFORMANSLARININ DEĞERLENDİRİLMESİ

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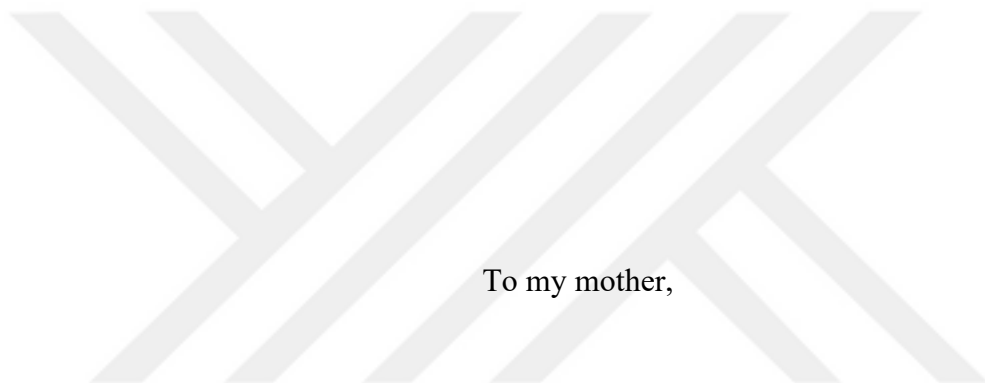
Toksik özelliklere sahip ısı yalıtım malzemelerinin kullanıcılar ve ekosistem üzerindeki etkisi doğal ısı yalıtım malzemeleri arayışlarına yol açmıştır. Bu çalışma, mantar, hindistan cevizi ve selüloz bazlı ekolojik ısı yalıtım malzemelerinin özelliklerini sergilemeyi ve örnek bir ahşap çatıklı yapıda bu malzemeleri kullanarak yapının ısı ve nemsel davranışlarını değerlendirmeyi amaçlamaktadır.

Amorim ve CelluBor'dan temin edilen ekolojik ısı yalıtım malzemelerinin (Corkoco, Expanded Corkboard, CelluBor) fiziksel, termal ve higrik özellikleri ODTÜ Mimarlık Fakültesi Malzeme Koruma Laboratuvarı'nda yürütüldü. Burada yoğunluk, gözeneklilik, termal iletkenlik, özgül ısı kapasitesi, su buharı geçirgenliği ve kılcal su emme hakkında veriler toplandı.

Ardından WUFI Plus simülasyonu ile ekolojik ısı yalıtım malzemelerinin örnek ahşap yapıdaki kullanımının ısı ve nemsel özellikleri karşılaştırıldı. Araştırılan dört örnekten en iyi malzeme özelliklerini gösteren malzemenin genişletilmiş mantar pano (EC1) olduğu görülmüştür. Çalışılan bütün malzemeler enerji kullanımı ve ısı yalıtımı açısından TS 825 standardına göre kabul edilebilir değerlerde sonuçlar vermiştir. Seçilen ahşap çatık yapıdaki ısı ve nemsel performansın da ideal olarak yine EC1 ile sağlandığı görülmüştür.

Anahtar Kelimeler: Ahşap karkas yapı, doğal ısı yalıtım malzemeleri, enerji performans simülasyonu, ısıl ve nemsel (higrotermal) performans simülasyonu





To my mother,

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LIST OF ABBREVIATIONS

ABBREVIATIONS

BEI	Building Energy Index
DHW	Domestic Hot Water
ETIM	Ecological Thermal Insulation Materials
EPA	Energy Performance Assessment
EPI	Energy Performance Indicators
EPS	Expanded Polystyrene Insulation
ETIM	Ecological Thermal Insulation Materials
EUI	Energy Unit Intensity
GHG	Green House Gas
GW	Glass wool
HAM	Heat, Air, and Moisture
HBCD	Hexabromocyclododecane
HCFC	Hydrochlorofluorocarbons
HVAC	Heating Ventilation Air Conditioning
LCA	Life Cycle Assessment
OSB	Oriented Strand Board
OECD	The Organization for Economic Cooperation and Development
PBDE	Polybrominated Diphenyl Ethers
PIR	Polyisocyanurate
PE	Polyethylene

PP	Polypropylene
PU	Polyurethane
RC	Reinforced Concrete
RH	Relative Humidity
TI	Toxicity Index
TIM	Thermal Insulation Materials
TWC	Total Water Content
XPS	Extruded Polystyrene Insulation
VOC	Volatile Organic Compound
WC	Water Content
WFB	Wood Fiber Board

CHAPTER 1

INTRODUCTION

Since its inclusion in the built environment, timber has stood as one of the most preferred building materials since it is a natural, sustainable, renewable sourced material and due to its desirable properties in terms of stability and energy consumption. A contribution may be made to preserve the natural balance of the environment if designers and practitioners choose materials that use less energy during production and construction, can be recycled, have higher life-cycle assessment (LCA) values, and are non-carcinogenic. Timber stands as the best example that nature offers to cover them all (Bostancıoğlu & Düzgün Birer, 2004).

There is a common belief that timber buildings are more sustainable than their present-day substitutions, steel, and concrete. Yet, there is still a problem that timber buildings are not defined as fully sustainable because of some of their building components, such as preservatives, paints, adhesives, and glues which are hazardous and toxic, since they release volatile organic compounds (VOCs) into the air. To reuse and recycle wood as a building material or burn it for energy utilization, wood should not be contaminated with harmful materials, including preservatives or adhesives (Nomura, 2010). These chemical preservatives include copper chrome arsenate (CCA), boron compounds, and copper-based preservatives (Walsh, 2020).

Additionally, insulation materials used in buildings are crucial from ecological and economic aspects. They have similar thermal conductivity values that vary between 0.03 and 0.08 W/mK. For an acceptable energy consumption value in a building, insulation materials should have lower values than 0.04 W/mK. Insulation materials used to decrease energy consumption affects people's comfort and well-being. Designers and users should consider their environmental impacts during production.

Their production necessitates a tremendous amount of energy and resources while causing an unleashing of pollutants into the air. Ecological analysis of insulation materials is essential for sustainable buildings, but unfortunately, the economic factor is regarded as more critical than others in the market (Zelazna & Pawłowski, 2011).

Various types of timber frame buildings in Turkey have been built with regional characteristics from different regions of Anatolia. Some remaining examples tracing back to 17th century can be seen. They have been preferred for years due to their strong resistance to earthquakes, low cost, and easy accessibility to timber elements (Akan, 2004). Yet, there is a problem that they cannot be accepted as fully environmentally sustainable buildings when contaminated with toxic materials. Insulation materials are one of the components besides preservatives that are toxic to the environment in both production and usage phases.

It is widely known that one-third of total energy consumption worldwide and one-fifth of total greenhouse gas (GHG) emissions are caused by energy consumption in the built environment, including cooling and heating systems. This energy trend in the Organization for Economic Cooperation and Development (OECD) countries is unfortunately expected to increase between 1.5 to 2 percent yearly until 2040 (Cabral & Blanchet, 2021).

Since the EU directives set targets to decrease energy consumption in buildings for its member states there has been an interest in reducing GHG emissions and energy usage in the construction sector as well as others (Strandberg-de Bruijn et al., 2019). Regarding energy consumption in the building, insulation materials are the first building material that comes to mind, mainly produced by toxic-based materials or production methods.

1.1 Problem Statement

As Zelazna and Pawłowski (2011) pointed out, implementing effective and new products could reduce energy demand and the consumption of raw materials during the production process. The new technologies used for building products should promote energy usage from renewable energy sources and the usage of recycled or organic materials. For a building to be ecological and sustainable, all its components should be defined as environmentally friendly materials. The literature review indicates that it has been a problem defining timber buildings as sustainable because they include chemical and toxic building materials.

The research problems after the literature review are redefined in three aspects. First, using conventional insulation materials in timber framed buildings is an obstacle when aspiring to achieve the aim of environmentally sustainable timber buildings. This is because conventional insulation materials eventually cause toxicity by physical or chemical means due to usage, or a fire incident. Secondly, the condensation problems within the exterior layers of timber-frame structures affect natural insulation materials. Thirdly, the environmental impact of high energy consumption values of heating, ventilation, and air conditioning (HVAC) during the building use phase can be high.

The literature review mainly covers the topics of hygrothermal and energy-related performance of timber-framed constructions, focusing on insulation materials. The study compares energy performance and moisture control in timber buildings' by using ecological thermal insulation materials.

Ecological thermal insulation materials accepted to have slightly lower thermal properties and are more prone to decay because of moisture than conventional industry materials. However, ecological thermal insulation materials (ETIM) are valuable alternatives in terms of hygrothermal characteristics to conventional toxic insulation materials, whose environmental impact is more significant.

1.2 Aim and Objectives

This study aims to investigate higher energy efficiency in heating and cooling and in preventing condensation, while carrying out the search for fully environmentally sustainable timber buildings integrating ETIM.

The objective of the research is to analyze and present the energetic, hygroscopic, and thermal-related characteristics of insulation materials used in the envelopes of timber-frame buildings; and to compare the data gathered through laboratory experiments and simulation.

The scope of this study is first to investigate ecological thermal insulation materials' material properties suitable for timber-frame buildings. Then, apply these materials as input variables to gather results from energy assessment and moisture simulations of a selected timber frame building envelope as a substitute to toxic thermal insulation materials (TIM) while preventing heat loss and condensation.

1.3 Research Questions

In order to reach the objectives, the main questions of this research are set as follows,

- How do selected ecological thermal insulation materials behave in respect of hygric properties regarding water and vapor?
- Can ecological thermal insulation materials be efficient in lowering energy consumption values and improving thermal comfort in buildings?
- What kind of ecological thermal insulation materials should be used in timber framed structures to prevent condensation and heat loss?

1.4 Procedure

A methodology through this research is followed to answer research questions and reach the research aim. This procedure is firstly started with the introduction of ecological thermal insulation materials that are available in Türkiye. Then, four different materials are selected.

In this research step, the materials' physical, thermal, and hygric-related properties are examined, and data is gathered through laboratory tests.

In the second step, in the WUFI Plus simulation, which analyzes energy and hygrothermal performance, a timber frame building is modeled.

Then, selected properties of insulation materials such as density, thermal conductivity value, specific heat capacity, and water vapor diffusion factor are processed into performance simulation as the variables of envelope component. The model is subjected to the same climate data, internal loads, HVAC capacity, and indoor conditions.

As the result of the simulation, temperature and moisture changes in the building envelope, the consumed energy as outputs is obtained. These outputs are visualized and given in the results and discussion chapters.

1.5 Disposition

In the first chapter of this study, the problem statement, aims and objectives, and the procedure followed during the research are given.

The second chapter of this study contains the literature review, starting with the background and characteristics of timber. It continues with the energy consumption, environmental impact of buildings, and the performance assessment term and simulations in buildings, the background of thermal insulation materials, ecological thermal insulation materials, and condensation problems in insulation materials.

Finally, the literature review is ended with the formulas and definitions used to determine materials' physical, thermal, and hygric properties through laboratory experiments.

With the literature review, the essence of the problem, materials, and methods used in this study is aimed to be understood.

In chapter 3, the material and the method of this study are given, including five materials used in the research and the methodology followed step by step.

Chapter 4 is the part in which the final results collected during the research are given. The raw data that does not take part in the results are in the Appendices section.

Chapter 5 discusses the results of all data collected in chapter 4.

In the last chapter, the conclusion is presented as the result of the study, which is expected to be a resource in future studies.

CHAPTER 2

LITERATURE REVIEW

The literature review of this research is conducted on four different aspects. Firstly, wood as a material is researched to cover the timber-framed construction. Subsequently, the properties of timber in terms of sustainability, affordability, and easy constructability are also detailed in this chapter. The timber structures with properties mentioned above are easy and cost-effective to build, sustainable, and energy efficient. Then the historical background of timber structures from the early common era to the modern days are shown.

The second aspect of the literature review is the energy consumption and carbon emission of timber buildings. Energy and hygric-related performances of a building are given as well as the tools to calculate those performances.

The third aspect covered in the literature review is the insulation materials. Insulation materials are given by their history of usage in the built environment in the first place. Then their types and related properties are explained that cause the condensation and toxicity problems seen during occupants' use.

The fourth and the final aspect of the literature review are the explanation and formulas used during the laboratory experiments on thermal insulation materials, and the calculation of thermal related properties of building and its components.

2.1 Timber as a Construction Material

Through this study, the first thing explained will be the tendency towards construction with wood. Subsequently, timber properties will be described, though the focus will be on energy efficiency and moisture control in timber buildings. How

do thermal-related properties affect the energy efficiency and the other factors that effects energy performance, and how to control the moisture within buildings' envelope are the main questions regarding timber buildings.

Understanding what timber is, how it differs from wood, its properties, and how timber buildings evolved in time is essential. The term timber is used for wood that is cut from trees and then prepared to be used as a building or carpentry material.

Wood has thousands of different species. There are over 20,000 tree species worldwide, each appropriate for another type of job. Tree species are distinguished from each other by their color, texture, hardness, stability, durability, ease of drying, and fiber smoothness, e.g. It is also necessary to pay attention to the tree classification.

2.1.1 Characteristics of Timber

Timber as a material has been one of the most ancient and remarkable elements in building for centuries due to its distinctive properties. Along with this fact, developments in previous centuries and openness to innovation changed the general opponent opinions against timber for sure. With its sustainable qualities and advantages, it is possible to develop lightweight and high-performance components allowing energy-efficient and sustainable architectural products (Guo, Liu, Meng, Huang, Sun, & Shao, 2017; Lattke & Lehmann, 2007).

Properties of timber can be examined in physical, mechanical, chemical, ecological, commercial, and technological aspects. In this study, timber's ecology, energy, and finance-related properties are reviewed next to reduced construction time, price, and energy efficiency properties in timber constructions. The primary reason behind choosing timber buildings as the object of research was that wood is an energy-efficient material, and timber construction has shown much potential in energy-related properties.

The gross density of timber is low, so the thermal storage capacity of 350 Wh/m³K for spruce and fir is lower than other structural construction elements like masonry or concrete, which is 660 Wh/m³K. This value is disputable for thermal protection during summer. In terms of sound insulation, low gross density seems unsatisfactory in many cases, but timber absorbs the sound better than expected due to its porous and cellular structure (Steiger, 2007). At this point, it is essential to remind that timber also has lots of potential in terms of mechanical and physical aspects, including structure, strength against tensile and compressive stresses, and durability, besides energy-related aspects.

There are a couple of disadvantages that timber may face. First, wood could be deteriorated by a few chemical factors and pyrolysis reactions, biological, chemical, thermal, water and weather degradations, and water interactions. Some of them are directly related to the insulation material used in construction. Thermal degradation results from fire, lightning, and the sun. Water degradation results from rain, sea, ice, acid rain, and dew. Water interactions such as swelling, shrinking, freezing, erosion; and weather degradation is caused by water, heat, and UV radiation (Nilsson & Rowell, 2012).

Water, humidity, or atmospheric decays result in excessive moisture in timber structures. This decay led to rot, mold, insect damage, and wood moisture, eventually collapsing timber structure (Aras, 2013). Increasing natural durability and keeping the material dry are vital to prevent the wood from getting decay. The timber, which has a high risk of deterioration in traditional buildings or is used as a carrier, should be chosen from natural, durable species such as oak and chestnut. In addition, timber should be kept dry using vapor and water insulation materials. With a short wet and dry cycle, timber does not rot. Yet, the fact that using thermal insulation materials which prevents wood from drying, especially in roofs, has revealed a new problem, rotting of the timber roof structure (Erdoğan, 2003).

2.1.1.1 Naturality and Environmental Sustainability

Timber is a highly sustainable material, especially in the construction industry. In its raw form, wood is a renewable resourced material, which reduces CO₂ while releasing oxygen. Besides consuming less energy during the construction stage, the timber manufacturing process saves CO₂, resulting in energy efficiency and a lower ecological footprint (Khatib, 2016). CO₂ emissions of timber buildings during their life cycle are decreased chiefly due to the manufacturing process of wooden components using fewer fossil fuels and the opportunity to use by-products of wood processing as biofuel (Mahapatra & Olsson, 2015).

To understand the approach regarding timber construction in European countries, Viholainen et al. (2021) conducted a study covering topics such as citizens' conception to describe timber and perspective changing from country-based cultural changes. According to this study conducted in Austria, Denmark, Finland, Germany, Norway, Sweden, and the UK, it is seen that citizens in these countries rely on wood in terms of natural properties, visual characteristics, and indoor environment quality.

The primary dilemma in timber construction is if the need for wood can be satisfied without reducing the area of forest resources or destroying the ecological balance (Green & Taggart, 2017). The answer to this dilemma explained in Sustainability of Construction Materials (2016) as one of the most environmentalist building components would be probably timber, if it is obtained from sustainably managed forests. Another answer given by Erdoğan (2003) is that contrary to the popular belief, forest areas are constantly increasing in countries with high wood consumption per capita, meaning using timber allows forests to grow.

2.1.1.2 Economic Sustainability

In terms of economic sustainability, timber also has its benefits. As van de Kuilen, Ceccotti, Xia, He, and Li (2010) stated being lightweight compared to concrete and

achieving notable prefabrication possibilities are some of the significant advantages timber embodies as the structural element. Guo et al. (2017) also indicates that using engineered wood products in a 10-story building as a structural material would result in a 4% decrease in cost compared with the RC alternatives. According to another example from 2009 in the UK, where solid timber constructions are not typical in high-rise buildings, a nine-story residential building has been constructed with prefabricated engineered timber components. Economic profits of up to 30% have been seen in the operation phase, and waste is reduced on-site, despite the base cost of timber construction being 10% to 20% higher than the reinforced concrete (RC) (Kildsgaard, Jarnehammar, Widheden & Wall, 2013). The need for economical housing and efficient use of the material is setting the ground for interest in multi-story timber buildings in the future, according to Viholainen et al. (2021).

2.1.1.3 Energy Efficiency Properties

Lattke and Lehmann (2007) indicate that timber construction can limit the embodied energy content with low values and reduce the use of material resources. Embodied energy is the overall energy needed to process, manufacture, transport, construct, maintain, and demolish a material or product (Dixit, Culp, Fernandez-Solis, 2015).

Wood has thermal conductivity coefficient changes between 0.13 and 0.23 W/mK depending on the type of tree procured. Comparing these values with brick at 0.44 W/mK and concrete at 1.8 W/mK, it is easily seen that wood has significantly more favorable thermal insulation properties than other construction materials. On the other hand, thermal expansion of timber, unlike RC or steel, is so insignificant that it is easily disregarded (Steiger, 2007).

Alongside a better carbon reduction performance, timber has better energy-efficiency values when compared with alternative materials in construction, being bricks, steel, and RC. According to Steiger (2007), wood-infilled timber structures

with 12-16 cm thickness supply acceptable insulation results on their own yet using extra insulation materials is applicable for better results.

It is known that the operational process of the building composes most of the energy and carbon emissions of the total amount, and the initial construction of the building comprises a considerable amount of carbon emission as well. Construction stages, along with the production, preparation, and transportation of the materials, consume most of the energy and negatively impact the environment. Timber buildings consume 80% less energy when they are compared with RC framed structures. (Guo et al., 2017)

The thermal conductivity values of timber are lower than steel and concrete from the point of operating energy. Consequently, timber buildings have higher standards in insulation. Moreover, using wood is one of the best options for practitioners wishing to meet the standards of Passive House or construct a net zero energy or zero carbon building (Reyes et al., 2021).

Thermal insulation helps minimize the energy loss in the building in different climates. As stated by Lattke and Lehmann (2007), key strategies in constructing multi-storey residential timber buildings are sufficient thermal insulation and a high degree of air tightness to avoid the damage caused by water condensation to the building envelope. Therefore, timber buildings' details should be carefully designed to achieve good insulation values. (Lattke & Lehmann, 2007). The diagram of the material flow during the production of wooden products can be seen in Figure 2.1.

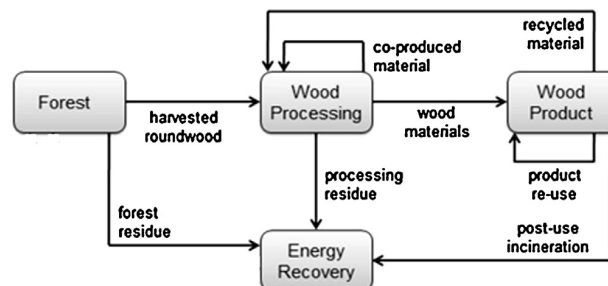


Figure 2.1. Material flow of wooden products as a schematic diagram (Dodoo, Gustavsson, & Sathre, 2014).

2.1.2 Historical Background

The use of wood and wood-based materials is increasing in favor of the trending aim of sustainability. Wood has been practically used in every aspect of life for almost as long as humanity has existed. It is one of the healthiest materials, cleanly-resourced, and environmentally non-polluting (Ryan, 2011). Alongside being renewable, wood consumes less energy during production when compared to other construction materials. As one of the most ancient building elements, wood is far from outdated. Being accessible to process, having high rigidity for its weight, exceptional insulation capabilities, and high endurance are some of the distinctive advantages of wood. It is used for both constructional purposes in roof structures, floor layers, and stairs and decoration purposes in doors, window framings, and facades (Švajlenka & Kozlovská, 2021; Kelley, Loferski, Salenikovich & Stern, 2000).

Man has used wood to make shelter for several thousand years. Using wood in habitational units goes back to 9000 BC in light timber frame structures on the Turkish and Iranian border. Similar techniques became popular around 8000-7000 BC with conic or cylindrical timber roofs on rectangular plans. The first example of timber wall construction was seen by 6500-6000 BC in Anatolia and Cyprus in dwellings with two stories, the first being mudbrick or stone and the second ones built in timber frame structures (Kelley et al., 1942/2000).

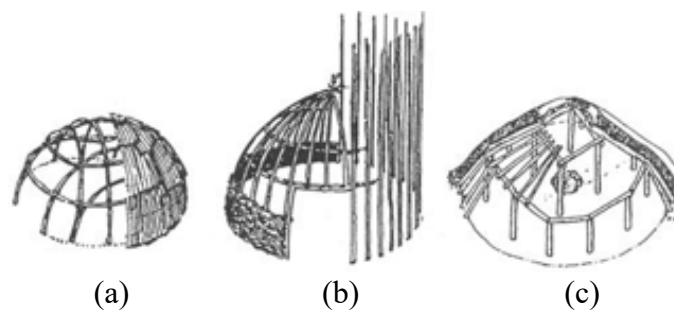


Figure 2.2. Some types of manufactured early timber shelters: (a) Paleolithic round hut; (b) South African hut, (c) circular earth lodge (Kelley et al., 2000).

The usage of timber became extremely popular in Northern Europe with the ability to shape and distort the material according to cultural and local user needs. Timber frame structures with rectangular plans and truss roof frames are seen commonly in Europe from around 5500 and 5200 BC. Then these construction techniques are brought to North America around the 17th and 18th centuries by Englishmen (Kelley et al., 2000).

The forestry industry is continually introducing natural and synthetic new timber-based materials. The growth of timber construction is also aided by new transportation technologies and rising demands for thermal insulation (Steiger, 2007). Turkish timber dwellings in the form we know today were shaped during the migration of Turks from the Middle East to Anatolia; then, they spread to Southern Anatolia and the Balkans. The construction techniques, therefore, are primarily alike, but the details change (Kıray, 2007).

Until recently, most local traditional structures in Turkey, as in many other regions of the world, were made of timber. Some examples of timber construction with vernacular architecture in Turkey represent hundreds of years of cultural heritage (Aras, 2013). Ottoman Empire, for its rule of 600 years, particularly during the 17th century, influenced local constructors in building timber-based dwellings in the form known as the Ottoman houses today (Güçhan, 2017). Timber structures were constructed in the 15th century and were still built until the 1960s. The main reasons why locals used extensive traditional timber construction methods in Northern, Southern, Middle, and Western Anatolia are social and cultural factors, material availability, and climatic conditions.

The seismic danger is another factor promoting timber structures (Aras, 2013). Even though most countries in the seismic belt, such as Canada and Japan, apply most of their buildings with a timber structural system, the popularity of timber buildings in Turkey has decreased since the 1940s. Yet, due to the approval of Eurocode 5 in 2018 by the Turkish government, Turkey now has a code of regulations in which the

materials, durability, structural analysis, and connections of timber buildings have mostly been covered (Çalışkan, Meriç & Yüncüler, 2019). Natural aging factors, fire, climate and earthquakes, abandonment, and inappropriate usage are some of the damages to the timber buildings. Still, other factors prevent users from choosing timber. Lack of economic and technical guidance for timber buildings prevents its use in both new and restoration projects (Aras, 2013).

The basis of modern timber-framed buildings is in North America with the need for new, simple, cheap, and quick settlements around the country's railroads. Timber was the most promising material in this changing environment and diversified climatic conditions. Timber buildings are influenced by industrial methods beginning from the 19th century. Timber construction, which had previously developed from traditional European timber dwellings, was transformed by steam-powered sawmills and machine-made nails in America (Steiger, 2007). Due to the industrialized process of timber building technologies, easy manufacture and construction are achieved. In addition, these technologies put forward the properties of recycling, renewable, and low carbon emission of timber buildings (Viholainen, Franzini, Lähäinen, Nyrud, Widmark, Hoen & Toppinen 2021).

In terms of the infill materials used in the timber frame building envelopes, there are several options, depending on the tradition of the region, which are *Bağdadi* and *Hımsı*. Under the *Hımsı* system the infill groups are divided into four depending on the type of infill material which are brick, adobe, stone, and tree and mud fill (Akan, 2004).

Brick as the infill material is used between 16th and 18th centuries and later disappeared due to lack of workmanship (Akan, 2004). It is seen mostly in Bursa, Bolu, and Ankara regions. These brick infilled timber-frame walls are placed in different brickwork patterns and not covered with a plaster (Günay, 2007).

Adobe, which is also known as sun-dried brick, is one of the oldest infill materials due to being easy to apply and a cheaper material. It is mostly seen in Kastamonu,

Çorum, Sivas, Çankırı regions. Yet, it is not durable against water, so it is plastered with mortar and lime (Akan, 2004; Günay, 2007). Stone infill is mostly used in divided triangular or rectangular parts of walls in Eastern Blacksea region houses, in which coasts and forests are characteristic to region (Akan, 2004). Another traditional infill method is weaving the timber branches and plastering with straw added earth on the outsides, known as “hu”. This method is mostly seen in İstanbul, İzmit region and around Adana (Günay, 2007).

Last filling method is known as *Bağdadi* method in Turkey, and it is obtained by lathing with timber. The interior space between the surfaces is either left empty or filled with light insulation material. Outer surface is covered with timber plates where the inner side is intermittently covered with laths obtained by splitting soft wood, then plastered with a mud and straw mixture on top of laths. The sizes of timber lath may differ 8x25 mm or 12x20 mm and the spacing should be 15 mm (Günay, 2007). Compared to *Hımsı*, *Bağdadi* structure is more sophisticated. Yet, a significant amount of laths and skilled labor are needed for their construction (Aras, 2004).

Timber frame buildings may also be covered with plaster or timber claddings. Especially in buildings located in inner Anatolian parts of Turkey are covered with plaster, while in coastal regions like Marmara and Blacksea buildings are covered with timber. Plaster can be made of a mixture including, mud, lime, or gypsum and water. It may be applied on plater wires, masonry, and *Bağdadi* laths. Timber cladding is mostly known in Turkey as *yalı baskısı*, which is overlapping and interlocking timbers in order to prevent wind and rain inside (Günay, 2007).

2.2 Energy Consumption and Carbon Emission

According to Berge, Butters, and Henley (2009), three sources of global warming are the production of energy, which is higher than the rest, the chemical industry, and the waste recycle. It is known that up to 40% of overall energy consumption

throughout member counties in the EU and one-third of worldwide consumption is constituted by the buildings and construction sector, which is relatively higher than the production or transportation industries. (Guo et al., 2017; McCoy, Zhao, Ladipo, Agee & Mo, 2018; Fumo, 2013). According to the amount of energy and resources consumed, the construction industry is responsible for planet pollution and the consumption of natural resources at the very most (Švajlenka & Kozlovská, 2021). For example, timber buildings need 30% less energy than concrete substitutes, as noted by Berge et al. (2009).

According to Švajlenka and Kozlovská (2021), economic development and increased living standards increased the global scale of energy resource consumption. The projections say global energy demand will be 50 percent higher by 2030, while fossil fuel reserves will meet 80 percent of this demand. 25 to 50% of the carbon ratio is initially released during production, may be recaptured during the building's lifecycle of 50 years. It is essential, though that this ratio does not significantly lessen the use of materials with high emission impacts (Berge et al., 2009).

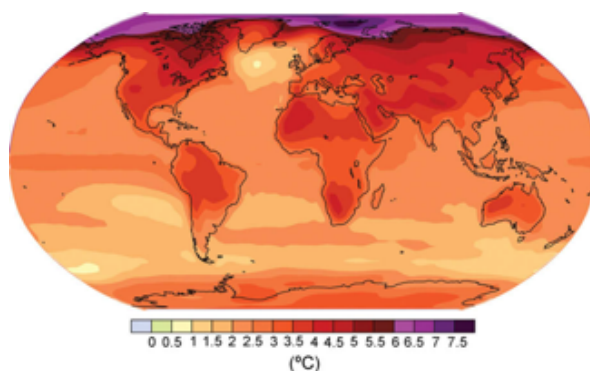


Figure 2.3. Projected surface temperature changes for the late 21st century (2090–2099) (Berge et al., 2009).

Three phases constitute the life cycle of a building is given by Huberman and Pearlmutter (2007) as: "pre-use phase known as embodied energy, use phase known as operational energy and post used phase known as demolition, recycling or reuse." Life cycle assessment and embodied energy are essential with respect to energy consumption. To save energy, the selection of improved materials and emission controlling techniques should be handled to cover the whole life cycle of a building. Those actions apply to construction materials since they are one of the crucial components in a sustainable building (Colinart & Glouannec, 2014). Effects of the materials on resources can be seen in Table 2.1.

Table 2.1 Effects on resources of some materials (Berge et al., 2009).

Material	Density (kg/m ³)	Raw Materials	Resource Reserves (Years)	Embodied Energy (MJ/kg)	Combustion Value	Water Resources (litres/kg)
Glasswool	15-30	3	35	35	2	1360
Rockwool	30-120	4, 1	2	20	1	1360
PE	940	1 (41)	2 (63)	110	431	-
PP	940	1 (41)	2(63)	115	43	-
EPS	10-50	1 (41)	2 (63)	125	48	-
XPS (HCFC)	20-62	1 (41)	2 (63)	133	49	-
PUR	28-55	1 (41)	2 (63)	135	30	-
Cork Board	130	R	-	16,5	16	330
Wood Fibre Board	110- 350	R	2 (63)	36	17	-
Hemp Fibre	20-40	R	2 (63)	40	17	-
Loose Cellulose	20-60	-	-	19	15	10
Wool	18	R	1 (43)	29	4	-

R: recyclable

1: Crude Oil

2: Natural Gas

3: Lime, Manganese, Potash, Quartz, Coal

4: Boric Salts, Lime, Quartz, Soda Ash

Residential buildings in Europe are responsible for 16% of the final energy use, while commercial buildings have a rate of 10%. On the other hand, the buildings in the US have 40% of the total energy, which is the same value as the 7.7% of the carbon emission of the world in total (Guo et al., 2017). The ratio of the energy utilization in urban buildings in different regions is given in Figure 2.4.

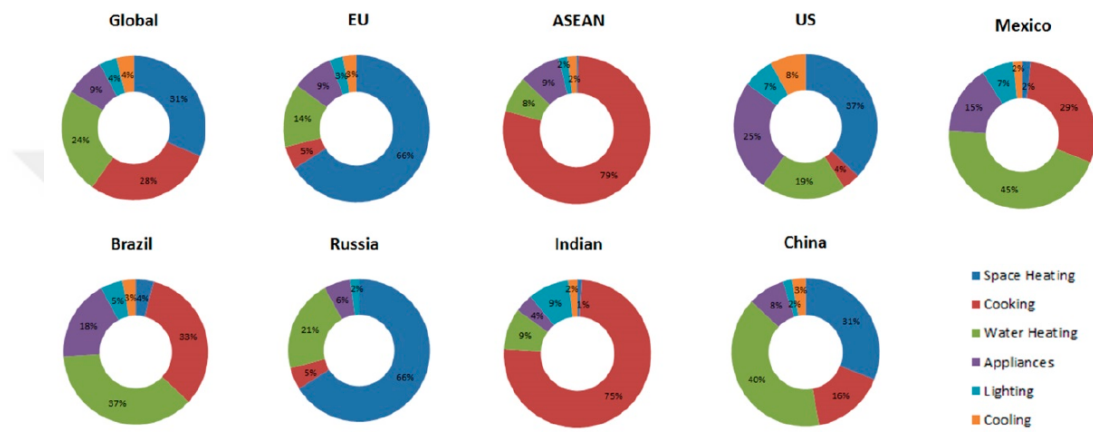


Figure 2.4. Energy Consumption in Buildings of Selected Countries/Regions (Guo et al., 2017).

Since non-renewable resourced materials are limited and pollute the environment much more than their substitutes, increasing energy consumption worldwide has become a massive problem. According to Kocaman, Sisman, and Gezer (2011), 86% of overall energy consumption is based on fossil-based resources. Turkey's energy consumption situation does not seem promising regarding the type and amount of energy used. Energy consumption is crucial for Turkey since it is a country dependent on energy sources abroad. Material-, energy-, and cost-wise, energy saving is mandatory for the proper use of insulation materials to sustain efficient use of energy with existing energy resources (Kallioğlu, Arca Batı, Karakaya & Durmuş, 2016). The distribution of total gas consumption in Turkey is given in Figure 2.5.

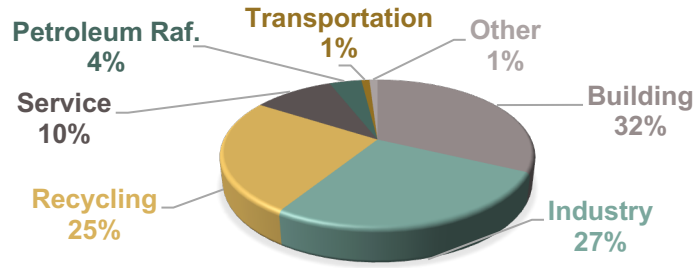


Figure 2.5. Distribution of gas consumption within sector in Turkey (Adapted from T.C. Enerji ve Tabi Kaynaklar Bakanlığı, 2022).

According to the report study conducted by T.C. Enerji ve Tabi Kaynaklar Bakanlığı (2022) for the 2020-2040 period, electricity consumption is expected to reach 370 TWh in 2025 and 591 TWh in 2040, according to the baseline scenario. The total energy consumption and production values between years 2018 and 2021 are given in Figure 2.6. As of 2021, Turkey's total electricity production is increased by 8.57% to 319,275 GWh since the year before. Source of this production is based 32.7% on gas ,31.4% on coal, 16.8% on hydraulic, 9.4% on wind, 4% on solar, 3.2% on geothermal energy (T.C. Enerji ve Tabi Kaynaklar Bakanlığı, 2022).

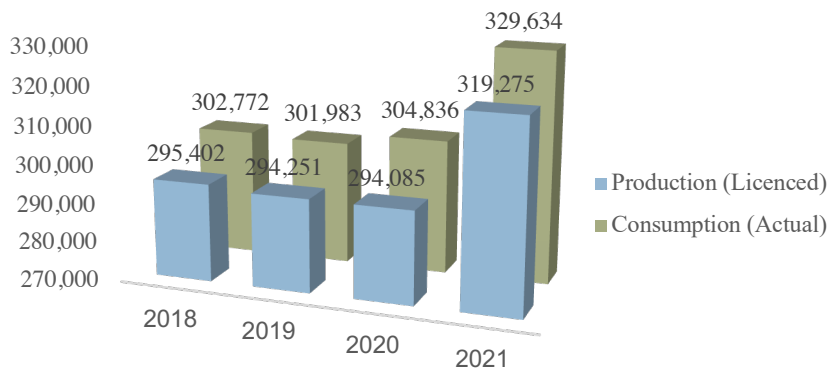


Figure 2.6. Energy Consumption and Production (GWh) in Turkey between 2018 and 2021 (Adapted from T.C. Enerji Piyasası Denetleme Kurumu Strateji Geliştirme Dairesi Başkanlığı, 2022).

Energy consumption is affected by five distinctive elements: building-related features, building technology, occupant-related features, occupant behavior, and climatic data (McCoy et al., 2018). Alongside the fact that electricity production stands as the main reason behind carbon emission, it is seen that due to the increasing electricity demand, the building sector has become one of the most significant factors in carbon emission (Hamid, Namli & Syawal, 2017).

The case of insulation materials taken as toxic materials is that foam-based materials include hydrofluorocarbons (HFCs) which emit greenhouse gases during both production and the material's lifetime (Berge et al., 2009). According to the results of the GHG inventory, the total GHG emission in Turkey in 2020 increased by 3.1% compared to the previous year and was calculated as 523.9 million tons (Mt) CO₂ equivalent. The total GHG emission per capita was calculated as 4 tons of CO₂ eq. in 1990 and 6.2 tons of CO₂ eq. in 2019. and 6.3 tons of CO₂ eq. in 2020 (Türkiye İstatistik Kurumu TÜİK, 2022).

2.2.1 Performance Assessment

Performance assessment tools can determine the buildings' performance, including energy. In this research, the performance assessment in buildings is dealt with in two aspects. The first one is the energy-related performance, including heating and cooling. The second aspect is the hygrothermal-related performance which includes air and moisture transfer.

2.2.1.1 Energy Performance Assessment

Some factors affect the energy performance assessment (EPA) methods, which are concerned with issues such as environment or energy. Objectives of these assessments are certification, decision-making, or performance in the whole-building level or singular levels detail. Therefore, assessment tools such as

simulation software and the buildings that apply to that kind of assessment should be used coherently (Wang, Yan & Xiao, 2012).

Energy performance assessment is explained as the determination of effectiveness of energy consumption in buildings by Wang et al. (2012) and building energy performance evaluation is an important feature to increase energy efficiency in the buildings. The reasons behind conducting an energy performance assessment are to determine whether the building meets the energy efficiency standards of the country and whether it could provide necessary indoor thermal comfort for the occupants of the building (Zhen & Zhang, 2018). Energy performance calculations have three main levels, building net energy (HVAC, fresh air, and hot water supply and lighting), building delivered energy, and total energy performance indicators (primary energy, CO₂ emissions, etc.) (Balaras, Dascalaki, Gaglia, Droutsa & Kontoyiannidis, 2007).

As for the Hamid et al. (2017), an analysis of the energy performance of the building is a study to not only increase the energy efficacy of the building by deciding on the factors that will have a vast effect on the energy consumption but also recommending the necessary measure to conserve energy. The authors define Building Energy Index (BEI) as “the indicator used to monitor the performance of energy consumption in buildings, acts as the reference point that provides the baseline for energy performance comparison.”

The quantitative data of energy performance assessment is known as Energy Performance Index (EPI), which kWh/m²/year, Energy Unit Intensity (EUI) represented with kWh/m². Six leading causes determine the performance of energy in a building which are indicated by Wang et al. (2012) as (1) climate, (2) building envelop, (3) building services and energy systems, (4) building operation and maintenance, (5) occupants’ activities and behavior and (6) indoor environmental quality.

Energy performance assessment test often includes characteristics related to temperature of the building, heating, cooling, energy consumption, average indoor temperature, relative humidity, building heat storage capacity, heat transfer coefficient of building elements, the total air volume of the air-conditioning system, etc. (Balaras et al., 2007).

The two reasons to set up methods and schemes for energy performance analysis are to classify the energy and the energy performance. Energy classification is a way to convey the energy efficiency and carbon emission-related data to construction supervisor and the public to promote the gains in efficiency and conservation of energy. On the other hand, energy performance diagnosis is achieved to point out the failures and the causes that result in unwanted performance in buildings and ensure the necessary steps to enhance energy performance (Wang et al., 2012).

2.2.1.2 Hygrothermal Performance Assessment

During the building design and construction, estimating the performance and lifetime of building elements, especially for sustainability features, is critical, including heat, air, and moisture (HAM) transfer processes and exchanges occurring in the envelope and their interactions with the internal and external surroundings to better forecast the hygrothermal behavior of buildings. There are various recognized modeling tools and simulation software for the thermal and hygric analysis of structures.

Due to the increase in the diversity of construction techniques and building products with technological development, it is now possible to gather data other than the experimental studies on the performance and durability of buildings during the usage phase. Today, some performance-related data has become available through calculation and can also be produced through simulation software. An essential purpose of using software is to ensure that the building is longer lasting, healthy, and sustainable under the climatic conditions of the region where it is built (Edis & Kuş, 2014). Hygrothermal performance-related failures such as moisture, mold, and

deterioration due to freeze-thaw cycle might be seen when the building envelope is not designed correctly by ignoring climate situation and user requirements.

2.2.2 Performance Simulation

Basic research methods for building simulations are field measurements, laboratory tests and hands-on calculations, and numerical analysis by computer simulations. The use of simulation tools is increasing in number and becoming widespread (Samancı, 2019). Building simulation methods should be well comprehended to understand the basics of modeling—the method of using a computer to design a virtual building construction called the building simulation. Simulations give measurable results in numerical formats. These results might include changes resulting from environmental factors and air environment, performance-related values of building energy consumption, and the environmental impacts on building material (Yang, Wi, Park, Cho & Kim, 2020).

To run a simulation, the user should provide input data from materials, building, site, weather, etc. Any lack of data might cause wide-scale errors compared to the actual situation (Yang et al., 2020). During the simulation implementation, users should supply data inputs related to building components and weather conditions (Hamid et al., 2017). To create a simulation environment, the type of the study object should be well decided. In the models, some parameters like building location, real-time occupation, the climate zone for this region, and environmental temperature can be included should be submitted as it is taken by the research of Guo et al. (2017). The use of simulations before and during the design is a critical contribution to obtaining a building with the desired performance and also provides benefits in terms of time and budget (Edis & Kuş, 2014).

Computational simulation can be used in different processes, purposes, and scales, such as estimating the performance of buildings and their components during design and analyzing their behavior in possible usage environments while developing

building products. Consequently, the software developed varies in terms of the purpose and scale of the investigation: In software such as EnergyPlus, the focus is on the evaluation of the systems to be used to ensure the energy performance of the building and provide the appropriate indoor conditions, while in software such as WUFI, the structural elements are integrated in terms of hygrothermal behavior; in software such as COMIS, indoor conditions to meet requirements such as air quality are analyzed (Edis & Kuş, 2014).

2.2.2.1 Energy Performance Simulation

An aspect of energy consumption calculation is energy performance assessment simulation. Building performance simulation is expanding in number that is conducted to create an energy model for the building (Aksamija, 2015). This model might include energy consumption and energy-related elements, including HVAC and lighting. Another method used in energy performance analysis by Kildsgaard et al. (2013) consists of three parts. The first is the design stage, where the dynamic energy simulations are managed. In the second stage, the calculated energy performance is compared with the monitored one. Finally, experience analyses on building service systems are conducted in the last step.

The tools that are provided by energy performance simulation are (1) prediction of the relation between the outdoor environment with the building's thermal behavior, (2) simulation of both daylight and artificial light effects on the building, and (3) estimation of size/capacity of the required tools to provide comfort related to sight and warmth, (4) calculation of the effects of building elements to one another, (5) controlling the compatibility with energy standards, (6) consideration of building as one whole system (Aksamija, 2015).

Several simulation toolkits and programs are currently used during the energy performance assessment. DesignBuilder, EnergyPlus, Passivhaus Projektierungs Paket / Passive House Planning Package Program (PHPP), Green Building Studio

(GBS), and Sefaira are the ones that are primarily used during the analysis of energy performances through simulation. Different versions are available according to the year release and year of the project assessment.

During the building energy assessment, heat conduction through walls and transfer of moisture in the porous structure of the wall, being exposed to not only temperature but also moisture content, is generally ignored (Barbosa & Mendes, 2008). That is why hygrothermal performance assessment models operate as simulations of building performance.

2.2.2.2 Hygrothermal Performance Simulation

Building envelope's thermal and hygric behavior is a significant part of the overall building performance. The processes of hygrothermal transport through a building enclosure are now studied better with software created and applied worldwide, just like the whole-building thermal modeling software (Künzel, Holm, Zirkelbach & Karagiozis, 2005). In addition, building simulation software on hygrothermal performance lets designers and architects control the insulation impact and prevent condensation before the construction starts (Banfill, 2021).

Yet, not much of this software takes hygrothermal interactions between air movements through the building envelope. Questions such as "How much HVAC energy is needed to sustain a hygienic indoor situation when the building has moisture?" and "How do elements of the building envelope behave with changing indoor air conditions?" are required to be responded for a comprehensive assessment on the hygrothermal activities on the building surface (Künzel et al., 2005).

To understand buildings' hydrothermal behavior, taking the heat, air, and moisture (HAM) transfer effect into consideration is necessary. This effect and changes in the building envelope due to indoor and outdoor environmental activities can be calculated with simulation software and modeling tools (Ferroukhi, Abahri, Belarbi

& Limam, 2016). For the software's calculation model, heat, humidity, and airflow can be individually or unitedly considered. The determination of software selection is affected by location and construction material features. Depending on the computational model, one-, two- or three-dimensional flow and static, static-variable, or variable regime flow can be modeled in simulations. Whether there is material differentiation in one direction in multi-layered elements, a one-dimensional calculation may be sufficient, while in material differentiation in two or three directions, a suitable calculation model should be selected. There are more than 50 integrated hygrothermal simulation software in global usage. The purpose of creation and scale of inspection designate the computation model mostly (Edis & Kuş, 2014). Some of the software used at the building component scale is given below in Table 2.2.

While creating the model, the components, and the environmental conditions in which the building is located should be defined. Materials can be selected from the software's database, or the detailed property data can be applied to the relevant interface. The features used in each software are different. While standard tests can obtain some property data, some require extensive tests and are not readily available for every material (Edis & Kuş, 2014). The properties of the material that is included as input are bulk density, porosity, thermal conductivity, specific heat capacity, moisture storage functions, water vapor permeability, and water absorption coefficient (Ramos, Delgado, Barreira & Freitas, 2009).

Table 2.2. Selected hygrothermal simulation software at component scale (Edis & Kuş, 2014).

Software	Moisture Flow Type	Moisture Type	Heat Flow Type	Material Properties	Environment Components
ID-HAM [10,11,12]	I, II	A, C	i, ii, iii, iv	1, 3, 4, 5, 6, 13	a, b, c, d, h
DELPHIN 5 [6,9,13]	I, II, III	A, B, C	i, iii, iv	1, 2, 3, 4, 5, 7, 8, 9, 11, 13	a, b, c, d, e, f, g, h
HygIRC-1D [9,14,15]	II, III	A, B	i, iii, iv	1, 3, 4, 5, 8, 9, 13	a, b, d, e, f, g, i, j
GLASTA [9,16]	II, III	A, B	i	1, 3, 4, 6, 7	a, b, d, h
WUFI 2D [3,9]	II, III	A, B	i, iii, iv	1, 2, 3, 4, 5, 6, 8, 10, 11, 12	a, b, d, e, f, g, h, i
Symbols: Moisture Flow Type: Moisture Type: Heat Flow Type: Material Properties: I: Convection A: Vapor i: Transmission 1: Density II: Diffusion B: Fluid ii: Convection 2: Porosity III: Capillarity C: Humid Air iii: Solar Radiation 3: Specific Heat Capacity 4: Thermal Conductivity iv: Latent heat 5: Sorptivity 6: Vapor Permeability 11: Water Conductivity 7: Vapor Diffusion 12: Specific Moisture Capacity 8: Fluid Diffusion 13: Air Permeability 9: Absorption 10: Diffusion Resistance F. Environmental Components: a: Temperature f: Windward b: Dampness Components g: Precipitation c: Air Pressure h: Long-Wave Radiation d: Solar Reflection i: Cloudiness e: Wind Speed j: Water Leak					

2.2.3 Environmental Impact and Sustainability of Buildings

Even if the term sustainable architecture started to become popular within the last couple of decades, the practice of sustainable architecture is considered as early as the architecture is known. Sustainability in architecture is based on a building's resource consumption and environmental impacts through all building lifecycle phases, including construction, usage, operational, and in some sources, demolition phases. Therefore, minimizing resource consumption, reducing waste production, and emission is considered sustainable architecture. In this respect, to obtain sustainable buildings with adverse environmental effects, using natural materials from local resources and taking the energy use of the building into account is necessary (Karabag & Fellahi, 2017). It is claimed by some researchers from the architecture field that vernacular architecture has been giving examples of sustainable architecture with its passive energy efficiency strategies and regional materials and techniques (Eiraji & Namdar, 2011).

Two primary global problems are the increases in buildings' energy consumption and the world population needing more spaces to accommodate can be balanced with sustainable architecture (Karabag and Fellahi (2017). Overall, the concept of sustainability primarily focuses on environmental and economic impacts in literature. Sustainable architectural design aims to achieve constructive effects on the environment with aspects of material selection, HVAC, and solar lighting, by benefiting energy-related and operational costs of a building. Three principles of sustainability are given in the Figure 2.7.

As indicated by Berge et al. (2009), several things can be applied to descend pollution in all building phases. That is to prevent using products emitting greenhouse gases and other harmful gases and pollutants more during the production phase, avoid moist situations in organic materials, increasing timber and other environmentally resource materials' usage.

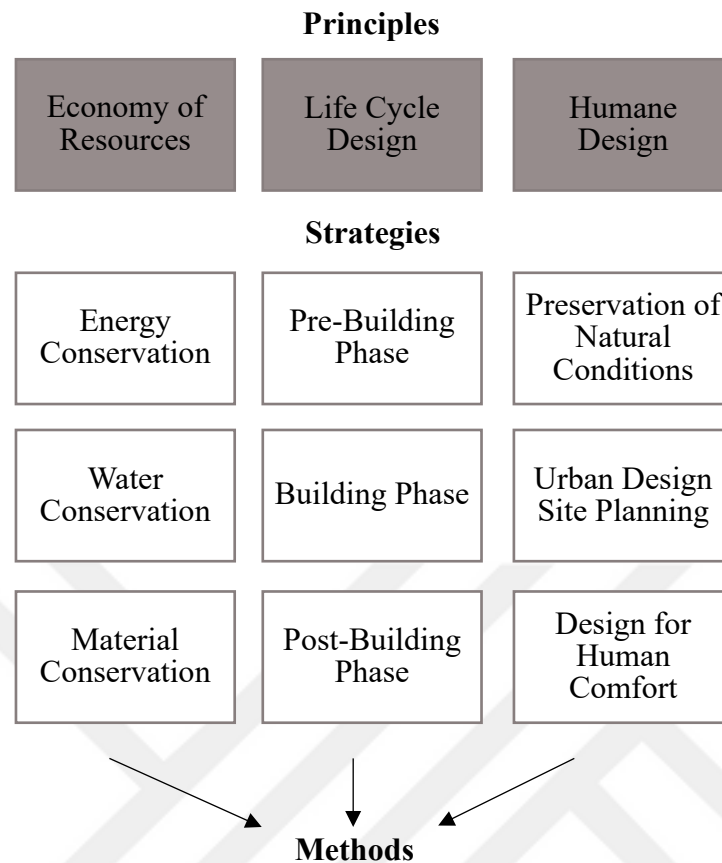


Figure 2.7. Framework for Sustainability Design and Pollution Prevention in Construction (Adapted from Karabag & Fellahi, 2017).

The economy of resources begins with the construction material production and goes through the buildings' lifecycle. Energy, water, and material conservation are three parts of economic sustainability, and each is special for building construction. Lifecycle design includes pre-, during, and post- stages of building. In this aspect, decreasing the input subsequently, the building output to the ecosystem is essential. This stage also covers the reduction of environmental effects of building materials' production stages. The final part of sustainability is human design, and it is strongly connected to the livability of all ecosystems, including flora and fauna. In this part, the focus is on enhancing the life quality for humans and other species that are users of the buildings (Karabag & Fellahi, 2017).

2.3 Thermal Insulation Materials

In a building with thermal insulation, the heating and cooling energy need to be lowered by two-thirds (Skaropoulou, Ntziouni, Kioupis, Tsivilis & Kakali, 2018). In the envelope of construction, the thermal insulation layer serves two primary purposes, to prohibit heat loss and to keep indoors at a desired and comfortable temperature. The efficiency of insulation material is determined by its thermal conductivity value. With a lower thermal conductivity valued insulation material, an insulating layer might be applied in smaller thicknesses since it is more effective (Lopez Hurtado, Rouilly, Vandenbossche & Raynaud, 2016).

In terms of insulation materials in the European market, there are two common groups of prevalent materials. The first one is inorganic fibrous insulation materials (wool-based products) and foam products (EPS, XPS, PU Foam) dominating the market with 90%. In comparison, the second group of natural materials with the remaining 10% mainly consists of mainly wood-wool. Among the materials primarily used in the European market, mineral wools are mostly preferred as stone wool and glass wool in the first place with 60% EPS, XPS, and PU foams. Below the group, organic foam insulation materials become second with having 27% of the market share (Zelazna & Pawłowski, 2011; Skaropoulou et al., 2018). Environmentally friendly substitutes of these materials have comparable or even better insulation properties, even though their market share is excessively lower (Hellová, Unčík & Cabanová, 2020).

Within these materials given above, some substances are used to increase durability and effectiveness yet contain toxic chemicals. Some of these materials are adhesive materials such as polymerized polystyrol and hexabromocyclododecane (HBCD) (Zelazna & Pawłowski, 2011).

From one point of view, the usage and production of conventional insulation materials are harmful to the environment and eventually become an inevitable factor in global warming. The material flow of the thermal insulation materials for 2015

and 2055 is shown in Figure 2.8. The thermal insulation materials used in the built environment nowadays, such as XPS, EPS, PU, and PIR foams, are mostly made of organic materials with high resistance thermal heat transfer properties and yet have adverse effects on the environment during production phases (Cetiner & Shea, 2018). Even though traditional insulation materials such as stone wool and glass fiber are organic, their resources are non-renewable, and production phases require higher embodied energy (Lopez Hurtado et al., 2016). High energy consumption has led researchers and designers to choose natural and non-toxic fiber materials providing higher moisture absorbing capacity and lower embodied energy over inorganic insulation materials, in the recent past (Cetiner & Shea, 2018).

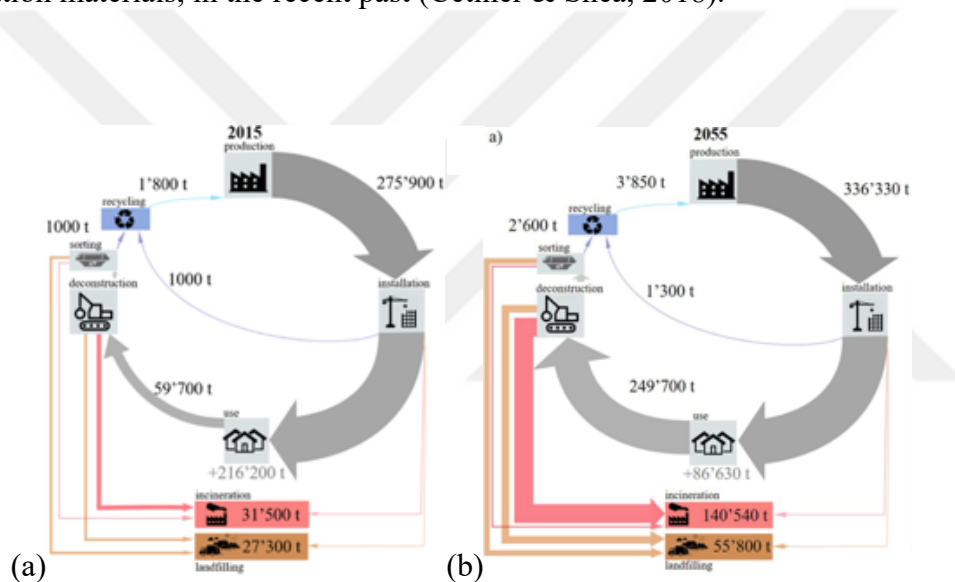


Figure 2.8. Flow of insulation materials in 2015 (a) and in 2055 according to the baseline scenario (b) (Wiprächtiger et al., 2020)

From another point of view, conventional insulation materials harm the users' health and well-being in general. As it is pointed out by Tiso, Just, and Mäger (2016), practitioners apply insulation materials with newer technologies to achieve sustainable lightweight timber frame structures with local and natural materials and to reduce the adverse effects on occupant health caused by the built environment. As

a result, a tendency has been seen to use natural products in the built environment. Miljan, Allikmäe, Jürgenson, Miljan, and Miljan (2018) have shown this tendency with the example of straw usage in sauna buildings to minimize energy usage values of the building by using locally found natural materials according to the EU's aim to enhance energy efficiency in buildings.

In terms of energy efficacy, mass distribution and inertia characteristics of timber frame construction have been more specific than concrete or masonry walls due to their non-homogeneity. Since the insulation is not homogeneous, the heat loss happens through thermal bridges. Building envelope should be properly designed in order to prevent air leakages and thermal bridges. Most heat losses are seen in timber-frame buildings at 35% through the walls, 25% through the roof, and rest in doors, windows, and floors at the same rate. That shows the importance of using suitable insulation materials and designing a proper thermal performance-based building (Cabral & Blanchet, 2021).

According to Berge et al. (2009), insulation materials require specific technical standards such as (1) significant thermal insulation properties, (2) long length or usage and durability, (3) resistance against fire, (4) being odorless, (5) deficient chemical activity and (6) capability to prevent moisture.

Table 2.3. Some thermal insulation materials in buildings (Berge et. al., 2009).

Material	Thermal Regulation		Air Regulation	Moisture Regulation	
	Insulation	Buffering	Tightening	Tightening	Buffering
Foam glass	Gu				Gu
Mineral Wool	Gu				Gu
Recycled Textile Mats		Lu			Lu
Foamed Plastics	Gu				
Fibers & Cellulose- Loose	Gu			Lu	Gu

Gu: In general use

Lu: In limited used

2.3.1 Background and Characteristics

Thermal insulation materials (TIM) have been used for millennia, beginning from caves with animal skin and fur forms and in later vegetable fibers, soil, and wood forms in settled life. With the industrial revolution, energy consumption increased by the end of the 19th century, and so did the price of gas and fossil fuel worldwide. Therefore, TIM has begun to draw attention due to decreasing heat loss and excessive energy consumption. During the 1950s, plastic-based insulation materials started dominating the sector, as seen in Table 2.4. Demand for insulation in the 1970s increased due to the global energy crisis. With the beginning of the 21st century, the environmental results of gases used in producing plastic foam materials such as HCFC and formaldehyde are seen clearly. Thus, a tendency has been seen for natural materials production and usage (Bozsaky, 2010; Bynum, 2001).

Table 2.4. Historical Development of TIM (Bozsaky, 2010).

Time	Reason	Progress	Thermal Insulation Mat.
7000 BC and earlier	Nomadic Life	Clothing material needs	Animal skins, fur, wool
7000 BC–1870 AD	Settled Life	Durable material requirement Vegetable fibers	Soil, wood, brick, straw, seaweed
1870-1950	The industrial Revolution Heat loss calculations	Natural TIM	Cork, wood wool and linen boards, cellulose
		Brick Element Development	Perforated brick, aerated concrete
		Artificial TIM	Asbestos, rock wool, glass wool, expanded glass, expanded clay and perlite
1950-2000	Plastic popularity	Artificial materials' spread Plastic foams	Polystyrene, PU, PE, and formaldehyde foams
Since 2000	Climate change & Global warming	Natural material revival	Cellulose, cork, straw, wool
	CO ₂ emissions from fossil fuels	High-tech products production	Transparent insulation materials, aerogels

Insulation materials are the sole factor that defines the buildings' energy-related performances. Therefore, thermal insulation should be measured to enhance a building's thermal performance and sustain a hygienic environment (Künzel, 1996). In addition to their thermal properties, fire resistance, soundproofing, mechanical strength, vapor permeability, environmental and occupant health-related effects are essential characteristics of thermal insulation materials. Currently, no single insulation material satisfies all the required properties (Bakatovich, Davydenko & Gaspar, 2018). As for TIM, the thermal conductivity value is expected to be smaller than 0.1 W/mK (Toydemir, Gürdal & Tanaçan, 2011). This study investigates their physical, thermal, and hygric characteristics to define insulation materials used in timber buildings.

One reason for the extreme energy consumption in buildings is based on the application of insulation materials with unremarkable qualities (Kocaman et al., 2011). According to Kocaman et al. (2011), Turkish rural buildings are built in heat wasting manner, and the electric energy used to heat buildings is almost 50% of both world's and Turkey's total energy consumption, while natural gas consumption holds 30% of overall energy power. These rates could only be lowered by appropriate insulation material selection. Materials with low thermal conductivity values should be selected, or construction elements should be insulated.

Air gaps and humidity levels of the TIM are defining factors. When the internal spaces between the material increase, the material becomes lighter and shows higher insulation behavior. Whereas the increased level of humidity adversely affects the insulating behavior. Therefore, thermal insulation materials should give lower air transmission values, which is R-Value, meaning overall heat transfer (Minke 2013).

Lack of proper insulation might result in building failures. Therefore, it is essential to control the humidity in construction for occupant life quality and structural purposes. High moisture content in construction elements might grow mold and decrease the components' durability and lifetime. Three hygroscopic materials control the indoor environmental humidity level, (1) the building envelope, (2) the HVAC system, and (3) the ceiling panel. That is why the hygrothermal behavior of building envelope is essential (Fauchoux et al., 2014).

TIM can be classified according to various criteria. One of them is the structure of the TIM. Materials are defined in three different groups. They are:

- fibrous, e.g., glass wool, rockwool
- cellular, e.g., PU, PE, polystyrene
- granular, e.g., calcium silicate, perlite (Deshmukh, Birwal, Datir & Patel, 2017).

According to the sources of materials, TIM might be handled in two different groups of inorganic and organic resourced.

TIM are divided into two main groups by their sources of raw materials. Both inorganic sourced and organic sourced materials have natural and artificial types. Divisions and examples can be seen in Figure 2.9.

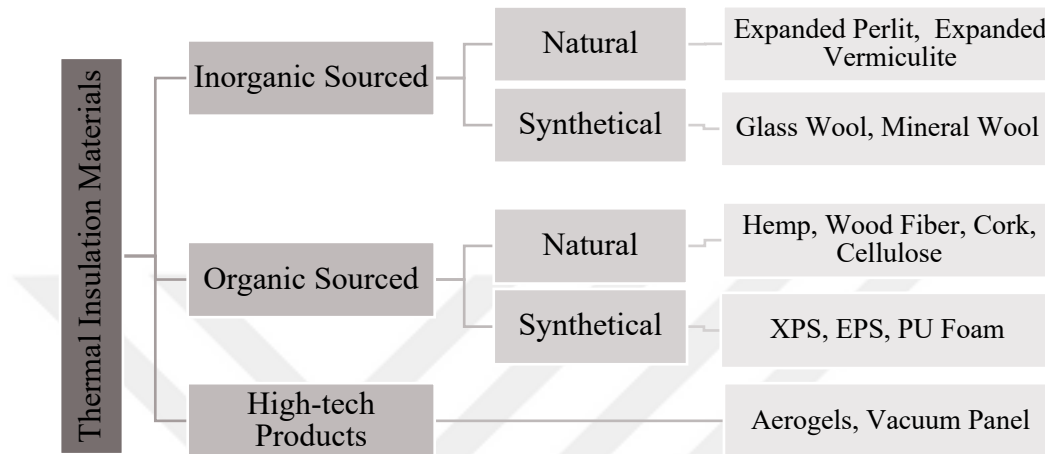


Figure 2.9. Classification of TIM (Deshmukh et al., 2017).

There are several problems with commonly used artificial TIM. Firstly, CO₂ emissions of conventional insulation materials are higher during production. Secondly and mainly, they tend to convey fire and are susceptible to emitting toxic gases that cause human losses in fire scenarios (Skaropoulou et al., 2018). The buildings constructed in the last few decades contain various heavy metals and chemicals that harm living organisms. These hazardous elements used in buildings are toxic when physically or chemically dispersed. Heat and cold changes, deterioration, and abrasion can cause physical dispersion. Chemically dispersion of hazardous materials is caused by fire, and toxic fumes are emitted. Petrochemical-based building elements such as formaldehyde, PU, phthalates, and flame retardants emit toxic chemicals under a chemical dispersion (Global Health & Safety Initiative, 2008). Pacheco-Torgal & Jalali (2011) say that the vast number of fire-related deaths are caused by toxic fume inhalation. According to former studies, increasing death

rates are possible because of the increasing amount of combustible materials spreading poisonous fumes in the last couple of decades. Fire resistance of TIM is especially crucial for timber frame buildings since they decelerate the carbonization of timber and the TIM layer is the second protection layer after the cladding falls off (Tiso & Just, 2016).

PE foam and PU foam having a toxicity index (TI) above ten are found to be highly toxic materials by the studies of Hall and Harwood in 1995, Wu in 2001, Levin and Kuligowski in 2005, and Liang and Ho in 2007. After a 30-minute-long exposure, the gas concentration becomes deadly. Therefore, it is recommended that PE and PU foams without a non-combustible covering material should not be used or used at all (Pacheco-Torgal & Jalali, 2011).

Some of the building components with adverse effects on occupants' health are given by Huang et al. (2018) in Table 2.5. It is crucial to cumulate former information since some of the building materials have a longer lifetime in building or/and are used in other constructions as repurposed material.

Table 2.5. Examples of building materials and chemicals of concern and the potential negative health effects on occupants (Huang et al., 2018).

Product Categories	Material/Substances	Example chemicals	Example negative effects
Composite wood	Particleboard, OSB, plywood	Isocyanates, formaldehyde	a, b, c, d, e
Thermal insulation	Fiber, rigid foam, spray foam	Isocyanates, formaldehyde, asbestos (historical), Polybrominated Diphenyl Ethers (PBDEs)	a, b, c, d, e, f, g
Carpets including pads	Nylon, wool	Volatile Organic Compounds (VOC) such as styrene, ethylbenzene, xylenes, formaldehyde	a, b, c, d
Pressure-treated lumber	Solid wood, laminate	Chromated copper arsenate (CCA)	a, d, h, i

a: Skin irritation and sensitization
b: eye irritation
c: respiratory effects
d: cancer
e: lung disease
f: endocrine effects
g: reproductive effects
h: blood vessel damage
i: reduced nerve function

In both dispersion cases, toxic materials adversely affect users by exposure through breathing or skin contact. This exposure might occur because of industrial or residential incidents and natural disasters (Jaramillo & King, 2021). Regarding users' health-related inspections, cases such as but not limited to asthma, skin irritations, nausea, headache, reproductive impairment, congenital disabilities, and cancer are seen because of short- or long-term exposure (Huang et al., 2018; Pacheco-Torgal & Jalali, 2011). Dermal exposure is calculated through gaseous intake of chemicals in gas form and dermal contact with the building element, shown in Figure 2.10.

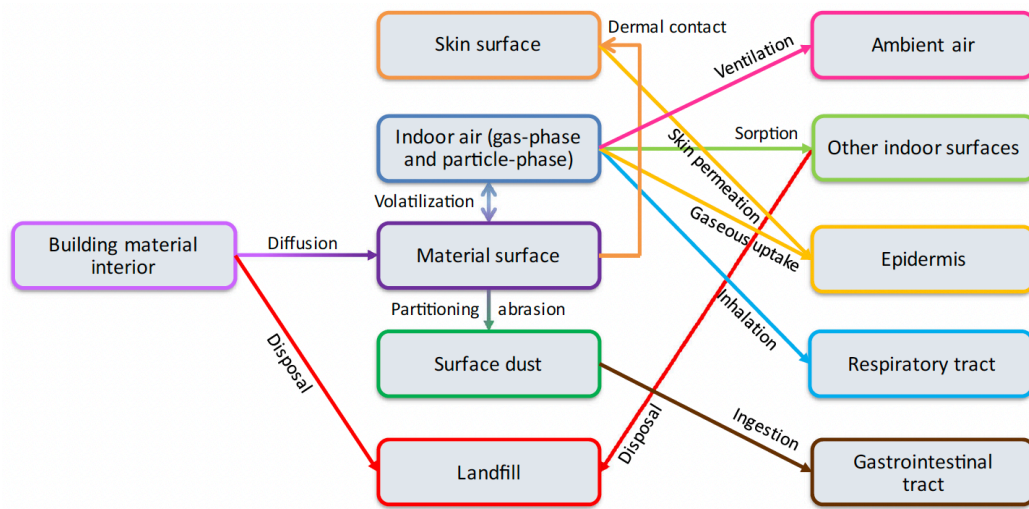


Figure 2.10. Chemical transfer and exposure channels in construction materials during the usage stage (Huang et al. 2018).

According to Global Health & Safety Initiative (2008), both users and designers should be well informed to shape the marketplace to raise the share of less hazardous building components in the light of the increasing awareness of health issues regarding building materials.

2.3.2 Ecological Thermal Insulation Materials

Thermal insulation materials used in the construction industry are produced mainly from petrochemicals or natural sources based on natural (such as hemp, wool, cork, clay etc.) or recycled (such as rubber, plastic, cellulose etc.) materials. Natural materials focusing on hemp, straw, wood, corn, coconut etc. drew the attention of researchers in the last decade (Bakatovich et al., 2018)

Ecological materials are renewable, natural-resourced, and have lower production impacts on the environment. The waste is low and recyclable (Ryan, 2011). As for natural insulation materials, hemp, sheep wool, jute, flax, cellulose, and hemp can be given (Lopez Hurtado et al., 2016). They have lower global warming potential

and energy demand from non-renewable sources than conventional materials (Bakatovich et al., 2018). Yet, in the European market, natural insulation materials draw lower attention in percentage than their conventional substitutes. Ecological thermal insulation materials are crucial to provide sustainability in the construction field and reduce the environmental impact of buildings. (Lopez Hurtado et al., 2016).

Organic insulation materials vary from conventional materials like plastic foam or mineral fibers. In this research, types of insulation materials are split into two groups traditional and ecological. Even though there are organic and inorganic-based conventional materials, the conventional kind of insulation materials in this research stands for petrochemical-based materials. Although plastic foams are chemically organic, they are not considered organic in this research. Organic insulation materials will be mentioned as ecological thermal insulation materials with natural sources throughout the paper to prevent confusion. Thermal conductivity values of some selected ecological thermal insulation materials are given in Table 2.6.

Table 2.6. Thermal Conductivity Values of Selected TIM

Material	Thermal Conductivity Value (W/mK)	Source
Raw Jute Fiber (untreated)	0.431	(Ghosh et al., 2019)
Clay Based Aerogel	0.330 – 0.040	(Skaropoulou et al., 2018)
Coconut Oil Impregnated Biochar	0.030 – 0.064	(Jeon et al., 2019)
Rice Husk Ash with Marble Waste	0.477 – 0.571	(Verma et al., 2021)
Olive Fiber Clay	0.428 – 0.593	(S. Liuzzi et al, 2018)
Lime – Hemp Concrete	0.07 – 0.11	(de Bruijn & Johansson, 2013)

When it comes to insulation, it is vital to evaluate the hygrothermal properties and hygroscopic behavior of materials to define their performances (Rode, 1998). For timber buildings, almost any commercially available insulation material can be used.

Yet, rigid foam panels including EPS and XPS are troublesome since they cannot allow timber shrinkage in the parts of a building. They are known as commercially available insulation materials commonly used in the construction industry. However, they are toxic and not compatible with natural materials such as timber. Fiber insulating material in panel form compensable for timber movement is superior since it can be compressed easily (Steiger, 2007).

A part of the increasing trend of lowering the environmental impact of construction, ecological building materials are started to be preferred among building owners and construction professionals. Some examples of ecological materials in the industry are fiber-based materials like plant fibers, cellulose, animal wool, and boron (Rode, 1998). However, the materials used in this research are limited to cork and cellulose.

2.3.2.1 Cellulose

Cellulose is made of various plants but is generally made from timber. The invention of loose-fill thermal cellulose made of shredded newspaper with water repellent and fire-resistant insulation was patented in 1893 in the UK. Cellulose is still used as thermal insulation material with a mixture of fire-resistant, mostly boron compounds and fungicide. Recycled cellulose is commonly used as an alternative to virgin cellulose. Energy use in the production phase is low, even lower for recycled options. In general, cellulose-based products, which have been popular since the 1920s, have significant moisture regulating qualities and are affected less by mold when compared to alternatives like mineral wool (Berge et al., 2009). The analyses conducted by Morgan et al. (2004) show that cellulose insulation does not contain potentially toxic inorganic chemicals like cobalt, chromium, and nickel. However, there are boron, calcium, sulfur, and sodium found to have been added as fire retardants. Boron is not considered a toxic material for users in a lower usage dose.

Loose-fill cellulose obtained from recycled paper can be used in defined spaces, and this application method is suitable for timber frame structures with closed volumes.

Since a building envelope is a “breathing” component, it is involved in the ventilation system of construction and should be air permeable. What is essential about cellulose is to conserve the material from dampness since the dampness in insulation material might increase the volume of the walls and result in deformation, subsequently, structural damage. Boron particles are included to strengthen the material to prevent rot and flammability (Steiger, 2007).

2.3.2.2 Cork

Cork is based on warm climates around northern Africa and southern Europe. It is a composition of dead cambium cells and resin combinations. Thermal insulation values are higher when the cork is expanded (Pfundstein, Gellert, Spitzner & Rudolphi, 2007). Expanded corkboards are left under pressure at higher temperatures, around 300°C, and in an autoclave for 20 minutes. At this temperature, the cork binds itself by its glue release. This resin is contained in the raw, so the material is entirely natural. The cell walls of cork granules are stretched, and thus thickness decreases. During this process, shown in Figure 2.11, the volume of the granules expands over twice, and the natural resins in the granules become binder. Expanded cork board, with a density between 80-500 kg/m³ and porosity around 75%, has high compressive strength, yet non-fire-retardant types are flammable. Heat and sound insulation properties are between 0.045-0.055 W/mK (Knapic, Oliveira, Machado & Pereira, 2016).

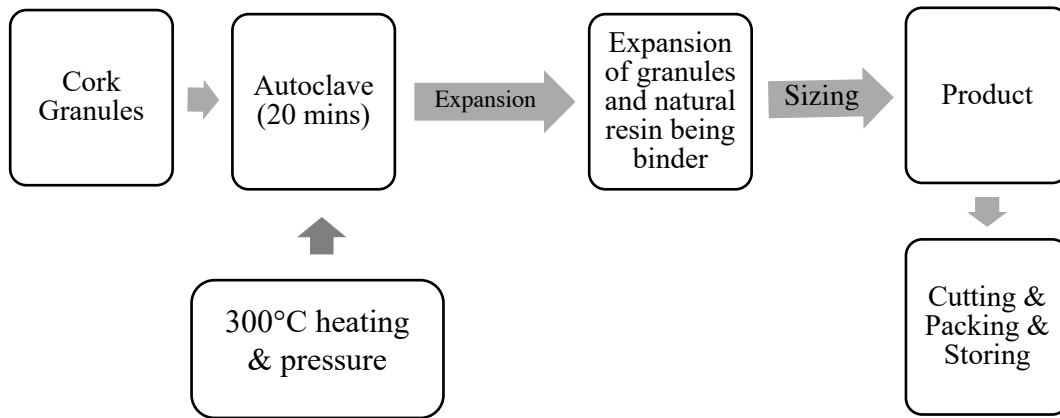


Figure 2.11. ECB Production Scheme (Adapted from Knapic et al., 2016).

2.3.3 Condensation Problems related to TIM

One of the disadvantages of natural material-based thermal insulation materials is high water absorption and, in some cases, poor fire response. Another point to cover on natural thermal insulation materials is the threat of biological attacks (Bakatovich et al., 2018). These disadvantages are summed by Lopez Hurtado et al. (2016) as high hygroscopicity and potential exposure to fungal growing effects. Moisture damage is crucial for timber buildings, and vapor resistance is much needed.

Moisture is an unwanted element that may have an adverse effect on building components and structures. The pervasive humidity absorption effect might damage the building. Since insulation materials are primarily fibrous and porous structured, the existence of water eventually causes failures in insulation materials, followed by the structural building system as a whole. This absorption mainly happens due to water vapor diffusion, yet it can also occur due to the capillarity effect (Hellová et al., 2020).

Buildings must have insulation to satisfy comfort standards, lower initial installation costs, and save energy use. Insulating comfort conditions should be kept optimum to avoid high energy consumption and condensation. Moisture and mold-related issues

resulting from condensation might decay insulation materials' life and shorten the lifecycle of a building. According to the temperature at which water vapor in the air releases moisture, sweat or condensation develops on surfaces during summer and/or winter. Without sweating, water vapor from the air can infiltrate a building material if it does not condense on the surface. When temperature and relative humidity (RH) indoor and outdoor environments are different, and when the vapor pressure is unequal between two sides of the building's surface, moisture failure occurs, namely condensation (Ünal, 2019).

The vapor moves from warm to cold sides. When the wall temperature decreases under the dew point temperature while the vapor movement, vapor particles condense either in the building wall section or on the wall's surface. Moisture content directly affects the thermal performance of the building, so the moisture transfer should be controlled. Increased moisture within the building envelope increases heat transfer and eventually decreases the buildings' thermal performance because building materials increase thermal conductivity. Alteration of one percent by volume of moisture content in the material affects the material's thermal conductivity value by three to five percent (Çengel & Ghajar 2015; Bynum, 2001).

Condensation occurs at the time when the moisture within the envelope is high on the interior and low on the exterior surfaces, and the interior environment is not sufficient enough to adjust the humidity. Consistent condensation may result in dampness reducing the thermal insulation properties of building components and causing decay (Steiger, 2007). In porous insulation materials, decreasing moisture is the main focus. Since the constant dry state is almost impossible, the equilibrium moisture content is essential (Hellová et al., 2020). Vapor transfer is expected on the exterior surface of the building, yet it is condensation between layers that should be avoided (Aslan Beregnana, 2015).

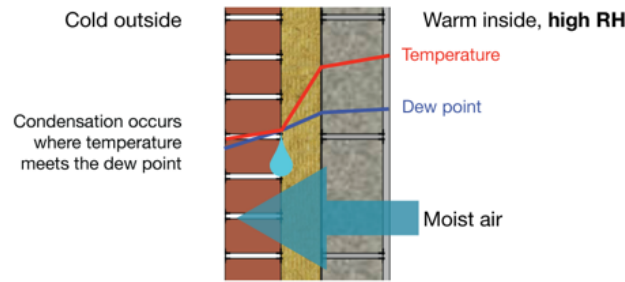


Figure 2.12. Condensation through wall section (The Green Self-Builder, 2022).

Ahead of the failures experienced is condensation arising from moisture. Natural materials tend to be porous and allow the steam to pass through the walls while balancing the inside humidity, known as the “breathing” of the envelope (Gaia Architects, 2003). Breathing of a wall refers to the controlled air passage through the layers. Air also transfers H_2O ; ergo, the water passage of any form of gas or liquid should be controlled. Without a breathing surface, water is captured within the envelope. The key to sustaining breathability is to control vapor permeability, hygroscopicity, and capillarity within the wall layer (Ryan, 2011).

In the study conducted to assess the hygrothermal behavior of wall components by Künzle (1996), calculation tools at the time showed that the best location for insulation materials is the exterior, and the thickness of the material is not distinctive as the type of the material. He underlines the risk of frost damage when the insulation material is applied when the frost is inevitable.

Since the dampness in insulation material directly affects timber and its structural properties, these materials should be protected from dampness to prevent condensation. Condensation occurs both from dampness coming from the outside and water vapor inside the building. Moisture affects building parts by not only the diffusion of water vapor but also the convection of interior air. Therefore, airtightness is essential for timber buildings (Steiger, 2007).

Moisture sources explained by Berge et al. (2009) are (1) precipitation, (2) leak from installation resulting in capillary or vapor absorption, (3) stored and released moisture from building materials, (4) groundwater, (5) airborne moisture from in or outdoor, (6) water spilled in wet areas of a building.

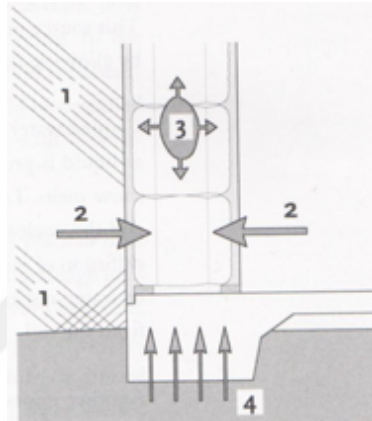


Figure 2.13. Moisture sources and wetting mechanisms (Berge et al., 2009).

However, synthetic materials used for insulation may prevent air and moist permeability (Ryan, 2011). Most temperate and cold climate nations are enacting progressively stronger regulations for improved thermal insulation of buildings to decrease energy consumption and climate emissions. Since less heat from the structure leaks through the walls to dry off any humidity that may have accumulated inside, this has resulted in increased humidity damage in some circumstances. Therefore, there is a greater need for accuracy in the planning and construction of well-insulated, low-energy buildings, which is not easy to accomplish. Because of this, it would be highly advantageous to use materials with exceptional hygroscopic properties—materials that can withstand and control humidity while allowing permeability (Berge et al., 2009; Gaia Architects, 2003).

2.4 Laboratory Experiments

The terminologies and equations, and the methods for the laboratory analyses conducted on research materials according to the testing standards mentioned in the pertinent sections, are defined in this section.

2.4.1 Bulk Density

Bulk density (ρ , kg/m³), which is also called the apparent density in the literature, is the ratio of the sample's mass to the apparent volume of the sample, including the pore space. It is calculated by the formula given in Equation 2.1. (TS EN 1936:2007; ASTM C20-00(2022)).

$$\rho = \frac{m_{DRY}}{V_{DRY}} \quad (2.1)$$

where,

m_{DRY} : Mass of the dry sample, (kg)

V_{DRY} : Volume of the dry sample, (m³)

2.4.2 Apparent Porosity

Apparent porosity (ϕ , % by volume) is the ratio of the total volume of voids in the solid sample over the total volume. It is calculated by the formula given in Equation 2.2. (TS EN 993-1:2020; ASTM C20-00(2022)).

$$\phi = \frac{(m_{SAT} - m_{DRY}) / d_{WAT}}{V_{TOTAL}} \times 100 \quad (2.2)$$

where,

m_{SAT} : Mass of the water saturated sample, (kg)

m_{DRY} : Mass of the dry sample, (kg)

d_{WAT} : Density of water at 24°C, (kg/m³), 997.32 kg/m³

V_{TOTAL} : Volume of the dry sample, (cm³)

2.4.3 Specific Heat Capacity

Specific heat (c , J/kgK), representing a thermophysical property of a material, is the heating energy required to raise the temperature of the material by one degree Kelvin per unit of mass. As expressed in the definition of specific heat, heating energy results from energy transfer between two zones, which might be given in Joule or Calorie. It is calculated with formulas in Equation 2.3. and 2.4. (TS EN ISO 11357-4:2021; ASTM E1269-11(2018)).

$$c = Q / (m \times \Delta T) \quad (2.3)$$

where,

c : The specific heat capacity, (J/kgK)

Q : Heating energy, (J)

m : Mass of the sample, (kg)

ΔT : The temperature change in the sample, (K)

$$Q = V \times I / t \quad (2.4)$$

where,

Q : Heating energy, (J)

V : Voltage, (V)

I : Current, (amp)

t : Time, (sec)

2.4.4 Thermal Conductivity Coefficient

Thermal conductivity (λ , W/mK) is given as the amount of heat being transferred to alter unit temperature through material's unit thickness. It is called as the materials' ability to convey or conduct heat. Weight, temperature, moisture content, and material structure are the sole factors that affect the conductivity. Thermal conductivity measurement tests are performed according to standards ASTM C518-21, TS EN 12667:2003, and TS ISO 8302:2002. The calculation for thermal conductivity is presented in Equation 2.5.

$$\lambda = \frac{Q \times L}{A \times \Delta T} \quad (2.5)$$

where,

λ : Thermal conductivity, (W/mK)

Q : Energy, (W)

A : Area, (m²)

L : Thickness, (m)

ΔT : Temperature Difference, (K)

2.4.5 Water Vapor Permeability

Water vapor permeability is defined as “the time rate of water vapor transmission through unit area of flat material of unit thickness induced by the unit vapor pressure difference between two specific surfaces, under specified temperature and humidity conditions” (TS EN 12086:2013; TS EN ISO 12572:2016). With the water vapor permeability test conducted, four outcomes are gathered, which are water vapor transmission rate (WVTR, g/hm²), and water vapor permeance (WVP, g/m²sPa), water vapor permeability (δ , g/(msPa)), water vapor resistance factor (μ , unitless), and water vapor diffusion-equivalent air layer thickness (s_d) which is given in meters.

Water vapor transmission rate (WVTR, g/hm²) is “the steady water vapor flow in unit time through unit area of a body, normal to specific parallel surfaces, under specific conditions of temperature and humidity at each surface” as given in ASTM E96/E96M-22 and the calculation formula is in Equation 2.6.

$$WVTR = \frac{G}{t \times A} \quad (2.6)$$

where,

WVTR: Water vapor transmission rate, (g/hm²)

G: Change in mass, (g)

t: Time, (h)

A: Area of the sample through which water vapor is evaporated, (m²)

Water vapor permeance (WVP, g/Pasm²) is expressed as the rate of water vapor transmission through material's unit area under unit vapor pressure difference between two specific surfaces at given humidity and temperature conditions. The formula for the calculation of permeance is given in Equation 2.7. Another unit used to define permeability is the “perm”. It is defined in US or SI units and known as US Perm and Metric Perm, respectively. 1 “US Perm” equals to 1.75x10⁷ g/Pasm²(ASTM E96/E96M-22).

$$WVP = \frac{WVTR}{\Delta P} \times \frac{1}{3600} = \frac{WVTR}{S \times (R_1 - R_2)} \times \frac{1}{3600} \quad (2.7)$$

where,

WVP: Water vapor permeance, (g/Pasm²)

WVTR: Water vapor transmission rate, (g/hm²)

ΔP: Vapor pressure difference, (Pa)

S: Saturation vapor pressure at specified temperature, (Pa) (2982.6 Pa at 24°C)

R₁: RH in the containers, (%)

R₂: RH in the desiccator, (%)

Water vapor permeability (δ , g/Pasm) is expressed as the “time ratio of water vapor transmission through a unit area of flat material with a unit thickness caused by a unit vapor pressure differential between two particular surfaces, under predetermined temperature and humidity conditions” in ASTM E96/E96M-22. The water vapor permeance (WVP) defines a performance of the component and not a property of a material, while the water vapor permeability is a property of a material. Formula for δ is given in Equation 2.8.

$$Permeability = WVP \times thickness \quad (2.8)$$

Water vapor diffusion resistance factor (μ , unitless) refers to a metric that compares a material’s water vapor resistance to that of a layer of static air with the same thickness and climate conditions. It may be found with Equation 2.9 or Equation 2.10.

$$\mu = \delta_{air} / \delta \quad (2.9)$$

$$\mu = s_d / t \quad (2.10)$$

Water vapor diffusion-equivalent air layer thickness (s_d , m) defines the thickness of a static air layer that has the same WVTR as the tested subject under the same measurement conditions. Calculation for equivalent air thickness of water vapor diffusion is given in Equation 2.11.

$$s_d = \mu \times t = \left(\frac{\psi L \times A \times \Delta P}{I} \right) - S_l \quad (2.11)$$

where,

s_d : water vapor diffusion-equivalent air layer thickness, (m)

μ : Water vapor diffusion resistance factor, unitless

t : Mean thickness of the sample, (m)

ψL : Constant, 6.89×10^{-6} (kg/m²)

A : Area of the sample through which water vapor is evaporated, (m²)

ΔP : Partial vapor pressures on two sides of the sample, difference between 100% RH and 40% RH at 24°C (kg/m²) (22.377 mm Hg = 304.2167 kg/m² at 24°C)

I : Weight change in unit time, (kg/h)

S_l : Thickness of the air beneath the sample, (m)

Classification of the water vapor diffusion-equivalent air layer thickness (s_d , m) and water vapor transmission rate (WVTR, g/hm²) values of building materials according to TS EN ISO 12572:2016 standards are shown in Table 3.5. According to the standards, the building materials with s_d values higher than 1.4 m have low, s_d values between 0.14 m and 1.4 m have medium, and s_d values lower than 0.14 m have high permeability. WVTR values smaller than 0.6 g/hm² show low, values between 0.6 and 6.0 g/hm² show medium, and values more prominent than 6.0 g/hm² show high permeability.

Table 2.7. Material classification of water vapor permeability according to s_d and WVTR values.

Permeability Class	s_d (m)	WVTR (g/hm ²)	WVP US Perm
Very low Permeability			<0.1
Low Permeability	>1.4	<0.6	1 > WVP > 0.1
Medium Permeability	0.14 < s_d < 1.4	0.6 < WVTR < 6.0	10 > WVP > 1
High Permeability	<0.14	>6.0	>10
Source	(TS EN ISO 12572:2016)		(International Code Council, 2020)

2.4.6 Capillary Water Absorption

With the capillary water absorption test, three values of samples are examined, which is the capillary water absorption coefficient (A , kg/m²s^{0.5}). Capillary water

absorption coefficient (A , $\text{kg/m}^2\text{s}^{0.5}$) is given in RILEM (1980) as the amount of water absorbed by the dry sample surface in contact with the water at a given time. It is calculated by using Equation 2.12. The slope of the line in the capillary absorption diagram is absorbed water mass times unit area (kg/m^2) over square root time ($\text{s}^{0.5}$) (ASTM C1794-19; TS EN ISO 15148:2004).

$$A = m/\sqrt{t} \quad (2.12)$$

where,

A : Capillary water absorption coefficient, ($\text{kg/m}^2\text{s}^{0.5}$)

m : The mass of water absorbed per unit area until time t , (kg/m^2)

t : Time passed after the capillary rise starts, (s)

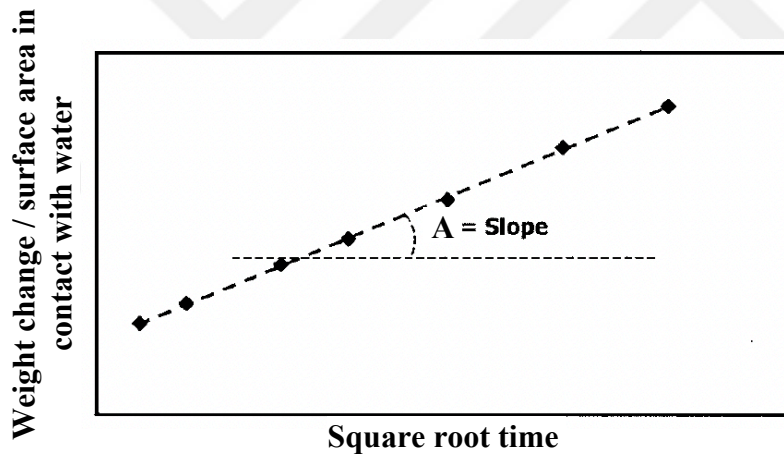


Figure 2.14. Capillary Water Absorption Test Result (Mukhopadhyaya, Kumaran, Normandin & Goudreau, 2002).

2.5 HAM Simulation Equations

The terminologies and equations, and the methods for the heat, air and moisture (HAM) simulation conducted on timber frame case building with selected ETIM

according to the standards mentioned in the pertinent sections, are defined in this section.

2.5.1 Thermal Transmittance Value

The thermal transmittance value (U , W/m²K) as given in TS 825 is “the rate of heat flow in either a single or composite material(s)”. It is determined by calculation in the formula in Equation 2.14. The heat energy is divided by the surface area and the difference of temperatures between the building system’s both sides. It is expressed as watts per square meter, per degree kelvin, or shortly as W/m²K.

$$U = \frac{1}{R} = \frac{1}{R_{si} + \frac{d_1}{\lambda_1} + \frac{d_2}{\lambda_2} + \frac{d_n}{\lambda_n} + R_{se}} \quad (2.13)$$

where,

U : Thermal transmittance, (W/m²K)

R : Thermal resistance, (m²K/W)

d_n : thickness of the n-th component layer, (m)

λ_n : rated value of the thermal conductivity of the n-th layer, (W/mK)

R_{si} : Inner heat transfer resistance, (m²K/W)

R_{se} : Outer heat transfer resistance, (m²K/W)

Table 2.8. U values recommended to be considered as the maximum value according to the regions for floor (U_F), for external walls (U_E), and for roof (U_R) (TS 825:2013).

	U_F	U_E	U_R
	W/m ² K	W/m ² K	W/m ² K
1 st Region	0.66	0.43	0.66
2 nd Region	0.57	0.38	0.57
3 rd Region	0.48	0.28	0.48
4 th Region	0.38	0.23	0.38
5 th Region	0.36	0.21	0.36

2.5.2 Energy Performance Index (EPI)

The Energy Performance Index (EPI, kWh/m²/year) is the key metric to benchmark the energy performance of building. It indicates the annual total energy consumed by a building measured in kilowatt-hours per total built up area. The area of unconditioned basements is not considered during determination of a building's EPI. It is considered as the most relevant and the simplest indicator for energy efficiency qualification of a building (TS 825:2013, EU Commission, 2016).

The ratio of surface area to volume is given as A/V in the TS 825:2013. This value is used according to the formula given in Table 2.9. to obtain the energy need of the building. The maximum and minimum energy values given for five regions in Turkey is in Table 2.10.

Table 2.9. Formula used to calculate the energy need of building (TS 825:2013).

	Formula for calculation of Q
	kWh/m ² /year
1 st Region	$36.7 \times A/V + 6.0$
2 nd Region	$63.7 \times A/V + 14.9$
3 rd Region	$74.2 + A/V + 22.4$
4 th Region	$83.4 + A/V + 31.0$
5 th Region	$88.7 \times A/V + 30.6$

Table 2.10. Minimum and maximum EPI values for buildings according to A/V ratios (TS 825:2013).

EPI	If $A/V < 0.2$	If $A/V > 1.05$
	kWh/m ² /year	kWh/m ² /year
1 st Region	13.8	44.9
2nd Region	28.5	82.3
3 rd Region	38.4	100.9
4 th Region	50.4	122.3
5 th Region	62.8	148.2

CHAPTER 3

MATERIAL AND METHOD

In this chapter, the materials and the method of the research will be given in sub-headings. The materials are divided into TIM, equipment, and lab apparatus used and simulation software. Then, the preparation process and description of the samples tested are given in detail.

Laboratory experiments to determine material properties in terms of thermo-and hygro-physical aspects were conducted. Experiments and simulation assessments of building energy and hygrothermal performance are the methods used in this research.

3.1 Material

There are four material groups in this research. The first one is the ecological thermal insulation materials (ETIM) selected. The other materials group is equipment, apparatus and other materials used to determine insulation materials' physical, thermal and hygric properties. The third material is the case study building designed by the author for a previous course used in simulation. The last type of material consists of the software, which is used for energy and hygrothermal performance assessment in the building envelope.

3.1.1 Insulation Materials

One of the materials used in the research is the ecological thermal insulation materials. The ETIM selected to be tested consists of two groups of cork and cellulose. Under changing hygrothermal conditions, building components' being especially ones with high permeability, hygric and thermal conditions change. Thus,

one part of the study was dedicated to the characterization of hygric and thermal properties of ETIM during experiments in the laboratory to compare their hygric and thermal behaviors. The properties used for the simulation have been taken from the fact sheets of materials' producers. The samples are summarized in Table 3.1. in terms of sample name, producer, production place, sample code, and basic properties. Four ETIMs were selected as the research materials; three of these, i.e., Expanded Insulation Corkboard, MDFacade, and Corkoco, are produced by Amorim in Portugal. CelluBor is produced by Çağ Mühendislik. The company specializes in cork-based materials whose production process is given under section 2.3.2. The four ETIMs are described in the following paragraphs.

- i. Expanded Insulation Corkboard: it is a sustainable construction material with moderate embodied energy, high indoor air quality, and good thermal, acoustic, and anti-vibration insulation, especially in building components such as walls, floors, roofs, and ceilings. It is obtained by processing 100% natural cork material into boards whose dimensions are 100 cm to 50 cm, and thickness is 3 cm. The product's technical specification is given in EN 13170: 2012. Its density as given in the producer's factsheet is $\pm 100 \text{ kg/m}^3$ and thermal conductivity value is declared as 0.040 W/mK by the Association pour la CERTification des Matériaux Isolants (ACERMI). Water absorption value is given as $\leq 0.5 \text{ kg/m}^2$ according to EN 1609:2013. Water vapor diffusion resistance is given as 20 according to EN 12086:2013, tensile strength perpendicular to faces is TS50, and compressive creep is CC (0.8/0.4/10)5. The thermal resistance value for 3 cm thickness material is given as $0.75 \text{ m}^2\text{K/W}$ (Amorim Cork Insulation, n.d.). Expanded Insulation Corkboard is produced according to EN 13170: 2012. In this research, it is named as expanded corkboard or EC1.
- ii. MDFacade: it is a material generally used in external applications in buildings. It was initially produced for Portugal Pavillion at Expo

Hannover in 2000. The material provides high thermal and acoustic insulation as well as mechanical stability. It is a healthy product being 100% natural sourced and fully recyclable. Board production dimensions are 100 cm to 50 cm, and thickness is typically 2 cm. Its density is given in the factsheet as $140 \pm 10 \text{ kg/m}^3$, and the thermal conductivity value is declared as 0.045 W/mK according to EN 13170: 2012. Short-term water absorption by partial immersion is given as 0.18 kg/m^2 , which is tested according to EN 1609: 2013. The water vapor transmission rate is 0.4555 g/hm^2 , and water vapor diffusion resistance factor is 54.61. These values are tested according to EN 12086: 2013. Fire reaction class of material is Euroclass E. It can be applied with adhesives or fixed mechanically (Amorim Cork Insulation, n.d.).

- iii. Corkoco: it is a combination of two natural raw materials with unique characteristics coconut fibre and cork. It provides excellent acoustic insulation performance and applies to ceilings, walls, and floors. The material shows high thermal and acoustic insulation as well as mechanical stability. It allows energy savings, and its durability is high with long-term effectiveness. The product is produced in $100 \times 50 \times 4 \text{ cm}$ sizes. The type of material used in the research is given as Corkoco 1+1, meaning it has 2 cm cork and 2 cm coconut fibre thickness. Its density is given in the factsheet as between 100 and 140 kg/m^3 , and the thermal conductivity value is declared as 0.044 W/mK by ACERMI. Airborne noise transmission in walls is 53 dB and impact noise insulation on the slab is 28 dB for the mentioned material (Amorim Cork Insulation, n.d.).
- iv. CelluBOR: it is a cellulose-based product that is produced by treating the cellulose fiber obtained from newsprint paper with boron-based chemicals. As a result of these processes, CelluBOR is able to be applied without adhesive by laying or filling methods. The type of CelluBOR product used as research material is named as CelluBor Dry Blow, that is

also known as cellulose wool and is locally produced by Çağ Mühendislik. It is a good quality thermal, sound, and moisture insulation material without any joints. More than 80% of the cellulose-based boron added material content is recycled waste newsprint. Due to its boron components, CelluBOR is anti-bacterial and does not allow insects and rodents to enter. Furthermore, CelluBOR does not contain ammonia-based materials, glass wool, rock wool, and asbestos. Fire reaction class of material is found Class E according to EN 13501-1:2007. According to European Technical Assessment by Deutsches Institut für Bautechnik, its application density is given between 30 and 60 kg/m³, and the thermal conductivity value is declared as 0.038 W/mK according to EN 12667:2001. The water vapor diffusion resistance factor of the material is given as 16 according to EN 12086:2013 (Çağ Mühendislik, n.d.).

Table 3.1. ETIM used as research material

Material	Expanded Corkboard 1	Expanded Corkboard 2	Corkoco	CelluBor
Product Name	Expanded Insulation Corkboard	MDFacade	Corkoco	CelluBOR Dry Blow
Manufacturer	A	A	A	B
Production Location	Portugal	Portugal	Portugal	Turkey
Dimensions (m)	1 x 0.5 x 0.03	1 x 0.5 x 0.03	1 x 0.5 x 0.04	loose filler
Code Name	EC1	EC2	CC	CB
Density (kg/m³)	≈100	100 - 140±10	140±10	30 – 60
Thickness (m)	0.03	0.03	0.04	
λ (W/mK)	0.040	0.045	0.044	0.038
μ (unitless)	20	54.61		16
s_d (m)		2.19		
Water Abs. (kg/m²)	< 0.5	0.18		

A: (Amorim Cork Insulation, n.d.)

B: (Çağ Mühendislik, n.d.)

3.1.2 Lab Equipment

Equipment which needed energy to operate and that were used for laboratory experiments are data logger, power meter, Protimeter, precision scales, heater, oven, and vacuum chamber.

Table 3.2. Equipment used for the tests.

Group	Name	Description	Picture
Measure	Data Logger	Three types of weatherproof HOBO® data loggers showing RH and temperature: -with screen -without screen, 1 probe -without screen, 2 probes	
Measure	Power Meter	UNI-T UT230B-EU model power meter has used to record the energy used for thermal tests. It shows voltage (V), current (A), power (W), power factor, frequency (Hz), total time (h), energy (kWh) and CO ₂ emission (kg).	
Measure	Protimeter	It is used to test moisture content in materials with two needle receivers as well as two additional probes. It gives humidity information in percentage.	
Measure	Precision Scales	Denver Instrument branded, model number SI-234. Maximum weighing capacity is 230 gr, and it works with a precision of 0.0001 gram.	

Table 3.2. (Cont'd)

Electric	Heater	JK Brand heater with 10 heating levels and two heating options which are 250 and 500 kW. It has 12.5 cm diameter and 122.72 cm ² surface area	
Electric	Oven	Stabil-Therm OV-18SC model laboratory oven works with 1759 Watts. The oven is kept at constant 60°C for all experiments.	
Electric	Vacuum Chamber	Heraeus Type DS 1 model chamber with a vacuuming capacity from 760 Torr to 0 Torr.	

Instruments and tools used during laboratory experiments are vernier caliper, plastic containers, plastic mesh, desiccator, insulation chamber, immersion system, distilled water, calcium chloride, paraffin, and stretch film.

Table 3.3. Apparatus and other materials used in the research.

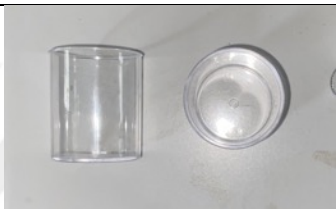
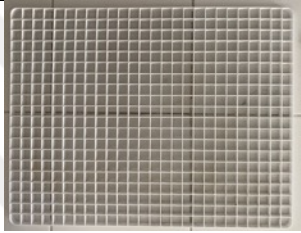
Group	Name	Description	Picture
Measure	Vernier Caliper	After the tips have been adjusted to fit across the points of selected material, the measurement is taken. The type of caliper used in this research is on a ruled scaled and it has a precision of 0.01 cm.	
Store	Plastic Container	Plastic cylindrical containers with 3.41 cm diameter, 4 cm height and 5.35 gr weight.	
Storage	Plastic Mesh	It is sized 38.5 x 30.5 cm. Each square gap has size of 1.5 x 1.5 cm. Plastic mesh is used in evaporation rate experiment to obtain a free surface to samples.	
Storage	Desiccator	Different sized sealed enclosures, which contains desiccants, used to conserve moisture-sensitive items. It is used to protect materials which might easily affect from humidity and eventually react with water. Lower compartment under the platform is filled with absorptive substances such as silica gel, calcium nitrate solution or calcium chloride particles.	
Storage	Insulation Chamber	Insulation chamber made of XPS, and its sizes are 30 x 45 x 23 cm.	

Table 3.3. (Cont'd)

Water	Distilled Water	Heated water that turned into vapor is condensed back into liquid in a different container is known as the distilled water. The machine to produce distilled water in the laboratory is also given.	 
Store	Paraffin	Used to seal materials and to achieve a water-resistant surface in materials for hygric experiments. Applied in liquid form with a brush.	
Store	Calcium Chloride	Sigma-Aldrich branded inorganic compound in the salt form, and it is shown in CaCl_2 . It is a white solid ball shaped crystalline in the room temperature and it is dissolved in water. It has a density of 2.15 g/cm^3 and molar mass is 110.98 g/mol .	
Store	Stretch Film	Regular and wide size stretch films used around samples to obtain water and vapor tight sealant that is not that chemically or physically distortive. Stretch film on top has 50 cm and stretch film below has 29 cm width.	

3.1.3 Case Study Building

The case study building is a small-scale timber frame dwelling designed in 2019 by the author as part of a course for her B.Arch. degree. It has been used to simulate the energy and hygrothermal performances of the selected ETIM. The location of the proposed building was Fatih district in İstanbul.

The reason behind the selection of this building as a case study is to estimate the building's energy and hygrothermal values before construction so that an optimized selection of building material would be achieved for the building's life cycle.

The dwelling is a two-storey timber frame building with 112 m² base floor area on a 187 m² plot. Total construction area is 224 m². There is total 3 bedrooms, 1 living room, and 2 bathrooms. Plans and sections can be seen in Figure 3.1.

Table 3.4. General information about the building.

Location	İstanbul, TR
Building Type	Housing (4 people)
Building Layout	Adjacent Order
Grass Area	187 m ²
Total Construction Area	224 m ²
Base Floor Area	112 m ²
Floor Number	2
Total Height	8.15 m
Floor Height	3 m

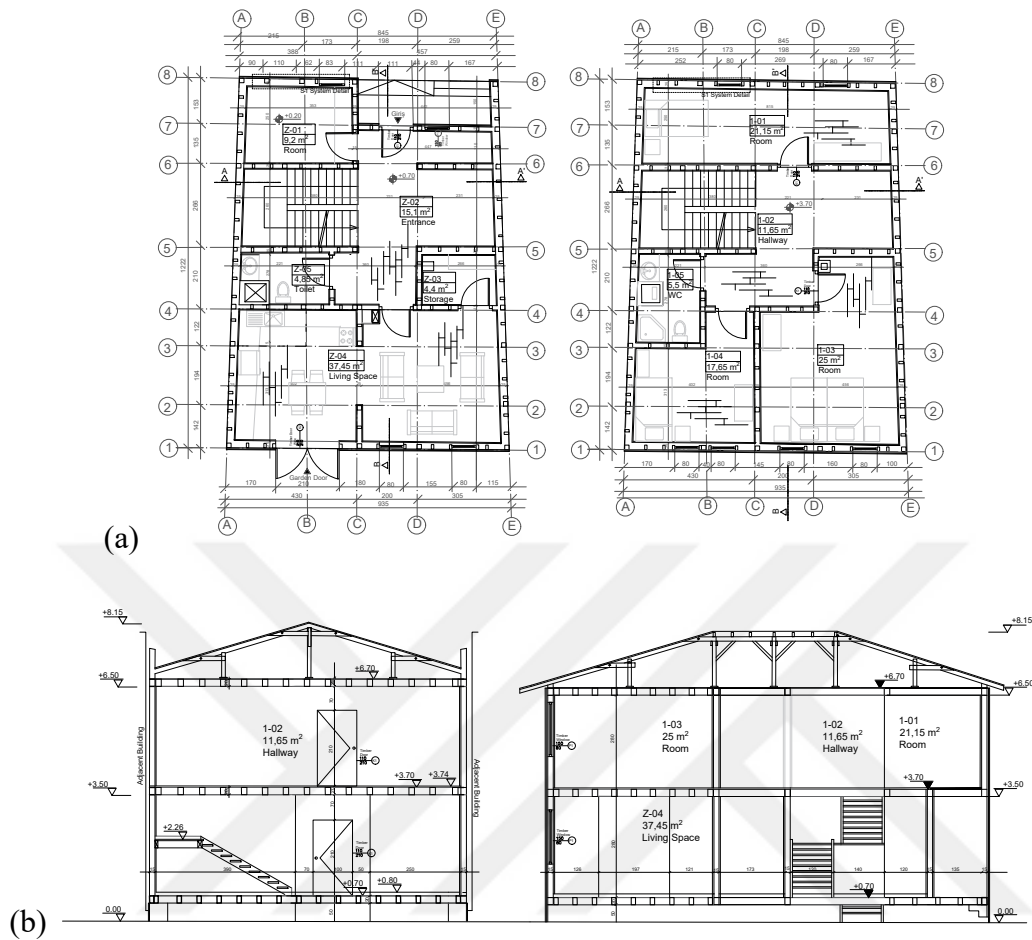


Figure 3.1. First and second floor plans (a) and AA (on the left) and BB (on the right) sections (b) of timber frame building.

Timber studs used has 15x15 cm dimensions and structural timber purlin for flooring has 12x20 cm dimensions. As for the building envelope, construction details and system section are given in the figures below. The same type of insulation layer is envisioned to be used in all floors, roof, and exterior wall sections. The façade is covered with a timber veneer cladding.

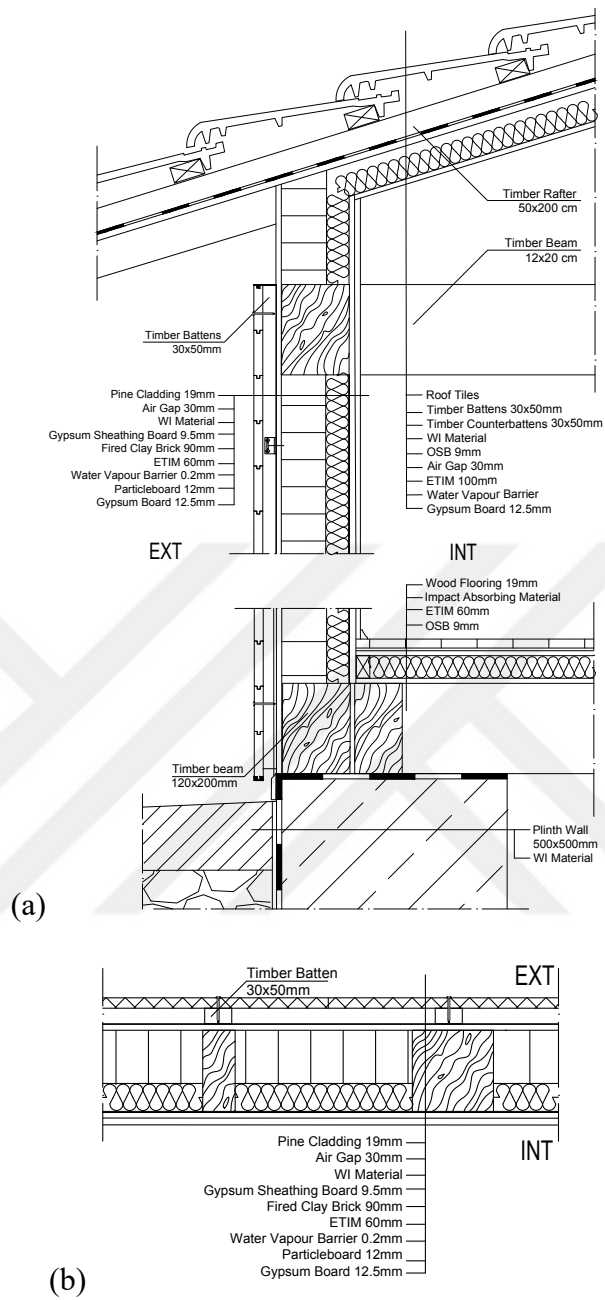


Figure 3.2. Construction details as section drawings belonging to roof and floor (a) in vertically, and external wall in horizontally (b) (Adapted from SINTEF Building and Infrastructure, 2016).

3.1.4 Simulation Software

A simulation software was used for the calculation of the building's energy and hygrothermal performance.

WUFI® Plus V.3.2.0.1

WUFI® Plus has been developed by the Fraunhofer-Institute for Building Physics in Germany. The version used for software calculations is WUFI® Plus V.3.2.0.1 with an educational license. It is a comprehensive heat and moisture simulation software. It figures out hygrothermal conditions in building components by simulation, also used as a tool to address comfort levels and energy consumption by simulating an indoor environment. The results gathered by this software are also heating and cooling energy demand, dynamic heat, and moisture flows for each building zone. In the end, it provides a full report of the building's temperature change showing hourly gradients, excess, and average daily temperatures per month as output (Fraunhofer IBP, 2019). In addition, building location, volume, envelope information, component layers, ventilation, and HVAC parameters are taken as input for simulations.

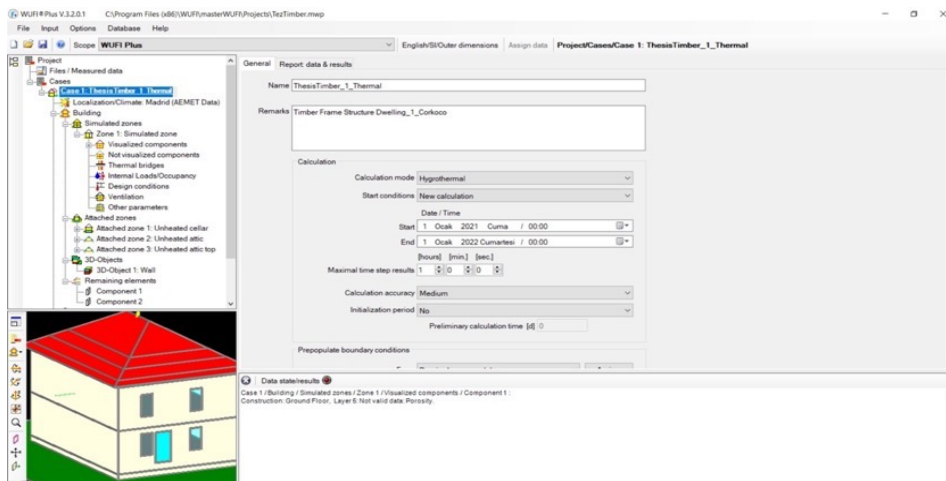


Figure 3.3. WUFI® Plus V.3.2.0.1 Software interface.

3.2 Method

The methods used in research are as follows; material preparation, determination of physical, thermal and hygric properties through laboratory tests, and building energy and hygrothermal performance simulation in software.

3.2.1 Material Preparation

Three cork-based and one cellulose-based samples given above is prepared for the analyses. The prepared samples are gathered in Table 3.5. in terms of sample codes, description of the sample and their dimensions. Naming the materials are done according to their raw material type, shapes, and number of samples. Examples for generic samples are given in the figure below.

Table 3.5. Brief Explanation of the ETIM samples used in the research

Sample Type	Sample Name	Description	Shape	Sample Code	Sizes (cm) (length x width x height)
EC1	Expanded Corkboard 1	Brown big granular board made of cork	Square Surface	EC1.s	8 x 8 x 3
			Rectangular Surface	EC1.r.	12.5 x 8 x 3
EC2	Expanded Corkboard 2	Brown small granular board made of cork	Rectangular Surface	EC2	12.5 x 7.5 x 3
CC	Corkoco	Two layered product made of coconut fibers and corkboard	Square Surface	CC.s	8 x 8 x 4
			Rectangular Surface	CC.r	12 x 8 x 4
CB	CelluBor	Wool like recycled waste newsprint with boron additives	Filled in Rectangular mold	CB	12.5 x 8.5 x 2.5

The nomenclature of the samples is given below in Figure 3.4. The type of the sample and the shape of the surface are distinctive to some of the tests conducted. Three parallel samples are prepared for each test, so the number at the end of the name refers to that ordinal number.

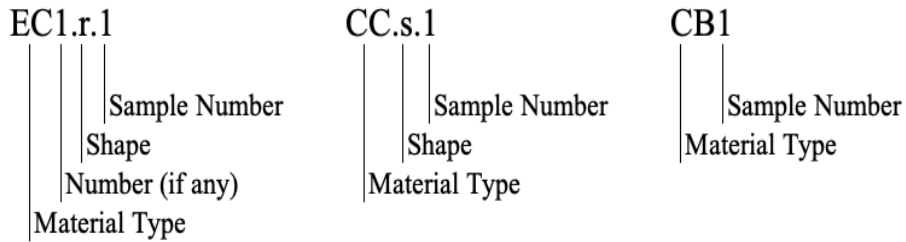


Figure 3.4. Explanation of the nomenclature of the samples EC1.r.1 (on the left), CC.s.1(in the middle) and CB1 (on the right).

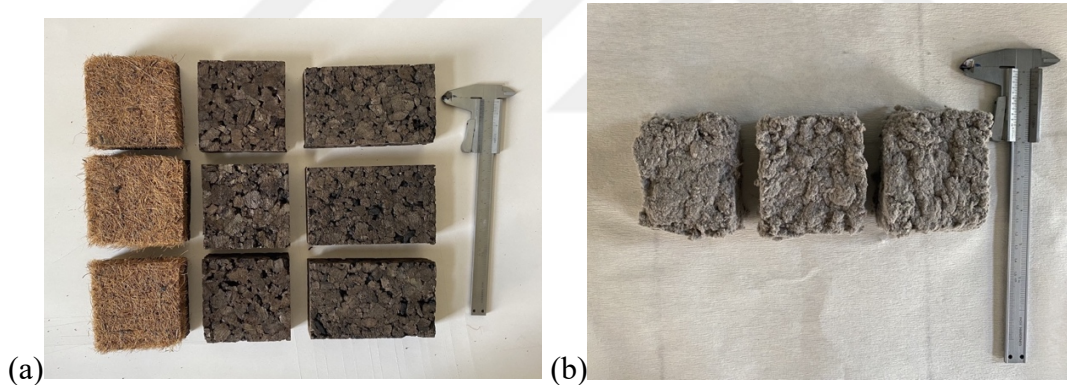


Figure 3.5. Cork based ETIM (a) with caliper scale CC.s (on the left) EC1.s (in the middle) EC2 (on the right) and cellulose based ETIM, CB (b).

Table 3.6. Samples and tests conducted.

Sample Name	TESTS					
	Physical		Thermal		Hygic	
	Bulk Density	Apparent Porosity	Thermal Conductivity	Specific Heat Capacity	Water Vapor Permeability	Water Capillarity Absorption
EC1						
EC2						
CC						
CB						

Material properties are gathered in three categories physical, thermal, and hygic. There are six tests conducted under three categories. Some tests were not applicable for one sample due to the dissolving problem in water. Conducted tests for each sample are given in Table 3.6. The analyses of material properties and performed methods, along with the standards followed for the aforementioned experimental analyses, are shown in Table 3.7.

Table 3.7. Tests and equivalent Standards to calculate properties of materials.

Material Property	Analysis Method
Physical Properties	
Bulk Density – (ρ), kg/m ³	ASTM C20-00(2022) TS EN 1936:2007
Apparent Porosity – (ϕ), % by volume	ASTM C20-00(2022) TS EN 993-1:2020
Thermal Properties	
Specific Heat Capacity – (c), J/kgK	ASTM E1269-11(2018) TS EN ISO 11357-4:2021
Thermal Conductivity – (λ), W/mK	ASTM C518-21, TS EN 12667:2003 TS ISO 8302:2002
Hygic Properties	
Water vapor diffusion-equivalent air layer thickness – (s_d), m	ASTM E96/E96M-22,
Water Vapor Diffusion Resistance Factor– (μ), unitless	TS EN 12086:2013 TS EN ISO 12572:2016
Water Vapor Transmission Rate – (WVTR), g/hm ²	
Capillary water Absorption Coefficient – (A), % by weight	ASTM C1794-19 TS EN ISO 15148:2004 RILEM (1980)

3.2.2 Determination of Physical Properties of ETIM

In this section, the analyses to determine the physical properties of insulation materials as laboratory experiments are conducted. These characteristics are given in three categories. The first one involves physical properties of bulk density (ρ), and apparent porosity (ϕ). These properties reveal the structural behavior of studied materials.

3.2.2.1 Bulk Density Test

For the analyses of bulk density, the standard of ASTM C20-00(2022) is followed. Specimens CC.r, EC1.r, EC2, and CB have been prepared as three parallel from each specimen. Samples were dried in the oven at 60°C to constant weight and recorded as the samples' dry weights (m_{DRY}). All measurements are taken with a sensitivity of 0.0001 g. For each material, four measurements were taken from the surface area and four from thicknesses with a caliper to calculate the volume.

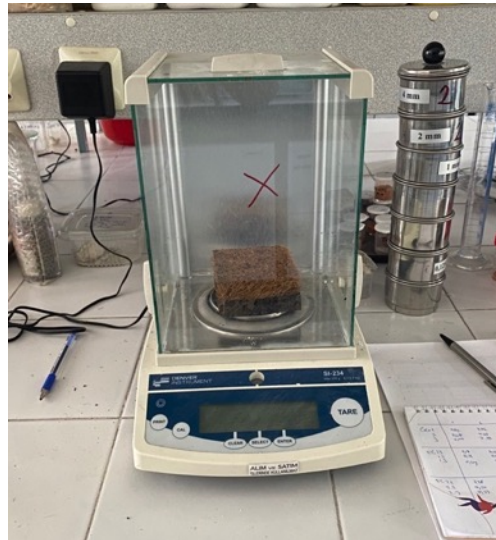


Figure 3.6. Weighing process of ETIM.

3.2.2.2 Apparent Porosity Test

For the analyses of apparent porosity properties of specimens, the standard of ASTM C20-00(2022) is followed. CC, EC1, and EC2 have been prepared as three parallel from each specimen. Samples were dried in the oven at 60°C to constant weight and recorded as the samples' dry weights (m_{DRY}). All measurements are taken with a sensitivity of 0.0001 g. Four measurements were taken from the surface area and four from thicknesses with a caliper to calculate the volume for each material. Then samples are immersed in distilled water in ambient laboratory conditions for 24 hours. Then, the samples immersed in water are put in a vacuum chamber at 0.132 atm. Since the samples should be kept underwater and they tend to float, extra weights are put on top of the samples. Saturated mass of materials is weighed (m_{SAT}). Change in mass is recorded as the weight of water, then the volume of water at 24°C is found by density. The volume of water, which is found by saturation mass over water density, is divided by the total volume of material to find the porosity ratio of material in percentage.

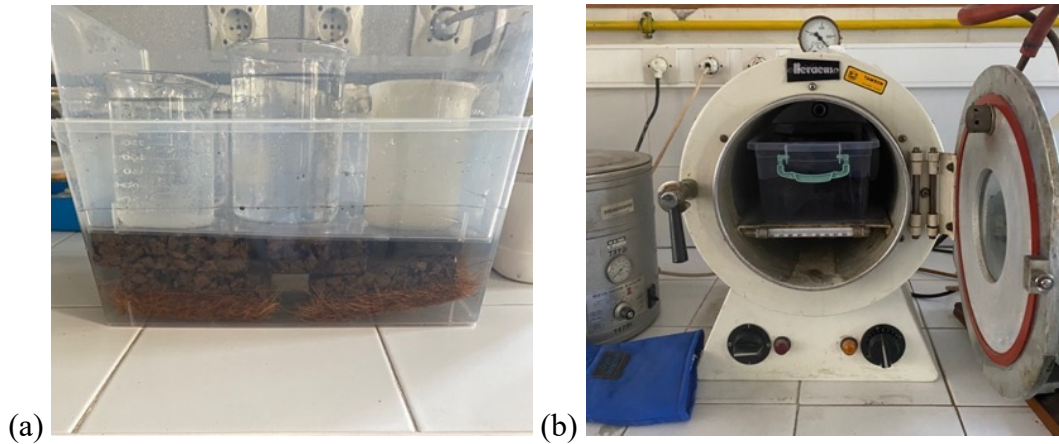


Figure 3.7. Water immersion (a) and vacuuming (b) to obtain saturated weight of materials.

3.2.3 Determination of Thermal Properties of ETIM

The second phase of laboratory analyses is conducted to determine specific thermal properties of ETIM, including thermal conductivity (λ) and specific heat (c). These properties reveal the thermal behavior of studied materials.

3.2.3.1 Specific Heat Capacity Test

TS EN ISO 11357-4:2021 is adapted as the standard to conduct specific heat capacity test. In the beginning, three parallel samples of CC, EC1, EC2, and CB are set and heated up to 60°C in the oven and settled in dry desiccators for a few hours until they reach a constant mass. Then, materials are left in a desiccator to cool down in ambient conditions. They were weighted, and data were recorded as the dry weights of the samples (m_{DRY}). In an insulated heating system, they are heated for approximately 5 mins. The power given in voltage and current is gathered with a power meter. The temperature difference is recorded with data loggers during heating.

3.2.3.2 Thermal Conductivity Coefficient

For the thermal conductivity coefficient ASTM C518-21 is followed. For each material, four measurements were taken from the surface area and four from height with a caliper to obtain surface area and thickness. The ambient temperature was 26°C, and relative humidity was 39%. Samples are heated between 2 and 3 mins. Heating energy is calculated with a power meter in kWh and divided by the time of total heating. The temperature difference between opposite surfaces of material is recorded with surface sensors attached to data loggers.

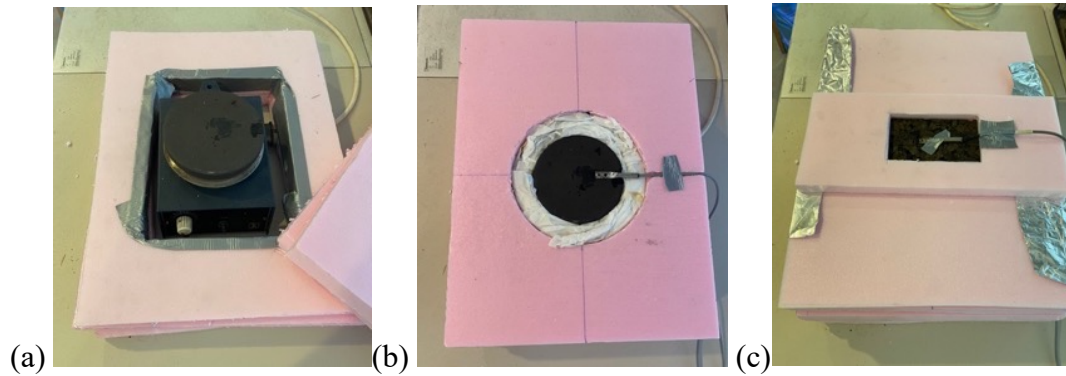


Figure 3.8. Section views from thermal conductivity calculation setup in ascending order (a) heater (b) sensor placed at the bottom of the material (c) and sensor on the top of the material.

3.2.4 Determination of Hygric Properties of ETIM

The third category of properties is hygric and involves water vapor diffusion-equivalent air layer thickness (s_d), water vapor diffusion resistance factor (μ), water vapor transmission rate ($WVTR$), and capillary water absorption coefficient (A). These properties reveal the hygric behavior of studied materials.

3.2.4.1 Water Vapor Permeability

In order to test materials water vapor permeability, the wet cup method given in ASTM E96/E96M-22 is followed. Before the experiment, three parallel samples of CC, EC1, EC2, and CB are prepared for each specimen. The thickness of each sample is measured by using a Vernier caliper on four sides in order to get an average of these measurements and record the thickness (t). Samples are placed on top of cylindrical containers, which have 3.41 cm diameter and 9.1 cm² surface area and are filled with distilled water with up to 2 cm air space between the sample and the surface or water. The samples on the containers were sealed with melted paraffin on four sides and the bottom surface exceeding the container boundary to prevent water vapor transmission from other surfaces. Figures for the apparatus are given in the

materials section above. The ambient relative humidity and the temperature were recorded. The samples are weighed with the accuracy of 0.001 g, and those weights were recorded as the initial values. Then in order to determine the water vapor permeability in controlled environment the container setups are placed inside desiccators filled with calcium chloride (CaCl_2) to protect the standard relative humidity levels ($50 \pm 5\%$ RH) and temperature at $24 \pm 1^\circ\text{C}$. The ambient environment is checked with data loggers. Each sample is weighed at 24h period intervals in order to record the weight loss caused by evaporation until weight loss per interval time becomes constant.



Figure 3.9. Desiccators filled with samples on the containers.

3.2.4.2 Capillary Water Absorption Test

Capillary water absorption test is conducted according to ASTM C1794-19. Before the experiment, three parallel samples of CC, EC1, and EC2 are prepared with the same surface area of each specimen tested. Firstly, the samples are dried in the oven at 60°C until they reach a constant weight, the materials are left in a desiccator to cool down in ambient conditions. Then the M_{DRY} is recorded. Samples are placed on a raised perforated plastic mesh over the immersion system. Distilled water was added to the immersion system until the samples were immersed to a height of 2 mm

from the bottom surface. The water level was kept constant by adding distilled water during the experiment. Relative humidity in the tub is kept constant ($50 \pm 5\%$). Weights of the samples are measured with 0.0001 gram sensitivity and at time intervals of 1-3-5-10-15-30 minutes, 1-8-12-24 hours and then every 24 hours until the samples have constant water saturation. At the end of the experiment, moisture content at the highest level is checked with Protimeter. In the end, the samples are dried in the oven at 60°C until they reach a constant weight, then left in a desiccator to cool down, and then the m_{DRY} is recorded.

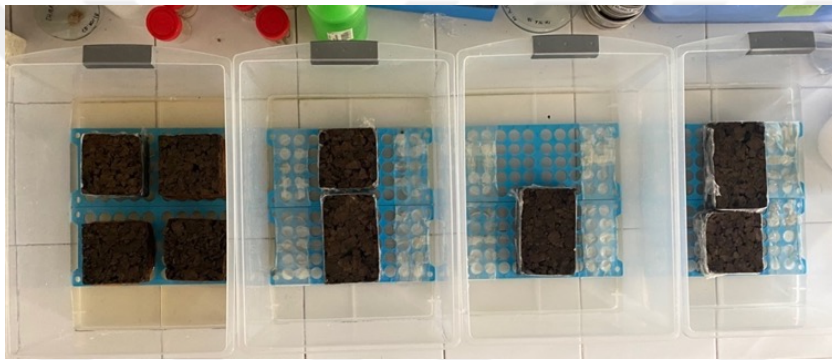


Figure 3.10. Capillary water absorption test setup.

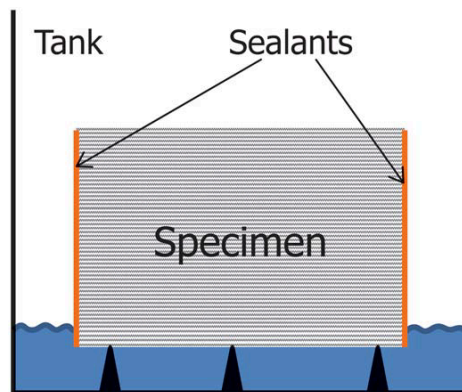


Figure 3.11. Capillary water absorption test setup diagram (ASTM C1794–19).

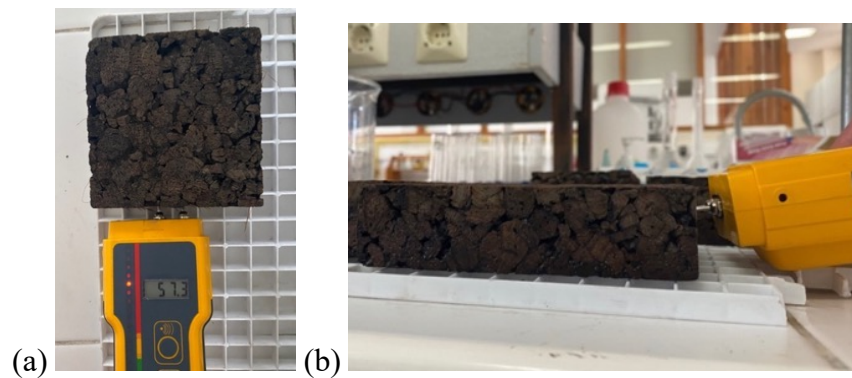


Figure 3.12. Moisture content check with Protimeter.

3.2.5 Building Energy and Hygrothermal Performance Simulation

In this section, simulation methods used within WUFI Plus for the determination of building performance in terms of energy and hygrothermal properties are explained.

The thermal response of a building is necessary for some time, yet it is essential to understand the moisture conditions and humidity effects of building next to the thermal conditions. Hygrothermal and energy performance simulation is done through WUFI Plus, a software that offers real-time calculations of heat and moisture transport of a building. Both one and two behavior of building components in real time conditions can be performed.

WUFI Plus simulates indoor environment conditions next to the hygrothermal conditions of building components. To achieve the most real-life calculations, the parameters offered are user-specified. Thermal comfort, heating and cooling loads, humidification and dehumidification tools are allowed to be interacted by the user.

3.2.5.1 Building Simulation Model

A timber frame building with 2-story and 224 m² total construction area, given in the material section, is simulated in software as the case study in WUFI Plus.

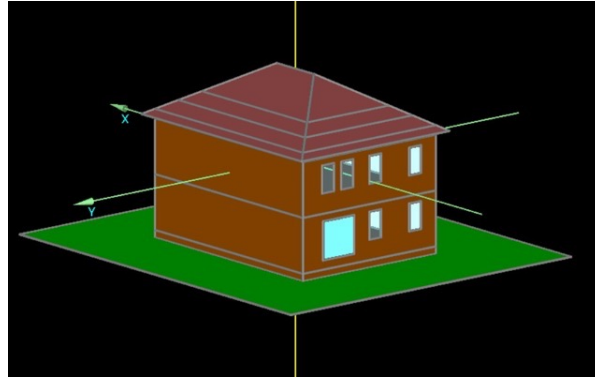


Figure 3.13. Building model made in WUFI Plus.

3.2.5.2 Operation Scheme

During the research, the operation scheme followed is:

- Composition of case study building as 3D simulation with building envelope components.
- Climate data selection from WUFI database as İstanbul, to control envelope condensation for temperature and relative humidity values according to TS 825:2013.
- Determination of material selection and thickness for each case building type according to values given in TS 825:2013.
- Determination of internal loads of timber frame building within the simulation period.
- HVAC capacities and working schedule according to the determined simulation period.

Since there are four different ETIM, four simulations have been run with CC, EC1, EC2, and CB as thermal insulation materials. All the parameters above are left constant for each simulation with dehumidification to control temperature, RH, and CO₂.

3.2.5.3 Climatic Region and Weather Data

According to the energy needs, Turkey has been classified into five regions in TS 825:2013. In order to give an idea, İzmir, İstanbul, Ankara, Kayseri and Kars are respectively in 1st, 2nd, 3rd, 4th and 5th regions. The climate for İstanbul in the 2nd region is given in Table 3.8. Climate data provided in the calculation is selected as İstanbul from the WUFI database.

Table 3.8. Temperature and Relative Humidity average values of İstanbul (TS 825:2013).

	Temperature (°C)	Relative Humidity (%)
January	2.9	79
February	4.4	76
March	7.3	75
April	12.8	74
May	18.0	74
June	22.5	70
July	24.9	71
August	24.3	74
September	19.9	75
October	14.1	80
November	8.5	79
December	3.8	80

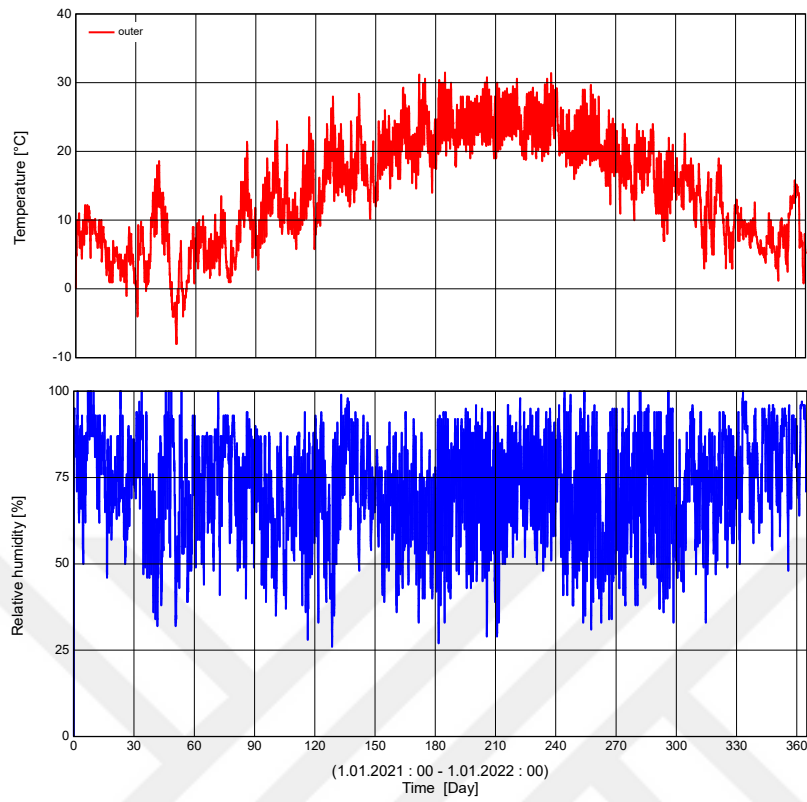


Figure 3.14. Temperature and Relative Humidity Values of İstanbul (WUFI Plus database).

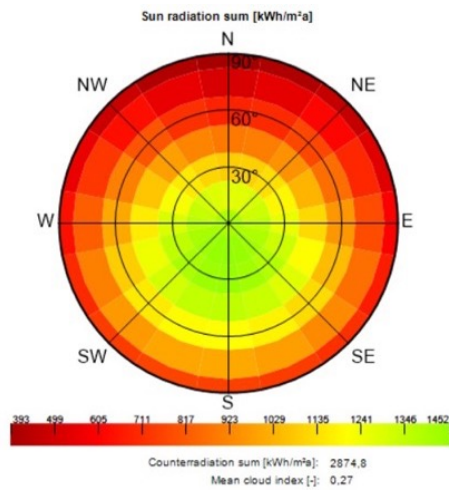


Figure 3.15. Sun radiation sum of İstanbul (WUFI Plus database).

3.2.5.4 Building Envelope Characteristics

As for the building envelope design, exterior walls, ground floor, roofing, windows, and doors are composed of the materials assigned in the timber frame building design. Inputs for the material properties are bulk density, porosity, thermal conductivity, specific heat capacity, and water vapor diffusion resistance factor of the building components. These values are taken from the software's database for every component other than thermal insulation materials. The inputs for ETIM were obtained through manufacturers' data sheets. The illustrated layers of the building envelope are given in Figure 3.16.

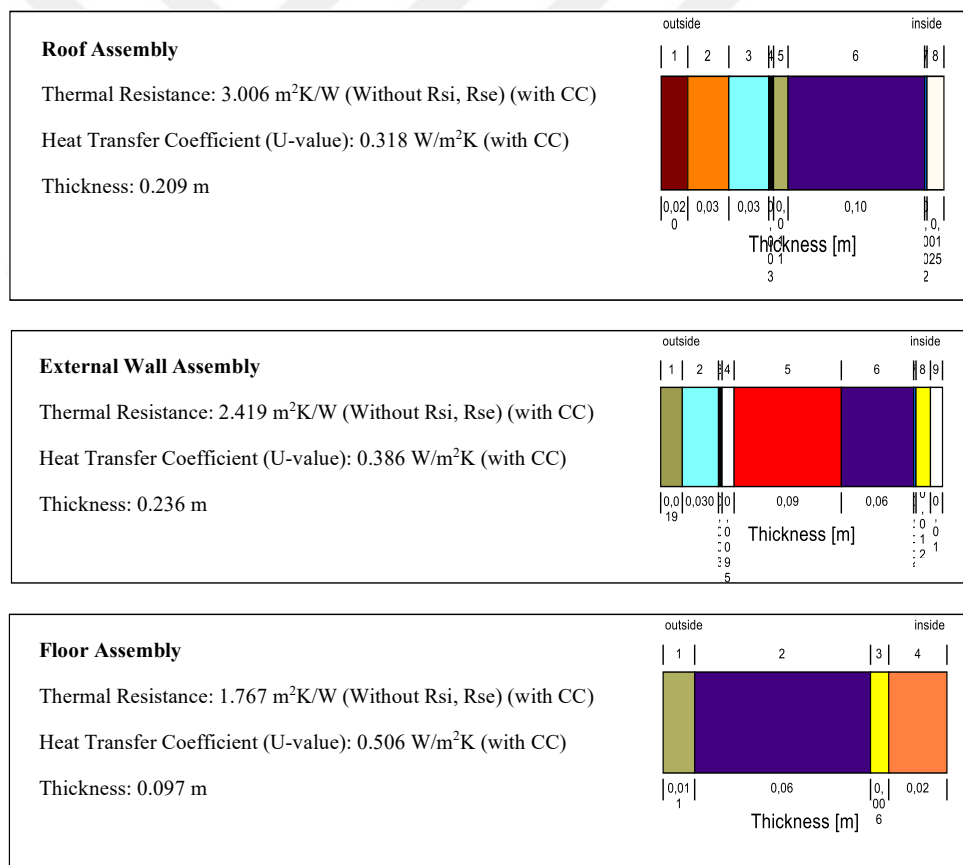


Figure 3.16. Building envelope assembly illustrations taken from WUFI Plus roof, external wall, and ground floor.

Each layer is designed accordingly with the design given in section 3.1.3. to obtain thermal transmittance values of each envelope component. The data regarding the building materials used in the envelope are given with thicknesses given below. Properties of ETIM is excluded in the table since there are four types of ETIM used as variables in the research.

Table 3.9. Building envelope layout with material selection and their characteristics.

Building Component	Material (exterior to interior)	Thickness (m)	Density (kg/m ²)	SHC (J/kgK)	TCV (W/mK)	μ value
Roof	Roof Tiles	0.02	1670	840	0.4	16
	Timber Batten	0.03	400	1400	0.09	126
	Air Gap	0.03	1.3	1000	0.18	1
	WI Material	0.004	715	1500	4	993
	OSB	0.011	650	1880	0.09	5
	ETIM	0.10				
	Vapor Barrier	0.002	130	2300	2.3	656
	Gypsum board (int)	0.012	625	850	0.2	8.4
External Wall	Timber Cladding	0.019	460	1880	0.09	54
	Air Gap	0.03	1.3	1000	0.18	1
	WI Material	0.004	715	1500	4	993
	Gypsum Sheathing Board (ext)	0.095	675	950	0.3	8.3
	Fired Clay Brick	0.09	800	850	0.18	15
	ETIM	0.06				
	Vapor Barrier	0.002	130	2300	2.3	656
	Particleboard	0.012	660	1700	0.14	56
Floor	Gypsum board (int)	0.012	625	850	0.2	8.4
	Timber Beam	0.20	400	1400	0.09	126
	OSB	0.011	650	1880	0.09	112
	ETIM	0.06				
	Impact Abs. Rubber	0.006	150	1400	0.04	10
	Wood Flooring	0.019	800	1600	0.15	51

WI: Water Insulation

OSB: Oriented Strand Board

PVC: Polyvinyl Chloride

SHC: Specific Heat Capacity

TCV: Thermal Conductivity Value

Timber framed windows and doors are used as building components. Size of windows are 0.8 x 1.5 m, while there are two types of doors with 2.1 x 2.1 m and 1.1 x 2.1 m sizes. All windows are operable with a double layer of glazing with the 0.57 solar heat transmittance value.

3.2.5.5 Internal Loads

As for the internal loads of the timber frame dwelling, the total building load calculated for 4-person family household during weekdays and weekends are selected. Since the indoor environment quality is not a part of the research, the building is taken as one space with no zones. Human activity for weekdays and weekend is given in the table below.

Table 3.10. Internal loads in building during the day.

Time (h)	Human Activity (met)	
	Weekdays	Weekend
0	0.8	0.8
6	1	0.8
6.5	1.2	0.8
7	1	0.8
8	0	1
8.5	0	1.2
9	0	1
12	0	1.2
13	1	1
14	1.2	1
14.5	1	1
18	1.2	1.2
19	1	1
23	0.8	0.8

3.2.5.6 Simulation Period

The simulation period is taken from January 1st, 2021, to January 1st, 2022. The heating period is taken between October 15th and April 15th, whereas the cooling and dehumidification schedule is taken between June 15th and September 15th. Mechanical ventilation is on during the year.

Table 3.11. Simulation and HVAC periods.

Simulation Period	01.01.2021	15.04.2021	15.06.2021	15.09.2021	15.10.2021	01.01.2022
Heating						
Cooling						
Ventilation						

3.2.5.7 Design Conditions

As for the design conditions, control temperature throughout the simulation period is limited to 20°C minimum, 24°C maximum for winter and 26°C maximum for summer, whereas control RH is limited between 45 to 55%. Maximum CO₂ concentration is fixed to 400 ppmv.

Table 3.12. Design control conditions.

Design Conditions	Minimum	Maximum
Temperature	20°C	26°C
Relative Humidity	45%	55%
CO ₂ concentration	-	400

3.2.5.8 HVAC Capacity

Before running the simulation, the last selection made is the HVAC used within the case study. The system used for heating is a condensing gas boiler with a solar collector for domestic hot water (DHW), a combination of storage tank and a radiator. The nominal heat power capacity of the used radiator is 50 kW. For cooling and dehumidification, a heat pump device with 40 kW and 50 kg/h capacity is used. The ventilation device has a 50 m³/h capacity.



CHAPTER 4

RESULTS

In this section, the results from the laboratory analysis to obtain physical, thermal, and hygric properties of cork and cellulose-based ETIM are given. In addition, the energy and hygric performance simulation results on the selected timber frame building with the aforementioned ETIM are further examined. All results are separately summarized below the relevant subheadings.

4.1 Physical Properties of Insulation Materials

The bulk density (ρ) and apparent porosity (ϕ) of expanded cork (EC1 and EC2), Corkoco (CC), and CelluBor (CB) samples are given on Table 4.1. and Figure 4.1. The values are calculated according to Equation 2. and Equation 2.2. Apparent porosity for CelluBor is not calculated due to the dissolving problem.

Table 4.1. Bulk density (ρ) and apparent porosity (ϕ) of ETIM.

Sample Name	ρ	ϕ
	kg/m ³	% by volume
CC	99.96±8.30	14.35±1.36
EC1	97.87±3.42	7.05±0.55
EC2	114.39±4.10	11.60±1.98
CB	90.88±10.72	-

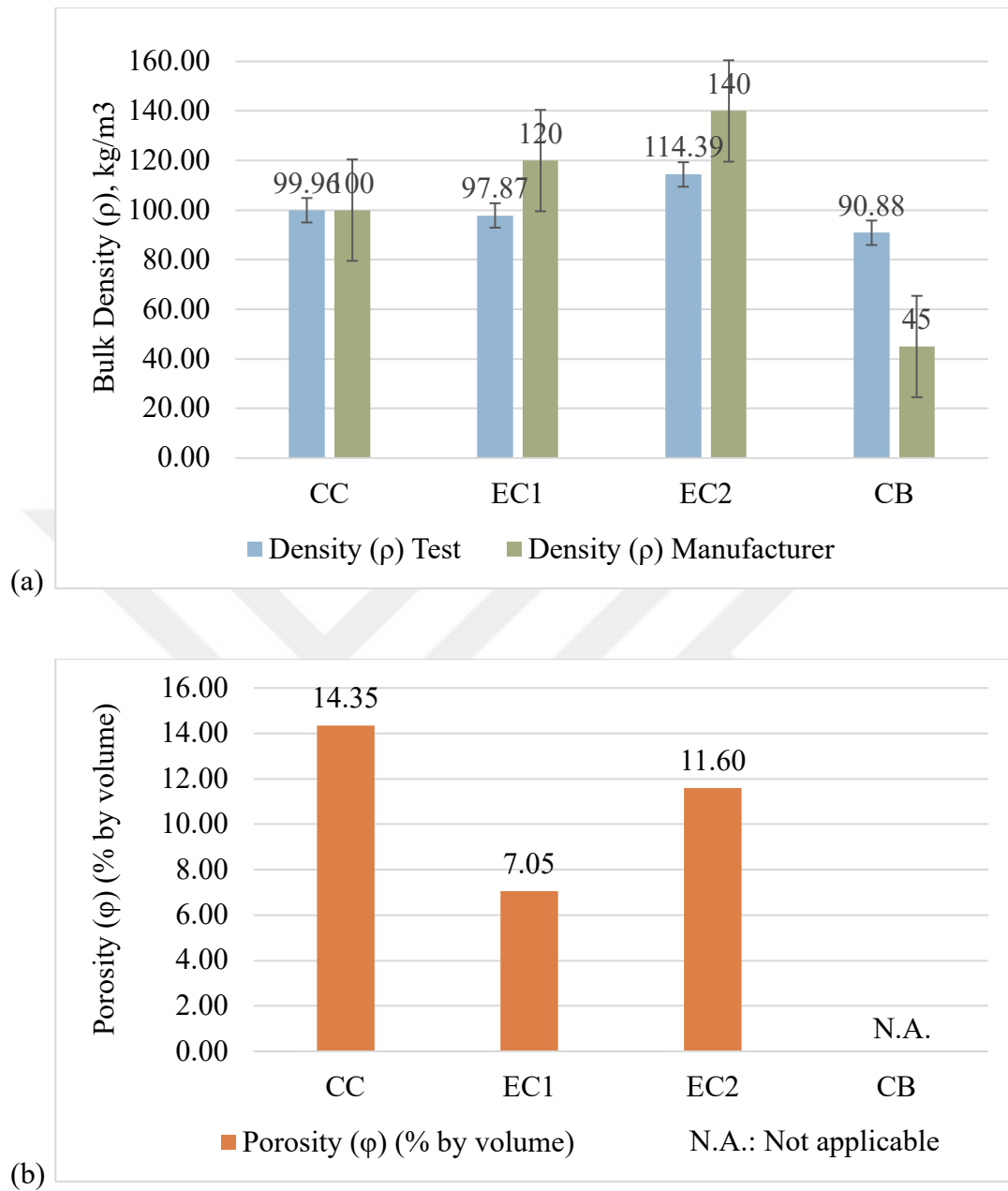


Figure 4.1. Bulk density (ρ) values manufacturers' info sheets and test at (a) and apparent porosity (ϕ) at (b) of ETIM.

According to the results given in the plots above:

- The bulk density values of CC, EC1, EC2, and CB are found 99.96 ± 8.30 , 97.87 ± 3.42 , 114.39 ± 4.10 , and 90.88 ± 10.72 kg/m³, respectively. EC2 stands as the material that has the highest density, while CB has the lowest density.
- The apparent porosity for the samples CC, EC1, and EC2 are found $14.35 \pm 1.36\%$, $7.05 \pm 0.55\%$, and $11.60 \pm 1.98\%$ by volume, respectively. EC1 has the lowest porosity ratio by circa 7% and CC has the highest porosity ratio which is a result of coconut fiber texture.
- The results for apparent porosity analysis showed that among cork-based samples the densest material is EC2 and the most porous material is CC. EC1 is the material with the lowest density and porosity.

4.2 Thermal Properties of Insulation Materials

The results of specific heat capacity (c), and thermal conductivity (λ) that are obtained from laboratory experiments for ETIM samples are given in plots below. The results are calculated according to Equation 2.3. and Equation 2.4. given in section 2.4.3 and section 2.4.4.

Table 4.2. ETIM's bulk density (ρ), specific heat capacity (c_{test}) and thermal conductivity (λ_{test}) values found through laboratory experiment and specific heat capacity (c_{manu}) and thermal conductivity (λ_{manu}) values taken from manufacturers.

Sample	ρ	c_{test}	c_{manu}	λ_{test}	λ_{manu}
Name	kg/m ³	J/kgK	J/kgK	W/mK	W/mK
CC	99.96 ± 8.30	$5,390.24 \pm 830.70$	1,400	0.232 ± 0.003	0.044
EC1	97.87 ± 3.42	$8,723.14 \pm 1588.56$	1,670	0.173 ± 0.005	0.040
EC2	114.39 ± 4.10	$7,078.51 \pm 427.71$	1,560	0.177 ± 0.002	0.045
CB	90.88 ± 10.72	$8,035.44 \pm 306.31$	1,550-	0.150 ± 0.014	0.038

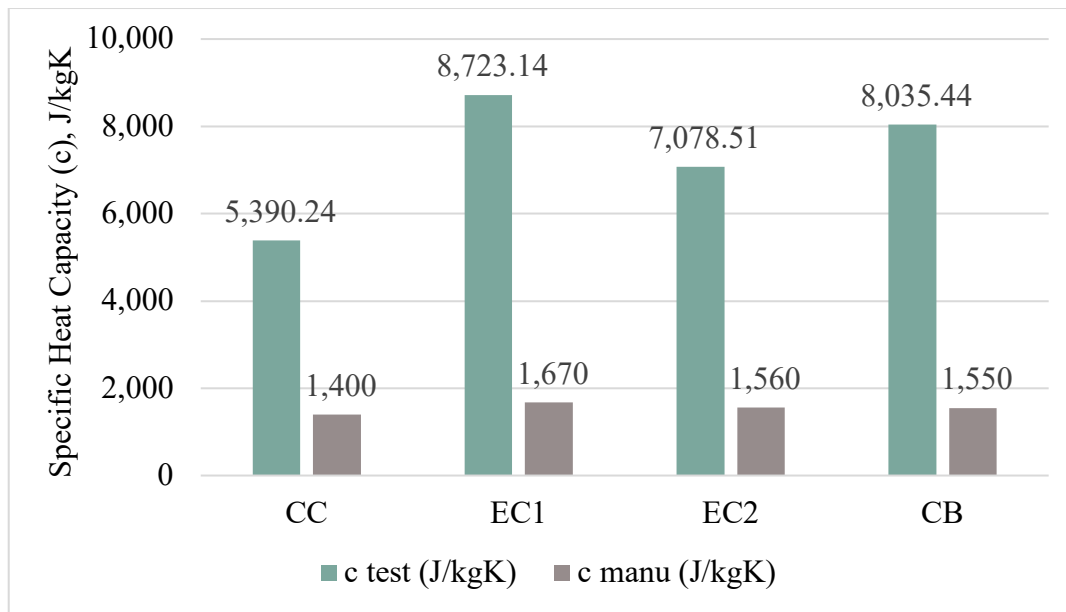


Figure 4.2. Test and manufacturers' data sheet based specific heat capacity (c) values of ETIM.

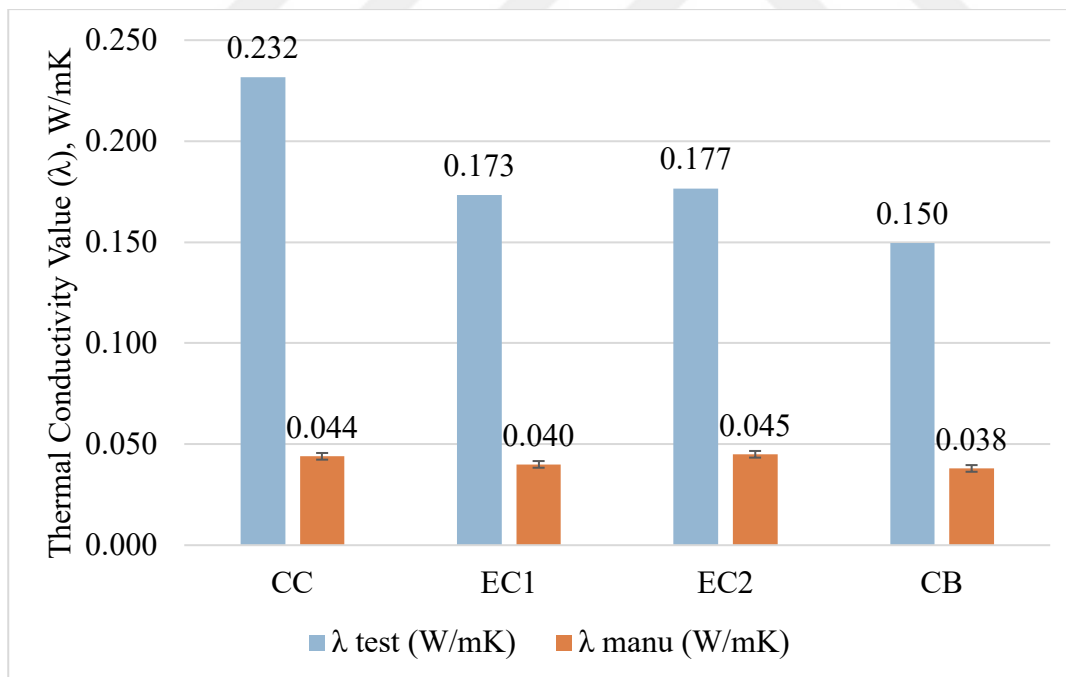


Figure 4.3. Thermal conductivity (λ) values of ETIM (found through laboratory experiment and manufacturers' data sheet)

According to the plotted results, which are gathered in ambient conditions of 39% RH and 26°C:

- The average specific heat capacity values of CC, EC1, EC2 and CB are found to be 5,390.24, 8,723.14, 7,078.51, and 8,035.44 respectively.
- The specific heat capacity of Corkoco has the lowest value within all samples. EC2 and CB has shown close results in terms of specific heat capacity.
- The results show that the specific heat capacity of EC1 is higher than the rest of materials, with 8,723.14 J/kgK.
- Thermal conductivity values are determined as 0.232, 0.173, 0.177, and 0.150 respectively for CC, EC1, EC2 and CB in the laboratory experiment. Results show that Corkoco has the highest thermal conductivity value within researched ETIM, whereas CelluBor has the lowest value. Expanded Corkboards of different densities have shown close values.
- As for thermal conductivity values, all values that are found through laboratory experiments are seen higher than the number given through producers' data sheet. That is mostly because of the ambient conditions obtained in laboratory and the lack of experiment setup which may conduct instant heat.

4.3 Hygric Properties of Insulation Materials

The water vapor permeability, and capillary water absorption test results conducted to ETIM are given below in detail.

4.3.1 Water Vapor Permeability

The results of water vapor permeability test conducted on all ETIM samples, which gives the water vapour diffusion-equivalent air layer thickness ($s_{d,m}$), water vapor

diffusion resistance factor (μ , unitless), water vapor transmission rate (WVTR, g/hm²) are shown in Table 4.3., Figure 4.4., and Figure 4.5.

Table 4.3. Water vapor diffusion resistance factor (μ), equivalent air layer thickness of water vapor permeability resistance (s_d), water vapor transmission rate (WVTR), and water vapor permeance (WVP) of ETIM.

Sample	thickness	μ	s_d	WVTR	WVP
Name	m	unitless	m	g/hm ²	US Perm
CC	0.040	2.10±0.23	0.082±0.09	20.73±2.01	67
EC1	0.030	10.96±2.89	0.326±0.167	6.69±2.61	20
EC2	0.030	14.29±2.57	0.433±0.077	4.71±0.86	14
CB	0.025	2.14±0.17	0.076±0.004	21.77±0.85	75

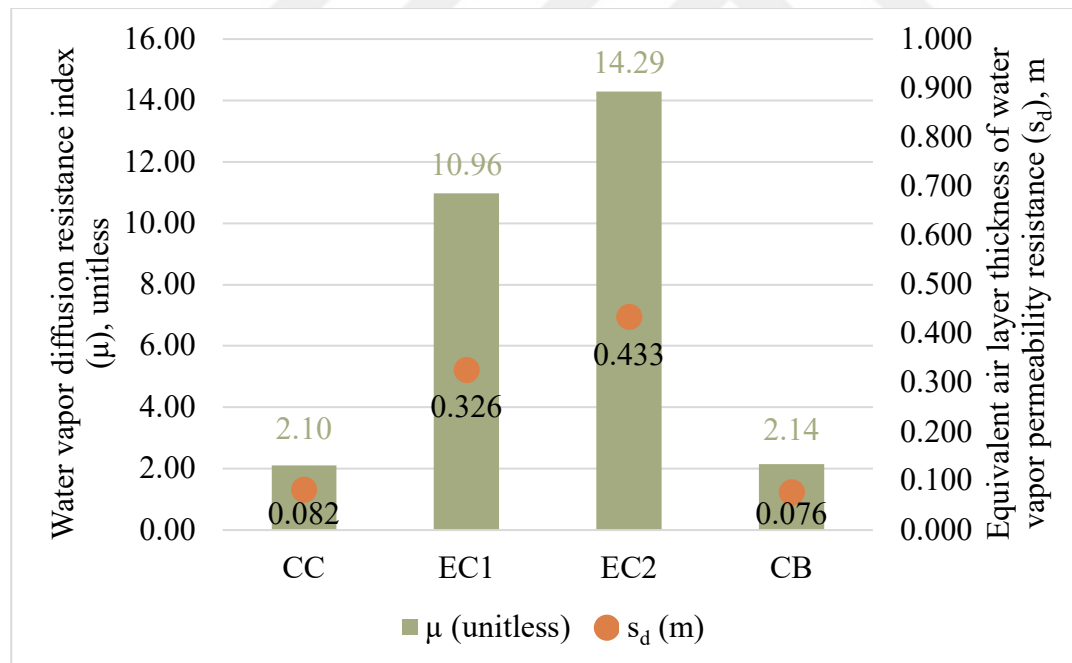


Figure 4.4. Water vapor diffusion resistance factor (μ), and water vapour diffusion-equivalent air layer thickness (s_d) of ETIM.

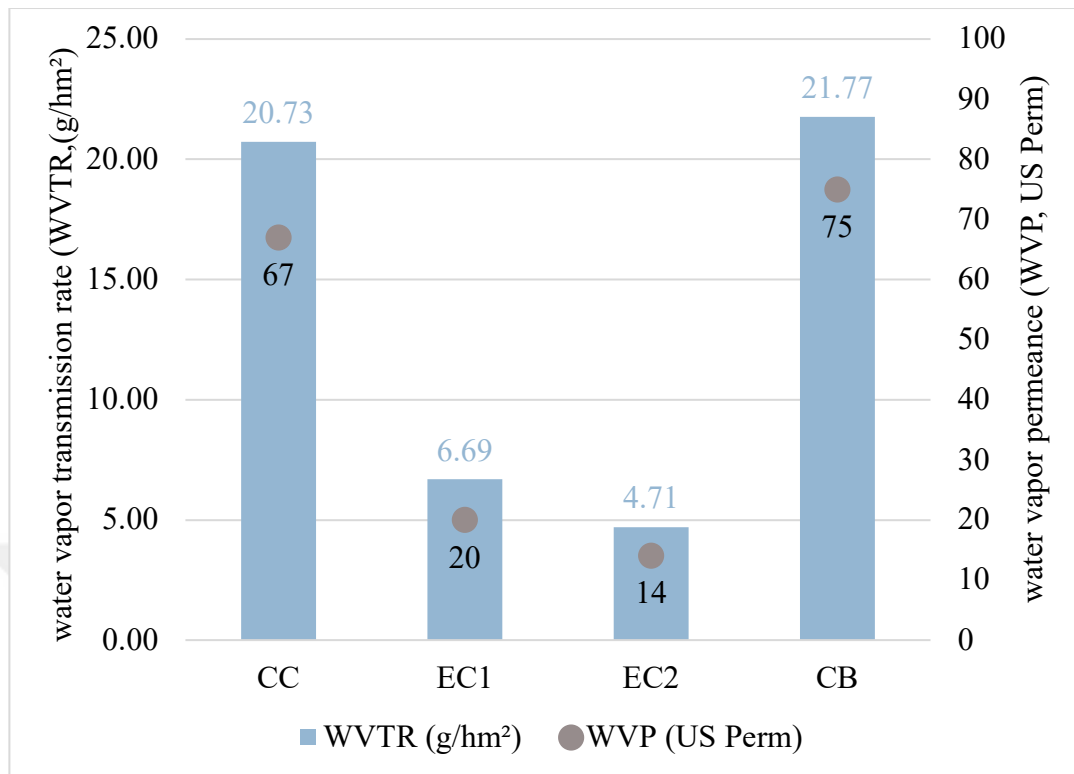


Figure 4.5. Water vapor transmission rate (WVTR), and water vapor permeance (WVP) of ETIM.

According to the results presented in Table 4.3., Figure 4.4. and Figure 4.5.:

- The ambient conditions provided during the tests are relative humidity of $50 \pm 5\%$ and temperature at $24 \pm 1^\circ\text{C}$.
- Water vapor diffusion resistance factor values (μ) for ETIM samples are found between the range of 2.10 and 14.29. μ values for samples CC, EC1, EC2 and CB have determined 2.10, 10.96, 14.29 and 2.14, respectively. Corkoco has the lowest μ while EC2 has the highest. Corkoco and CelluBor showed close values. The most resistant type to water vapor diffusion is found as EC2 since it has the highest μ value due to its low porosity.
- The equivalent air layer thickness of water vapor diffusion (s_d) values of CC, EC1, EC2 and CB samples are found 0.082, 0.326, 0.433 and 0.076

respectively. According to (TS EN ISO 12572:2016), Corkoco and CelluBor are classified as highly permeable which have lower s_d value than 0.14, while Expanded Corkboard samples are determined as materials in medium permeability class having s_d value between 0.14 and 1.4.

- Water vapor transmission rate (WVTR) values are found 20.73, 6.69, 4.71 and 21.77 respectively for CC, EC1, EC2, and CB samples. CC, EC1 and CB samples having larger values than 6 g/hm², are classified as high permeable materials. Yet, EC2 sample has a lower WVTR value meaning it has medium permeability.
- In terms of water vapor permeance, the CC, EC1, EC2 and CB samples have determined 67, 20, 14, and 75 US Perm respectively. Corkoco has the highest WVP value, while MDFacade (EC2) has the lowest.

4.3.2 Capillary Water Absorption

The results of the water absorption by capillarity test of ETIM samples which is capillary water absorption coefficient (A) are given in Table 4.4. Figure 4.6. and Figure 4.7.

Table 4.4. The capillary water absorption coefficients (A) of the surface perpendicular to the rising direction of CC, EC1, EC2 and CC.

Sample Name	ρ	A
	kg/m ³	kg/m ² s ^{0.5}
CC	99.96	0.0462
EC1	97.87	0.0100
EC2	114.39	0.0076

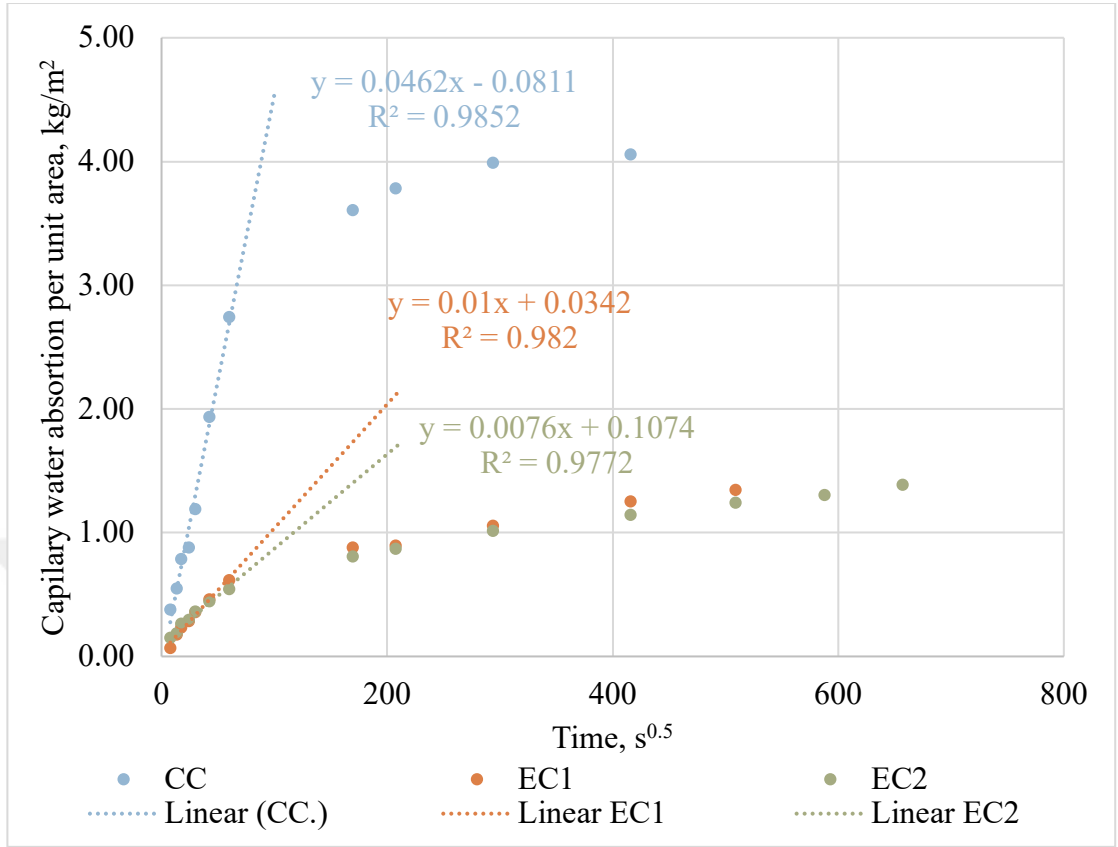


Figure 4.6. Capillary water absorption coefficient of the surface perpendicular to the rising direction of CC, EC1, and EC2.

According to the plots shown, the results, obtained in ambient conditions $50 \pm 5\%$ RH and $24 \pm 1^\circ\text{C}$, are summarized below:

- The maximum capillary water absorption coefficients perpendicular to the rising direction (A values) of CC, EC1 and EC2 are found 0.0462, 0.0100 and $0.0076 \text{ kg/m}^2\text{s}^{0.5}$ respectively.
- Capillary water absorption behavior of Corkoco is differs from the others with the highest value determined by 0.0462.

According to the measurements taken with the Protimeter and the vernier caliper on Figure 4.7., it is seen that the Expanded Corkboard samples have absorbed water up

till 1.98 ± 0.30 cm and between 16 to 25%. As for Corkoco samples, the compressed coconut fiber part has absorbed water up to 96%, while the corkboard part has absorbed water up for 0.57 ± 0.40 cm and between 40 to 48%.



Figure 4.7. Capillary water absorption check with Protimeter and caliper.

4.4 Energy and Hygrothermal Performance of Timber Frame Building

For the research, four types of thermal insulation materials are used, and four simulations have been performed with WUFI Plus software. The outcomes of simulations are as follows: the U-values of envelope, EPI of case building and the hygric properties of building components with selected ETIM.

4.4.1 Thermal Transmittance Value

The U-value for floor (U_F), external walls (U_E), and roof (U_R) for the case building designed with selected ETIM are given on Table 4.5. and Figure 4.8. The values are calculated according to Equation 2.14.

Table 4.5. The U values for floor (U_F), external walls (U_E), and roof (U_R) for case building designed with CC, EC1, EC2 and CB.

Sample Name	U_F	U_E	U_R
	W/m ² K	W/m ² K	W/m ² K
CC	0.506	0.386	0.318
EC1	0.473	0.367	0.296
EC2	0.514	0.391	0.323
CB	0.456	0.357	0.285
TS 825-2 nd Region	0.570	0.570	0.380

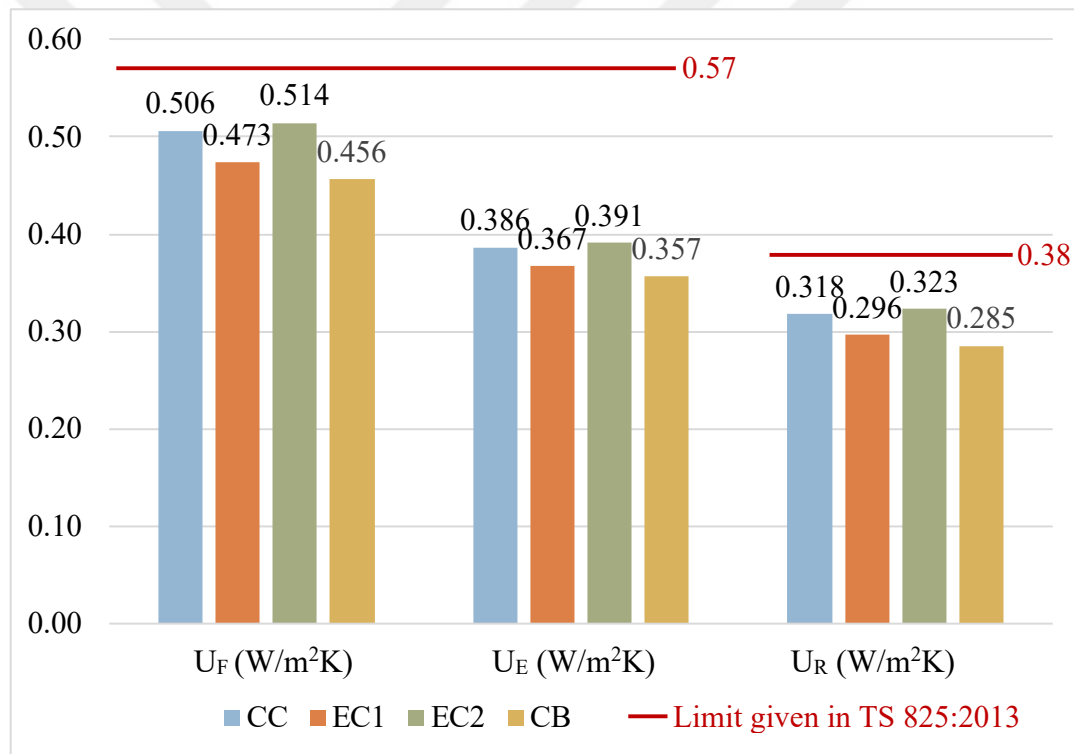


Figure 4.8. The U values for floor (U_F), external walls (U_E), and roof (U_R) for case building designed with CC, EC1, EC2 and CB.

According to the plots shown, the results are summarized below:

- The U values found with four ETIM on floor, roof and external walls are all lower than the maximum values given in TS 825:2013.
- The thermal transmittance values of floor component are the highest ratios between the samples. U_F CC is the U value of floor designed with CC and it is $0.506 \text{ W/m}^2\text{K}$, U_F EC1 is $0.473 \text{ W/m}^2\text{K}$, U_F EC2 is $0.514 \text{ W/m}^2\text{K}$, and U_F CB is $0.456 \text{ W/m}^2\text{K}$.
- The U values for external walls designed with ETIM are as follows: U_E CC is $0.386 \text{ W/m}^2\text{K}$, U_E EC1 is $0.367 \text{ W/m}^2\text{K}$, U_E EC2 is $0.391 \text{ W/m}^2\text{K}$, and U_E CB is $0.357 \text{ W/m}^2\text{K}$.
- The thermal transmittance values of roof components are the lowest between the envelope components. U_R CC is $0.318 \text{ W/m}^2\text{K}$, U_R EC1 is $0.296 \text{ W/m}^2\text{K}$, U_R EC2 is $0.323 \text{ W/m}^2\text{K}$ and U_R CB is $0.285 \text{ W/m}^2\text{K}$.
- The building components designed with EC2 have the highest U values, while the components designed with CB have the lowest U values. Components with EC1 have shown better and lower results in comparison to components designed with CC.

4.4.2 Energy Performance Index

The annual and monthly building heating and cooling loads calculated for the case of timber frame building design with selected ETIM are given on tables and figures below.

Table 4.6. Monthly energy consumption needs for buildings designed with selected ETIM.

	Q value (kWh)							
	CC		EC1		EC2		CB	
	Heat.	Cool.	Heat.	Cool.	Heat.	Cool.	Heat.	Cool.
January	1,748		1,682		1,761		1,613	
February	1,654		1,590		1,673		1,539	
March	1,401		1,345		1,419		1,289	
April	423		397		428		369	
May	147		132		148		113	
June	12	93	12	91	13	88	11	99
July		374		365		360		379
August		371		365		362		374
September		239		238		233		253
October		12		13		11		17
November	681		647		687		610	
December	1,529		1,465		1,541		1404	

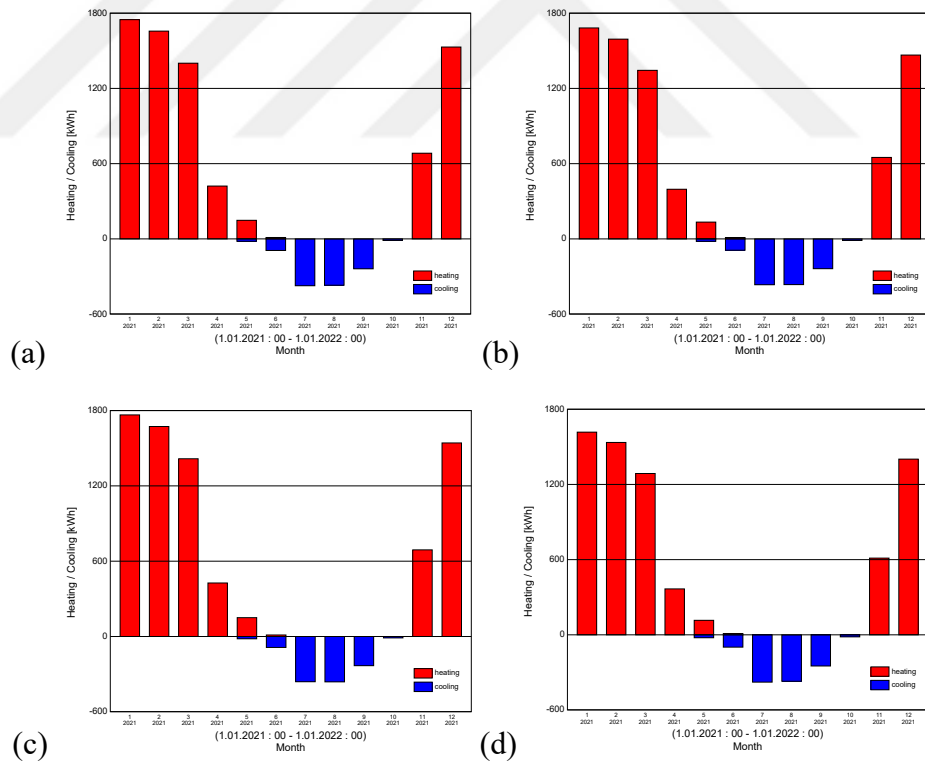


Figure 4.9. Monthly energy need charts of case buildings with CC (a), EC1 (b), EC2 (c) and CB (d).

Table 4.7. Energy needs for heating and cooling and EPI for case building designed with CC, EC1, EC2, and CB.

Sample Name	Annual Energy Need - Heating	Annual Energy Need - Cooling	Annual Energy Need - Total	EPI
	kWh	kWh	kWh	kWh/m ² /year
CC	7,699.9	1,100.2	8,700.1	38.84
EC1	7,275.0	1,092.6	8,367.6	37.36
EC2	7,674.8	1,074.1	8,748.9	39.06
CB	6,952.9	1,145.4	8,098.3	36.15

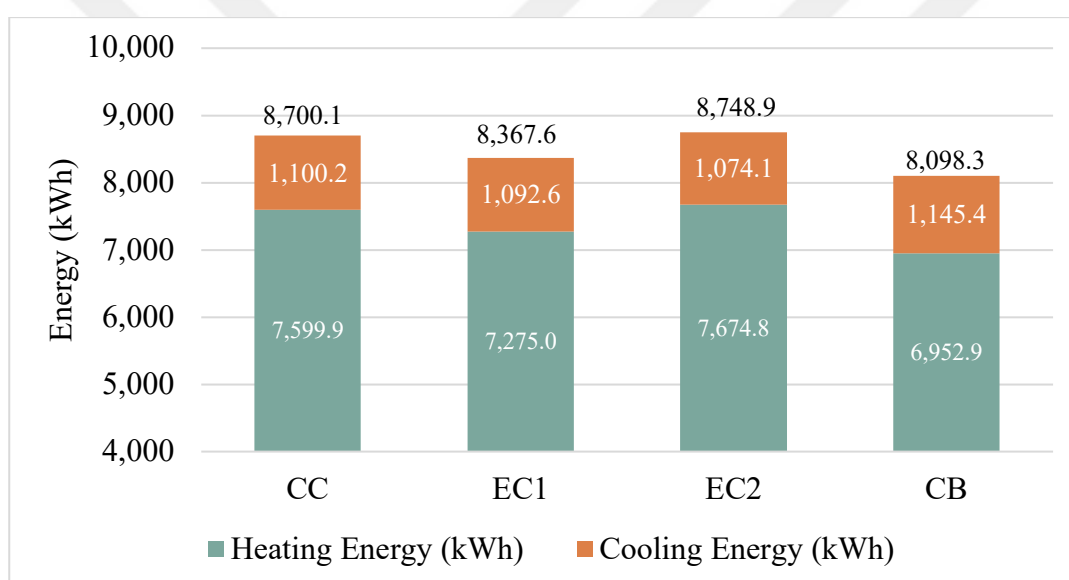


Figure 4.10. The energy values for heating and cooling for case building designed with CC, EC1, EC2 and CB.

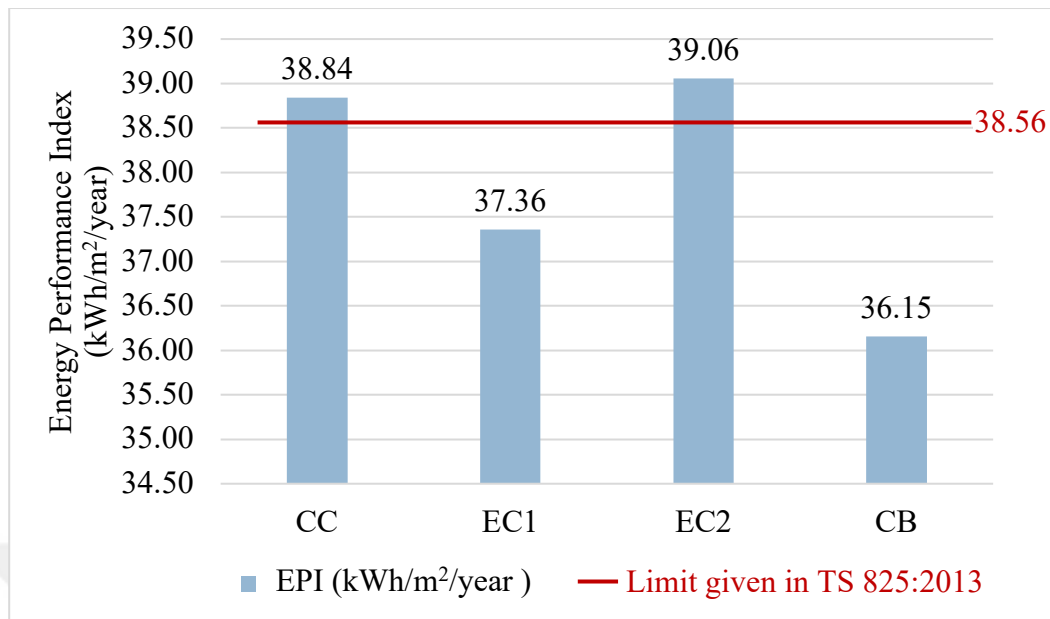


Figure 4.11. EPI values of case buildings designed with selected ETIM.

According to the plots shown, the results are summarized below:

- The highest heating energy is needed in January and highest cooling energy is needed in August among all buildings with different ETIM, while in October the least energy is needed.
- Heating energy needs of buildings shown a similar trend with the total annual energy need of buildings. Overall energy consumption need of building with EC2 is the highest with 8,748.9 kWh. 7,674.8 kWh of this energy is consumed for heating and 1,100.2 kWh is for cooling. The lowest total energy consumption belongs to the building with CB which is 8,098.3 kWh. 6,952.9 kWh heating energy is consumed in building with CB annually.
- Buildings with CC and EC1 has shown in-between results for annual heating and overall energy needs. For CC these values are respectively 7,599.9 kWh, 8,700.1 kWh, and for EC1 it is 7,275.0 kWh and 8,367.6 kWh.
- The annual cooling energy need for buildings with CC, EC1, EC2 and CB found as 1,100.2 kWh, 1,092.6 kWh, 1,074.1 kWh, and 1,145.4 kWh

respectively. EC2 has the lowest cooling energy need while CB has the highest.

- According to the formula given in section 2.5.2. The maximum EPI value for this building has been found as 38.56 kWh/m²/year from $63.7 \times 0.3715 + 14.9$. EPI values are found for buildings with CC, EC1, EC2 and CB as 38.84, 37.36, 39.06, and 36.15 kWh/m²/year respectively. EC2 has the highest EPI while CB has the lowest. All EPI values calculated are less than the maximum value allowed.

4.4.3 Hygic Properties of Building Components

Hygrothermal performances simulation results of floor, exterior walls, and roof according to the design given in section 3.6.7. are given below. These data are temperature and RH in the component, total water content (TWC) of the component, water content (WC) of each element combined. Moisture content of ETIM layers are given additionally.

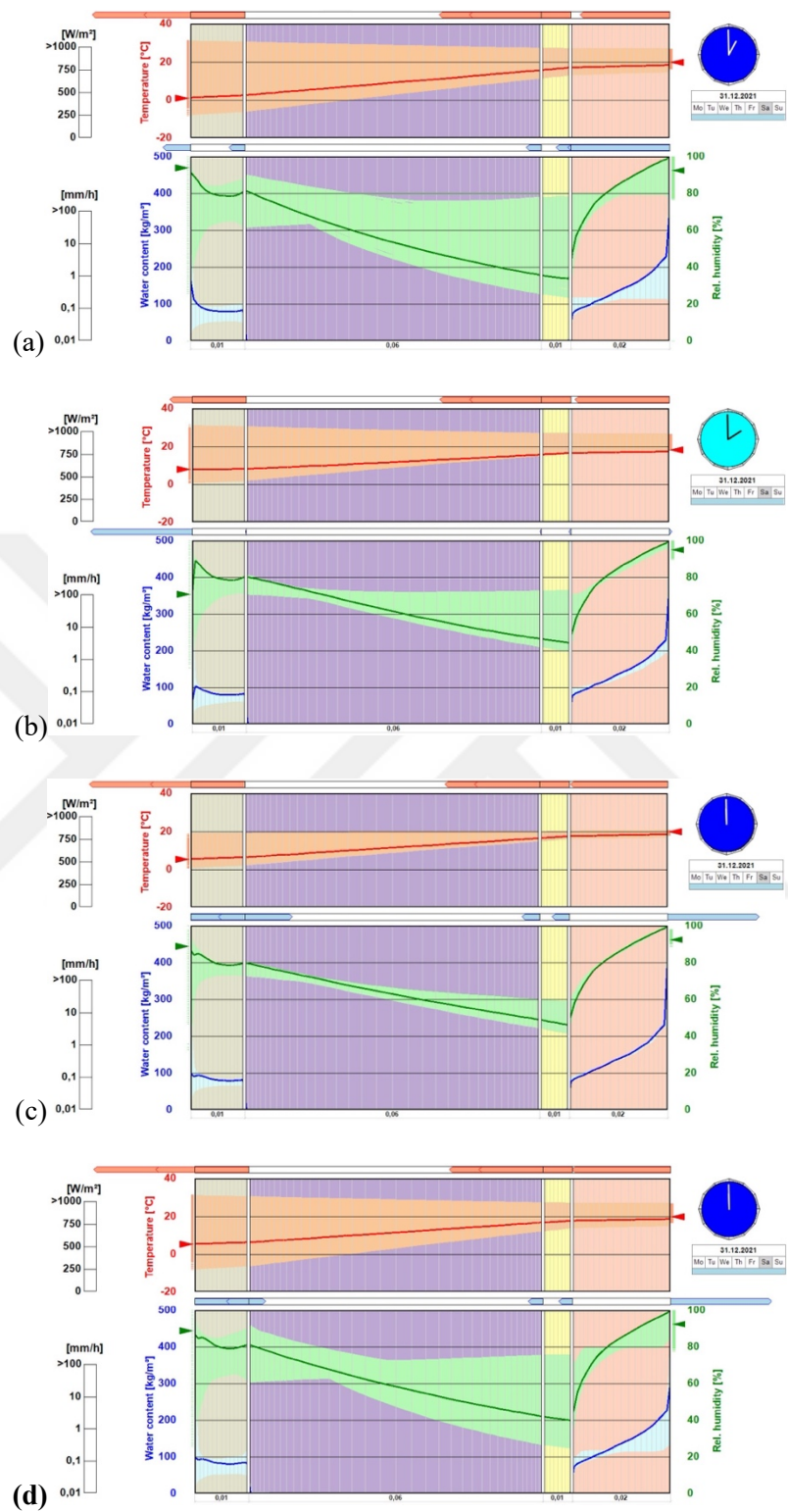


Figure 4.12. RH, WC, and temperature in cross-section floor layers with CC (a), EC1 (b), EC2 (c), and CB (d).

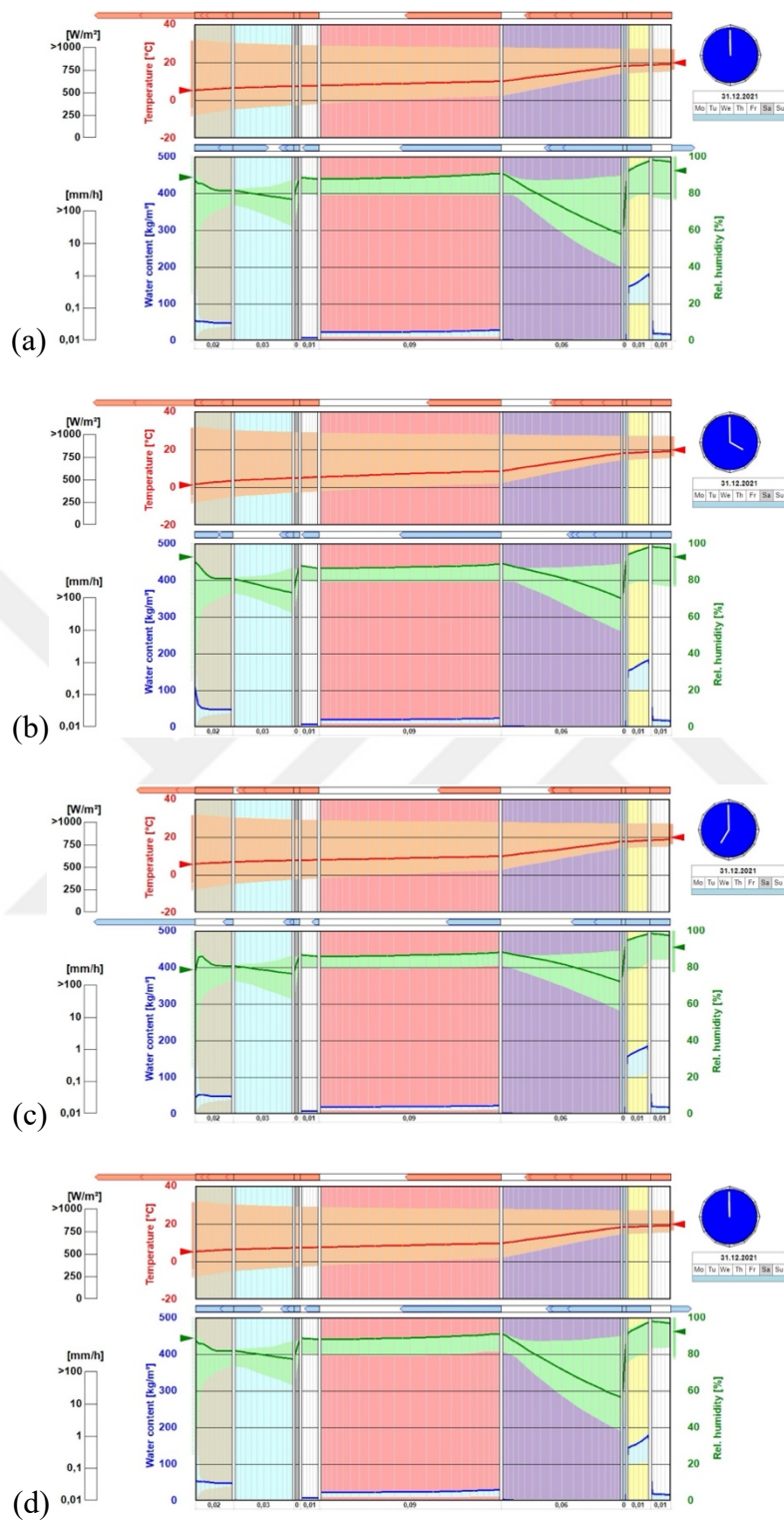


Figure 4.13. RH, WC, and temperature in cross-section external wall layers with CC (a), EC1 (b), EC2 (c), and CB (d).

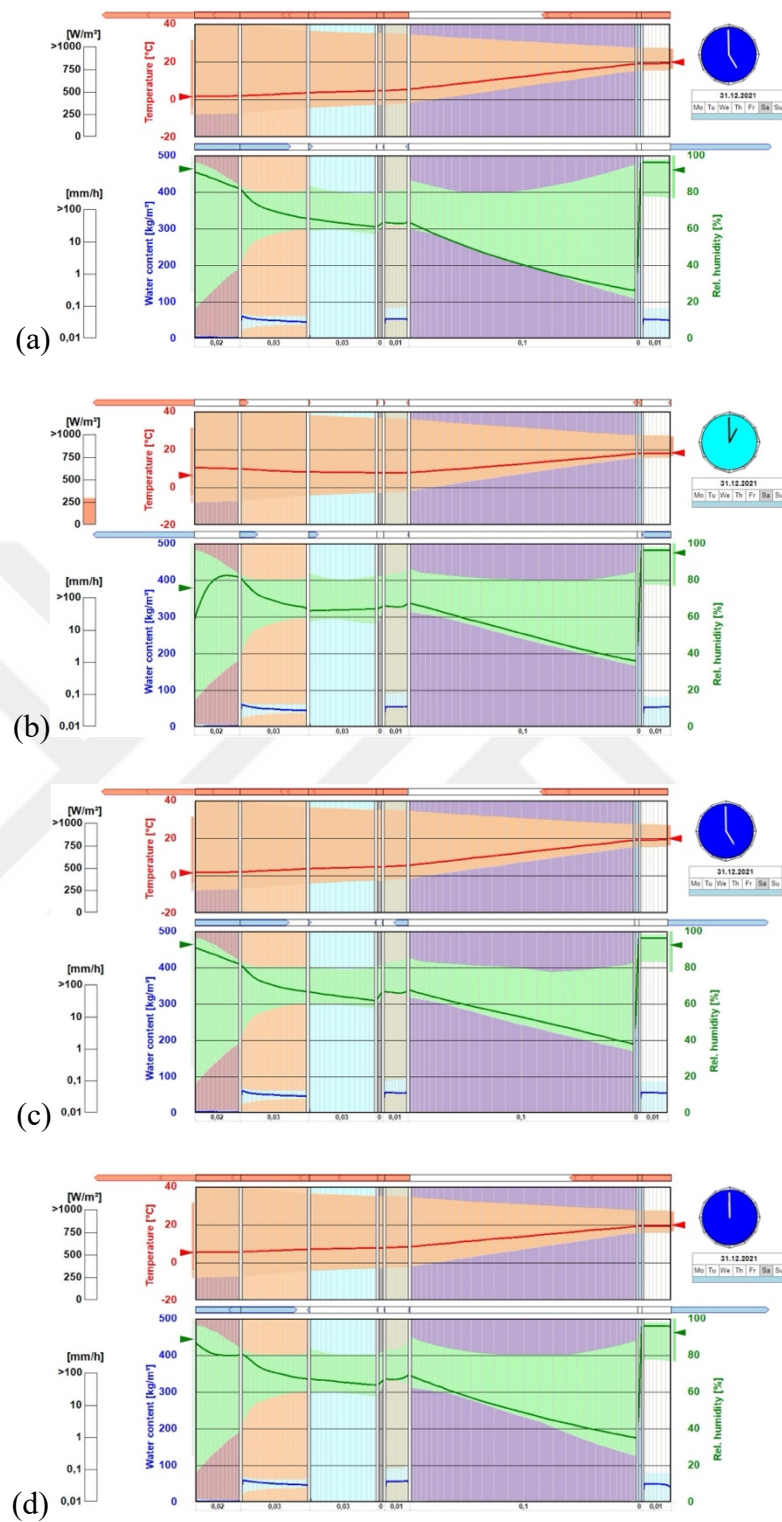


Figure 4.14. RH, WC, and temperature in cross-section roof layers with CC (a), EC1 (b), EC2 (c), and CB (d).

The colors on the background define the material layers in components as it is given in section 3.2.5.4. Horizontal red line on top of drawings refers to the temperature on the layers on the last day of simulation. Red area around is the range of temperature within the simulation period. Green line refers to RH levels on the layers, while green area is the range of relative humidity within the year. Blue line stands for the water content in layers and blue area is the range.

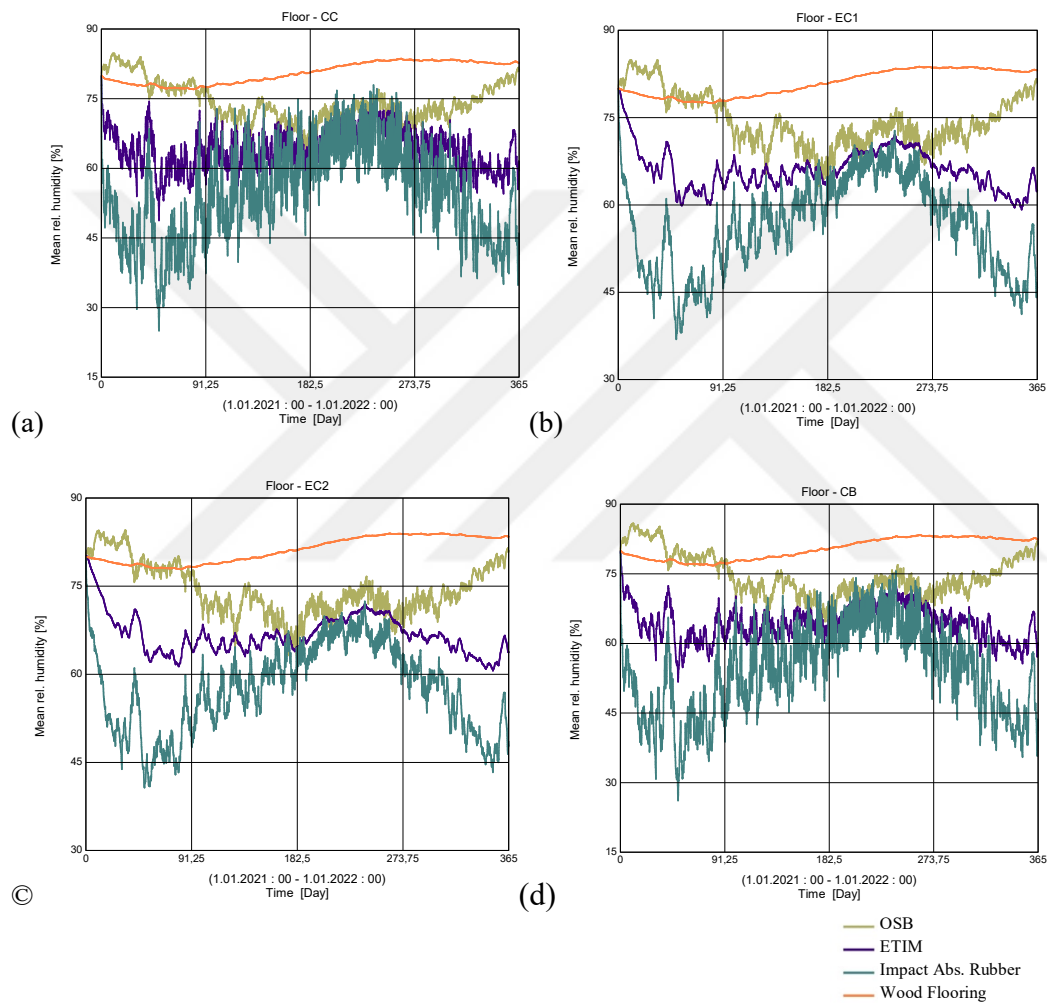


Figure 4.15. Relative Humidity amounts of floor with CC (a), EC1 (b), EC2 (c), and CB (d).

- Relative humidity ratios for floor sections does not reach more than 85%. Impact absorbing rubber has the least amount of relative humidity in its

structure, while wood flooring has the highest RH with values higher than 75%. RH for ETIM is the highest on winter and fluctuates between 48.74% and 80.0% in CC, 59.15% and 80.03% in EC1, 60.57% and 80.14% in EC2, and 51.67% and 80.0% in CB.

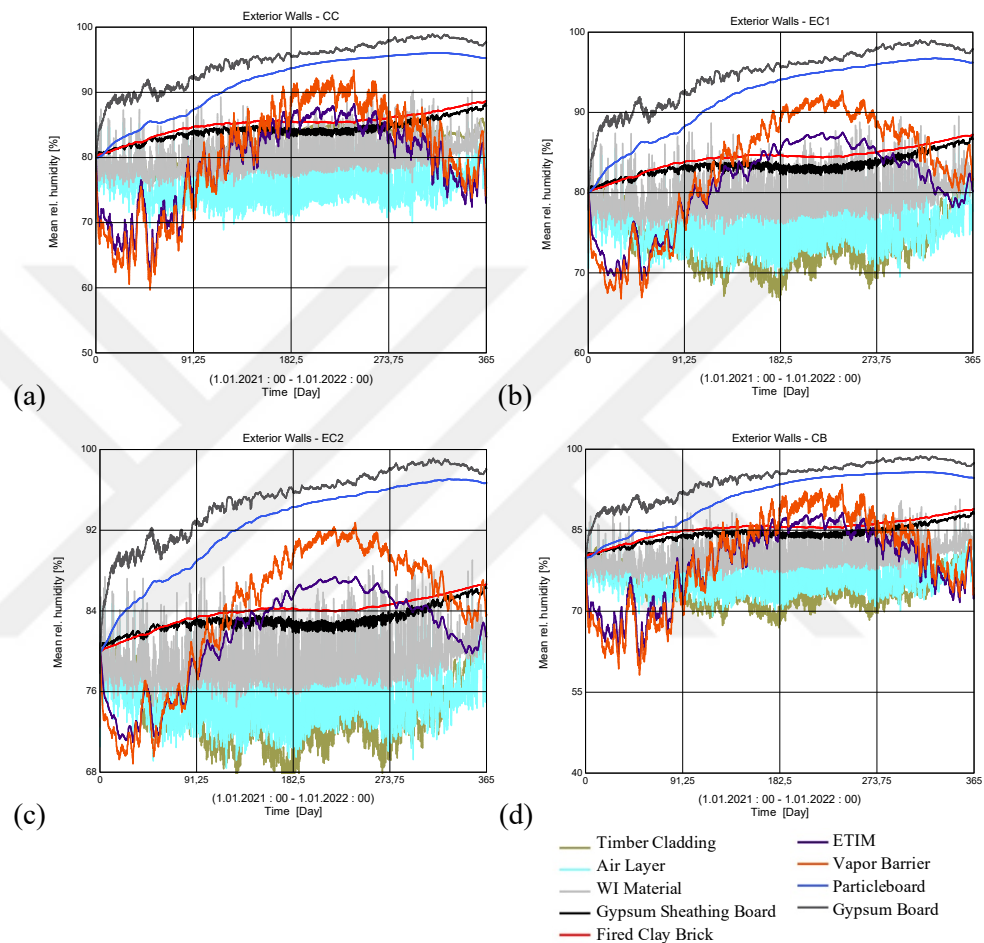


Figure 4.16. Relative Humidity amounts of external walls with CC (a), EC1 (b), EC2 (c), and CB (d).

- As for the RH in external walls, the particleboard has the highest RH higher than 80%. Wood cladding has the lowest RH. Fired clay brick has the most consistent RH values throughout the year. RH values for vapor retarder and ETIM has increased during spring and reached their maximum during July

and August. RH for ETIM is the lowest on winter and fluctuates between 60.94% and 87.38% in CC, 68.87% and 87.01% in EC1, 70.82% and 86.97% in EC2, and 59.84% and 87.42% in CB.

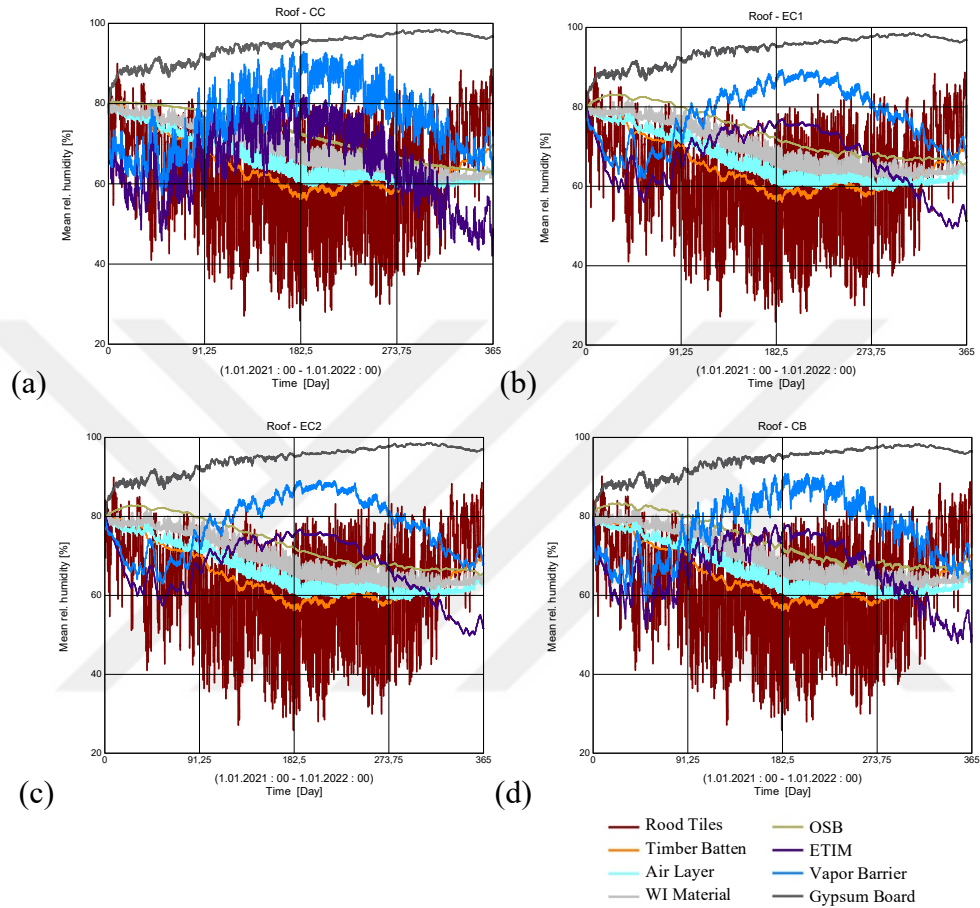


Figure 4.17. Relative Humidity amounts of roof with CC (a), EC1 (b), EC2 (c), and CB (d).

- Gypsum board has the highest RH within roof component elements. RH of capor barrier reaches more than 90% RH during summer. Roof tiles has the lowest RH values in general, which fluctuates between 31% and 87% through the year. RH of ETIM on roof is the lowest in December and fluctuates between 41.9% and 81.35% in CC, 49.70% and 80.0 % in EC1, 50.06% and 80.0 % in EC2, and 48.31% and 80.0 % in CB.

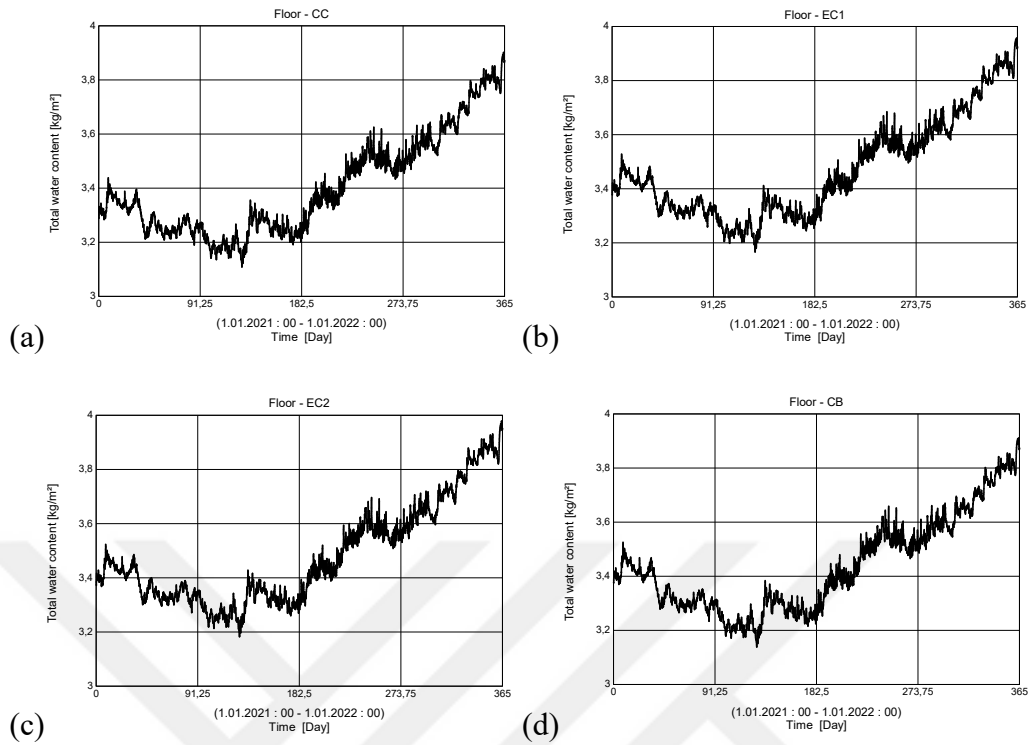


Figure 4.18. Total water content of floor with CC (a), EC1 (b), EC2 (c), and CB (d).

- Total water content in floor sections has shown the lowest values in May and the highest in December. Floor section with EC2 has the highest TWC and floor section with CC has the lowest. TWC of section with CC ranges between 3.11 and 3.90 kg/m², TWC of floor with EC1 is between 3.17 and 3.96 kg/m², with EC2, TWC fluctuates between 3.18 and 3.98 kg/m², and with CB this value is between 3.14 and 3.91 kg/m².

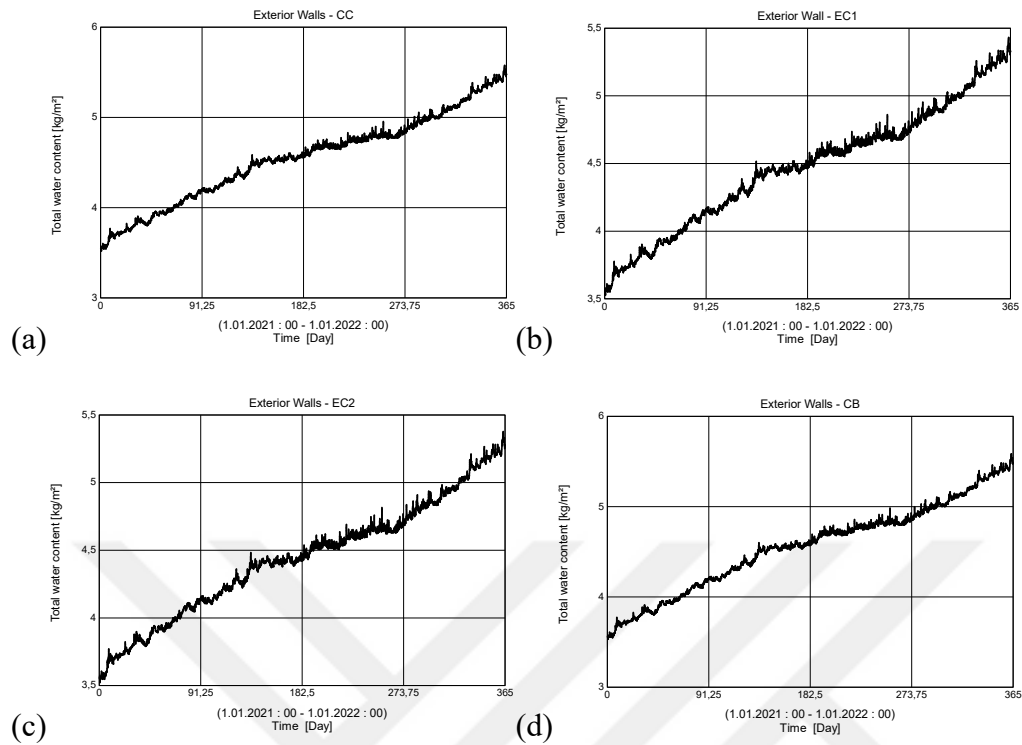


Figure 4.19. Total water content of external walls with CC (a), EC1 (b), EC2 (c), and CB (d).

- Total water content of external wall sections has shown the lowest values in January and the highest in December. Floor section with EC1 has the highest TWC and floor section with CC has the lowest. TWC of wall section with CC ranges between 3.52 and 5.58 kg/m², TWC of external wall with EC1 is between 3.53 and 5.43 kg/m², with EC2, TWC fluctuates between 3.52 and 5.38 kg/m², and in external wall with CB this value is between 3.53 and 5.59 kg/m².

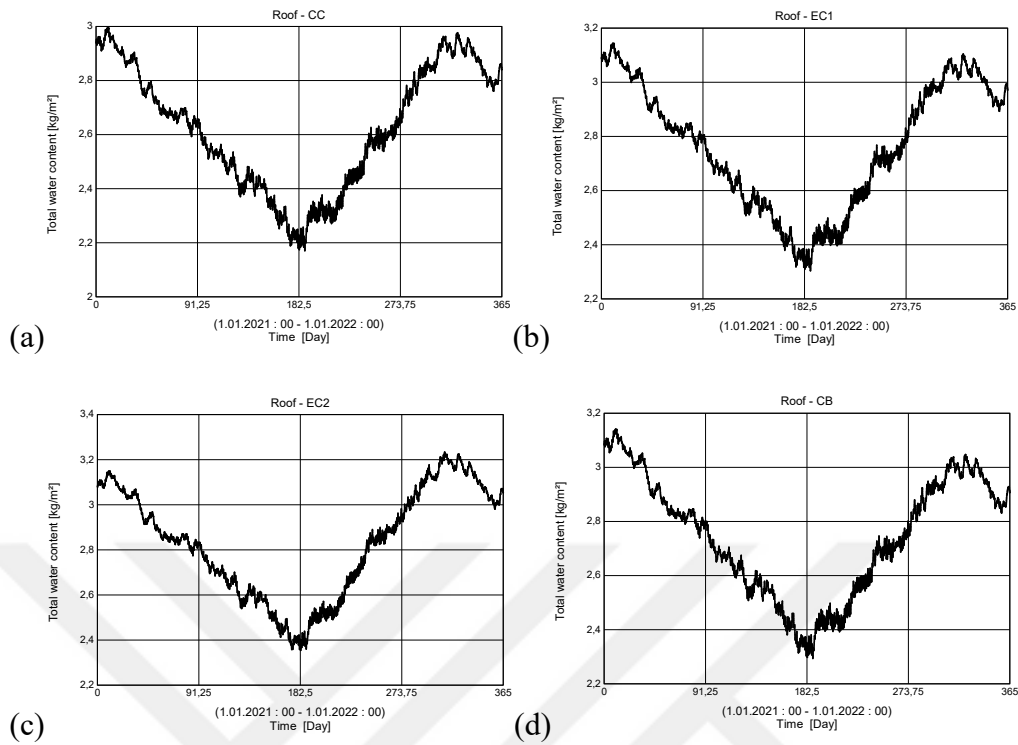


Figure 4.20. Total water content of roof with CC (a), EC1 (b), EC2 (c), and CB (d).

- Total water content of roof sections has shown the lowest values in July and the highest in January. Roof section with CC has the highest TWC and floor section with CB has the lowest. TWC of roof section with CC ranges between 2.17 and 3.00 kg/m², TWC of roof with EC1 is between 2.30 and 3.15 kg/m², with EC2, TWC of roof fluctuates between 2.35 and 3.24 kg/m², and in roof with CB this value is between 2.29 and 3.14 kg/m².

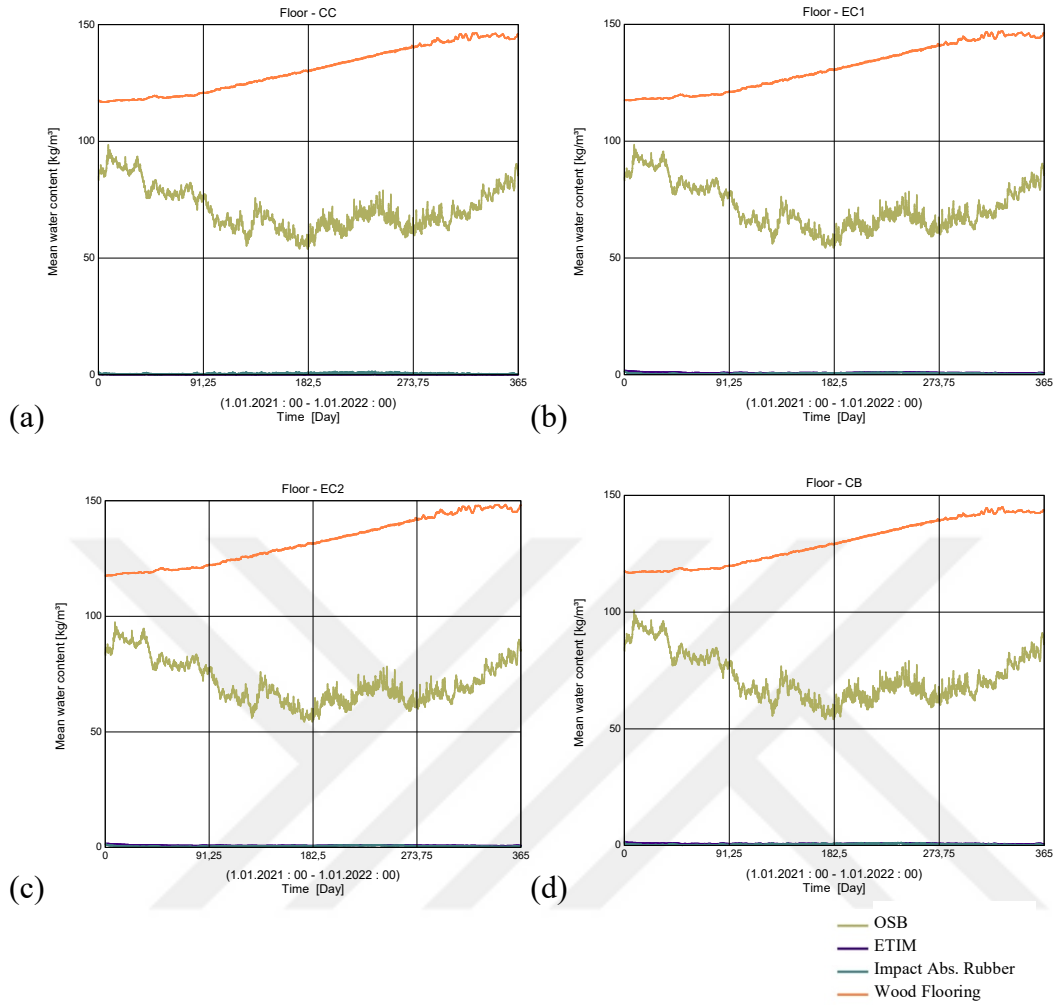


Figure 4.21. Water content ratios of all layers in floor designed with CC (a), EC1 (b), EC2 (c), and CB (d).

- The daily mean WC in floor sections has shown that the highest water content belongs to wood flooring. The lowest values belong to impact absorbing rubber and ETIM. WC of wood flooring in floor sections ranges between 115.61 and 147.91 kg/m², WC of OSB in floor sections fluctuates between 24.39 and 101.55 kg/m², WC of impact absorbent rubber in floor sections is lower than 1.69 kg/m². WC of ETIM in floor structure are given in the following figures, since it is not in the similar range with other layers.

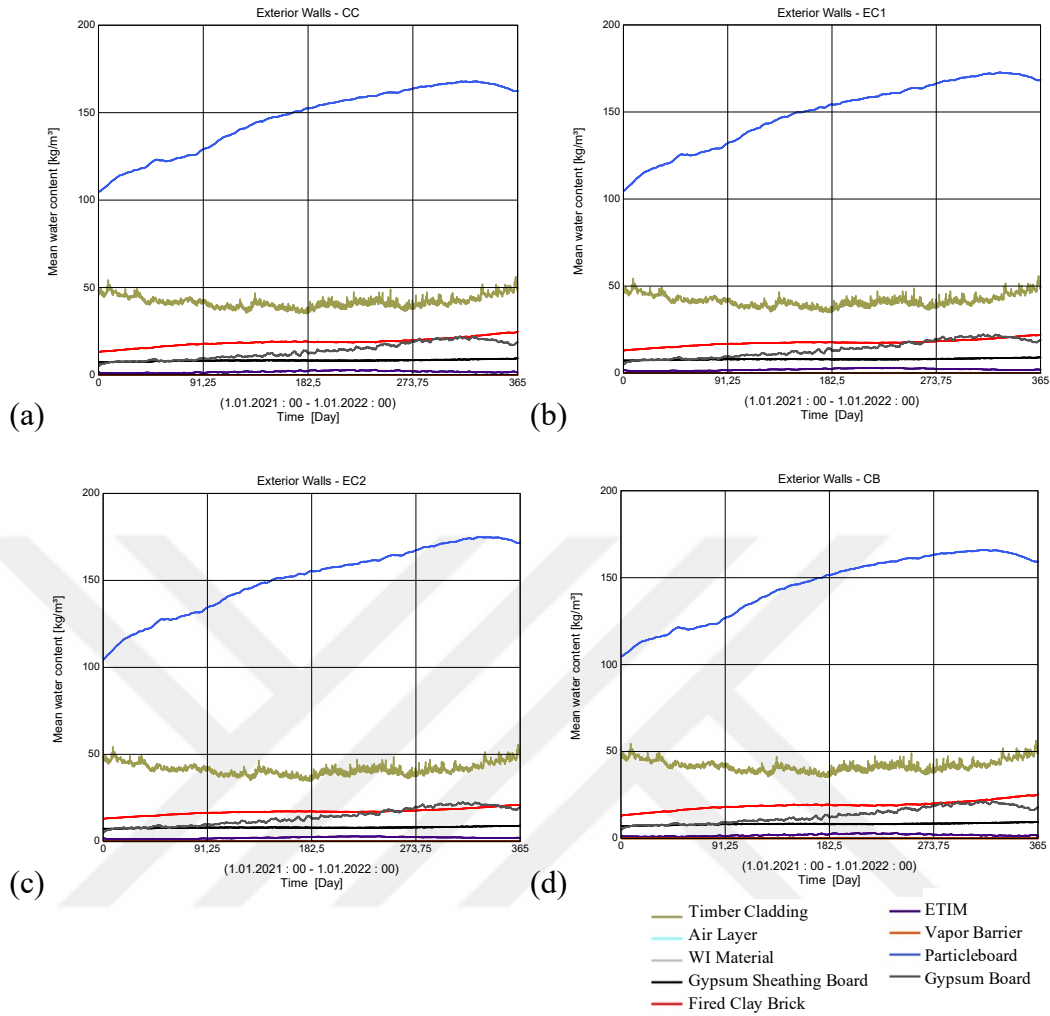


Figure 4.22. Water content ratios of all layers in external walls designed with CC (a), EC1 (b), EC2 (c), and CB (d).

- The daily mean WC in external wall sections has shown that the highest water content belongs to particleboard. The lowest values belong to vapor barrier and ETIM. WC of particleboard in external wall sections ranges between 103.62 and 164.51 kg/m², WC of timber cladding in external wall sections is between 38.67 and 57.21 kg/m², WC of fired clay brick in external wall sections fluctuates between 16.83 and 26.17 kg/m². WC of ETIM in external wall structure are given in the following figures, since it is not in the similar range with other layers.

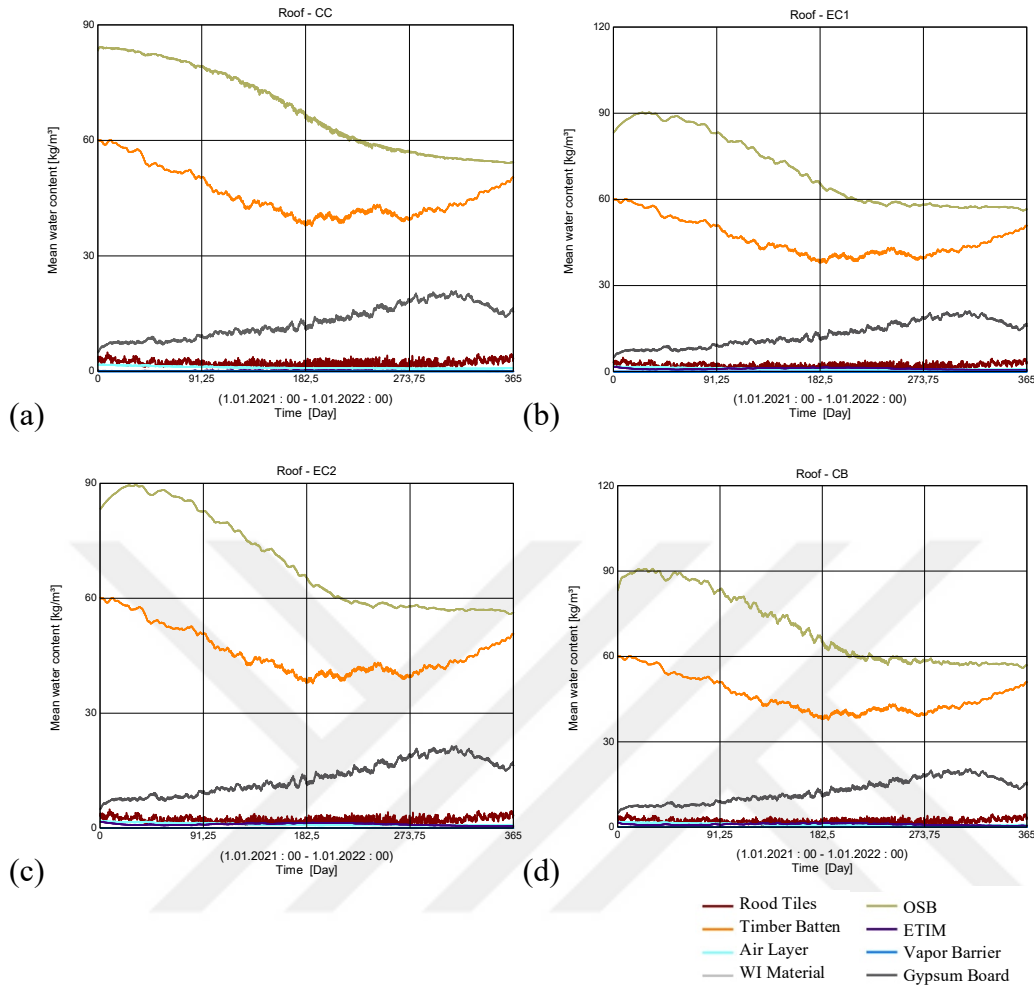


Figure 4.23. Water content ratios of all layers in roof designed with CC (a), EC1 (b), EC2 (c), and CB (d).

- The daily mean WC in roof sections has shown that the highest water content belongs to OSB. The lowest values belong to vapor barrier and ETIM. WC of OSB in roof sections ranges between 54.87 and 89.74 kg/m², WC of timber battens in roof sections is between 38.25 and 60.61 kg/m², WC of roof brick in roof sections fluctuates between 1.12 and 5.06 kg/m². WC of ETIM in external wall structure are given in detail in the following figures, since it is not in the similar range with other layers.

Table 4.8. Maximum WC (WC_{max}) of ETIM in floor, external wall, and roof.

Sample Name	WC_{maxF}	WC_{maxE}	WC_{maxR}
	kg/m ²	kg/m ²	kg/m ²
CC	0.27	2.74	0.35
EC1	1.76	2.87	1.75
EC2	1.69	2.74	1.67
CB	1.71	2.91	1.71

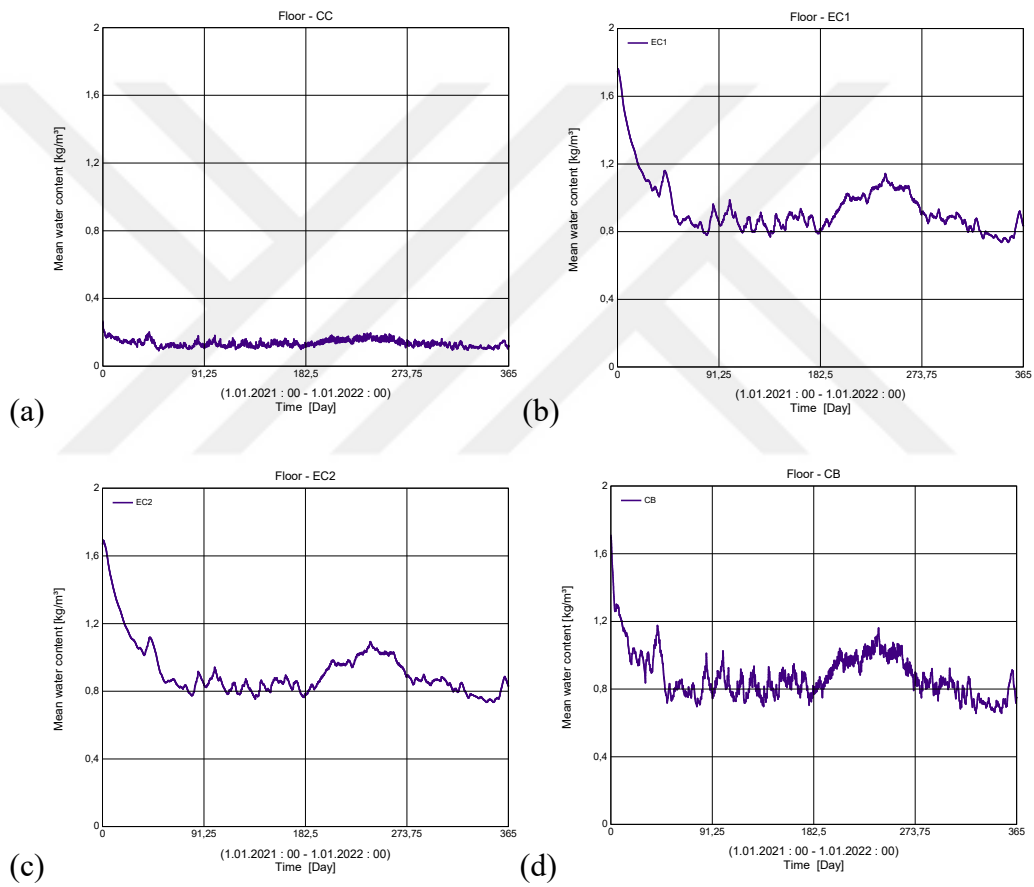


Figure 4.24. Water content ratios of CC (a), EC1 (b), EC2 (c), and CB (d) in floor.

- The daily mean WC of ETIM in floor sections has shown that the WC_{maxF} found as EC1 with 1.76 kg/m². The WC of CC in floor section ranges

between 0.09 and 0.27 kg/m². WC of EC1 in floor section is between 0.72 and 1.76 kg/m². The WC of EC2 in floor section is between 0.76 and 1.79 kg/m², and WC of CB in floor section fluctuates between 0.71 and 1.79 kg/m².

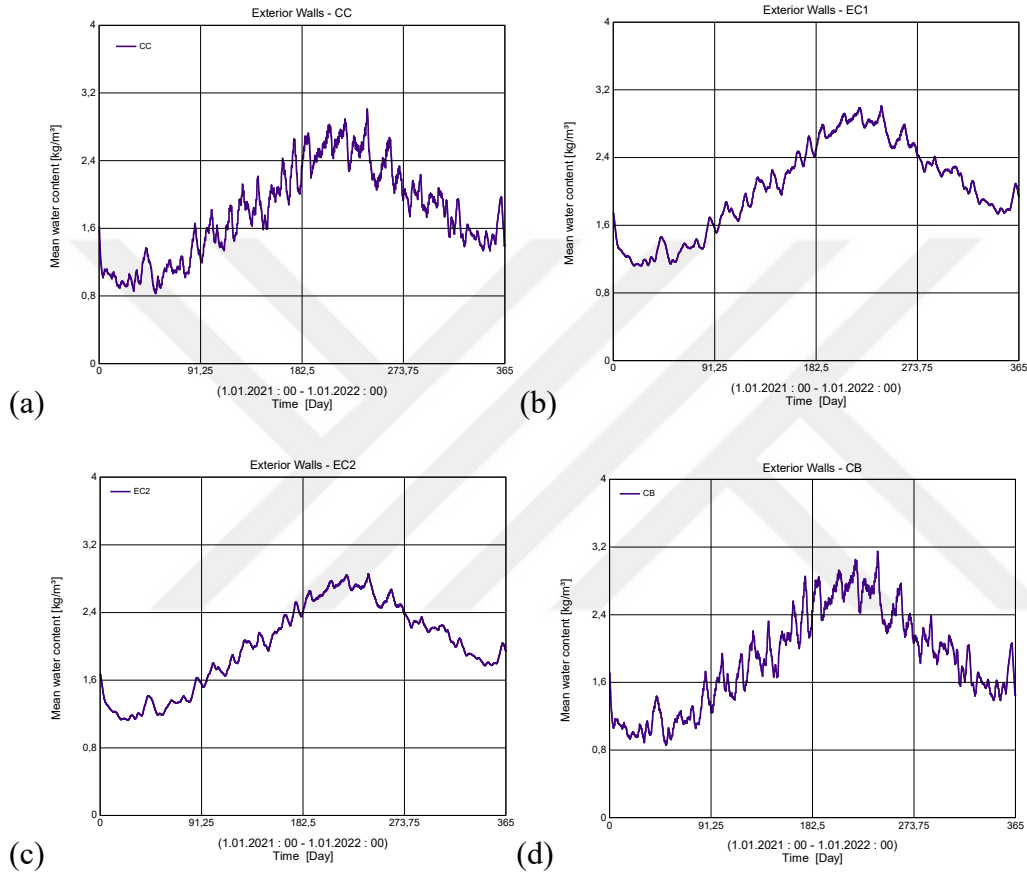


Figure 4.25. Water content ratios of CC (a), EC1 (b), EC2 (c), and CB (d) in external walls.

- The daily mean WC of ETIM in external wall sections has shown that the WC_{maxE} found as CelluBor with 2.91 kg/m². The WC of CC in external wall section ranges between 0.78 and 2.74 kg/m², WC of EC1 in external wall section is between 0.86 and 1.76 kg/m². The WC of EC2 in external wall

section is between 1.17 and 1.69 kg/m², and WC of CB in external wall section fluctuates between 0.89 and 2.91 kg/m².

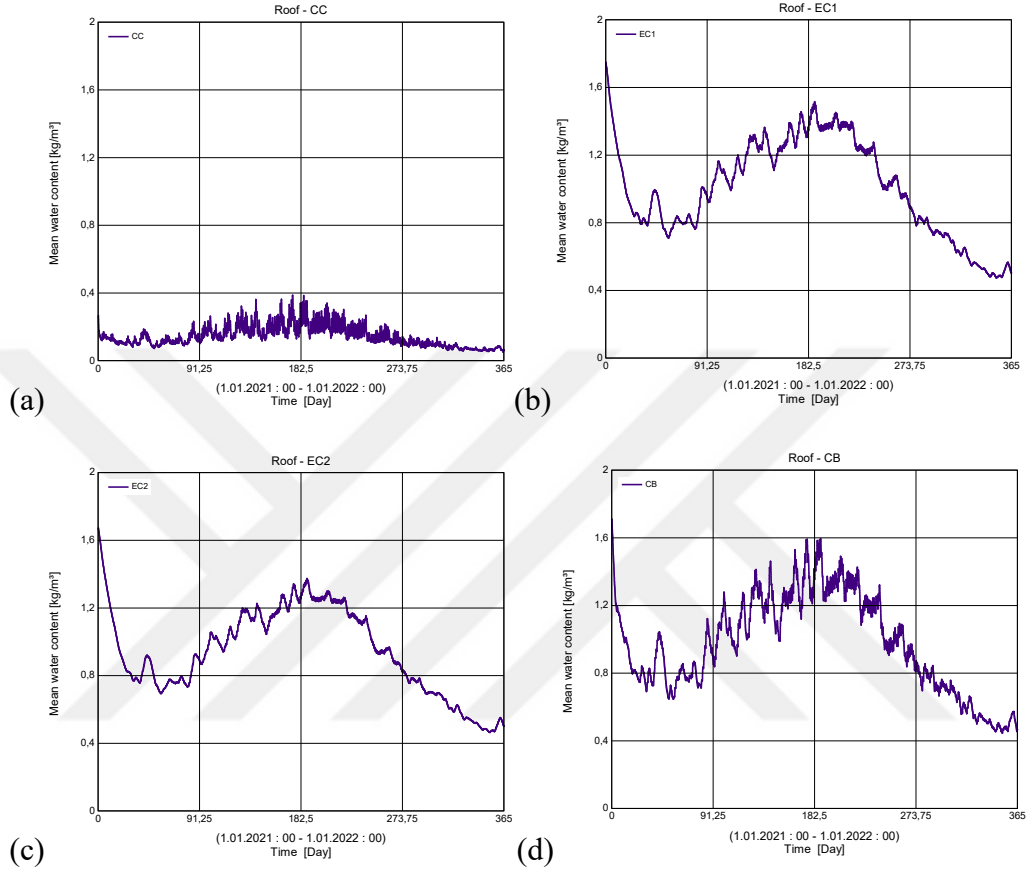


Figure 4.26. Water content ratios of CC (a), EC1 (b), EC2 (c), and CB (d) in roof.

- The daily mean WC of ETIM in roof sections has shown that the WC_{maxR} found as EC1 with 1.75 kg/m². The WC of CC in roof section ranges between 0.06 and 0.35 kg/m². WC of EC1 in roof section is between 0.52 and 1.75 kg/m². The WC of EC2 in roof section is between 0.51 and 1.67 kg/m², and WC of CB in roof section fluctuates between 0.44 and 1.71 kg/m².

CHAPTER 5

DISCUSSION OF RESULTS

In this section, the material property-related results taken from the laboratory experiments and the results gathered from building software simulation are interpreted together. The aim of the results' interpretation is:

- to evaluate four selected types of ETIM's thermal and hygric properties and to discuss their both limitations and potentials related to their thermal insulation component performances,
- to examine the timber frame building in terms of energy and hygrothermal behavior and explain the necessary actions to reach better performances.

5.1 Evaluation of Properties of Ecological Thermal Insulation Materials

The total data gathered on ETIM's physical, thermal, and hygric properties are discussed to comprehend their hygrothermal activity and subsequently compared with each other. Physical properties analysis represented a general approach of materials structure, thermal properties analysis showed the heat resistance capacity and energy requirement of heating. Analysis of hygric properties focused on understanding the drying behavior and breathing capability of ETIM. Cellulose-based samples are dissolved when contacted with water for hygric tests. Therefore, CelluBor should be protected from direct water exposure. The characteristics of ETIM achieved with laboratory tests and two other TIM taken from the study conducted by Ducoulombier and Lafhaj (2017), which are glass wool (GW) and wood fiber board (WFB) have shown in Table 5.1.

Table 5.1. The compiled data on basic physical, thermal, and hygric properties of the 4 ETIM studied (CC, EC1, EC2, and CB) and 2 others (GW and WFB) from literature for comparison.

Sample Name	ρ kg/m ³	ϕ % by vol.	λ W/mK	c J/kgK	μ unitless	s_d m	A kg/m ² s ^{0.5}
CC	99.96	14.35	0.232	5390	2.10	0.08	0.0462
EC1	97.87	7.05	0.173	8723	10.96	0.33	0.0100
EC2	114.39	11.60	0.177	7079	14.29	0.43	0.0076
CB	90.88	-	0.150	8035	2.14	0.08	-
GW (*)	32.70	-	0.034	928	2	0.20	0.0200
WFB (*)	176.30	-	0.046	1515	4	0.20	0.0015

(*): Values are from (Ducoulombier & Lafhaj, 2017).

Performance properties of ETIM compiled through laboratory tests are represented here together as criteria of bulk density (ρ), apparent porosity (ϕ), thermal conductivity (λ) and specific heat capacity (c), water vapor diffusion resistance factor (μ), water vapour diffusion-equivalent air layer thickness (s_d), and capillary water absorption coefficient (A).

In terms of physical properties of ETIM, concluded outcomes are summarized below:

- As for expanded corkboards, EC2 has both the highest density of 114.39 kg/m³ and a high porosity ratio of 11.60% by volume among the cork samples. This shows that during the production, the cork particles that are expanded with heat are compressed and therefore denser since the compression applied per m³ is increased. The pores in between are not compressed by the pressure applied on granules during shaping. Overall Expanded Corkboard 2 (MDFacade) has a potential as a porous and durable material with respect to physical factors.

- Corkoco has the bulk density of 99.96 kg/m^3 , apparent porosity of 14.96% by volume. The apparent porosity stands for the interconnected pores on the coating surface of the material. Apparent porosity determination test showed the Corkoco is the most porous which is due to the coconut fiber structure.
- For all tests the density of CelluBor is kept at a value which is closer to cork-based ETIM in order to observe the results of thermal properties in similar circumstances.
- According to the information given by Ducoulombier and Lafhaj, (2017), glass wool has a lower density than all of the tested ETIM with 32.70 kg/m^3 , and the density of wood fiber board is 176.30 kg/m^3 meaning denser than tested ETIM.

In terms of thermal properties of ETIM, concluded outcomes are summarized below:

- Due to testing environment drawbacks the thermal property related values of ETIM is beyond the reference values for thermal insulation materials. The thermal conductivity values are ranged between 0.232 and 0.150 W/mK and specific heat capacity values are ranged between 5390 and 8723 J/kgK in the ambient temperature of 26°C , and relative humidity of 40%.
- CB has the lowest thermal conductivity value of 0.150 W/mK which means that CelluBor shows the best resistance against heat transfer. Supporting the λ value found through test, the specific heat capacity value found for CB is the highest with 8,035 J/kgK. Due to the high c value, CelluBor can store heat properly, which is needed to keep the building in the optimum indoor air temperatures with lower energy consumption.
- Due to its fibrous and porous structure CC has the highest thermal conductivity value of 0.232 W/mK, shows a poor thermal insulation behavior. Likewise, the specific heat capacity of Corkoco with 5,390 J/kgK is the lowest among ETIM. It tends to lose the heat through the fibers and pores.

- Among the Expanded Corkboards, EC2 has higher thermal resistivity properties than EC1 due to its dense structure. Yet, due to the high porosity of EC2, the specific heat capacity of EC2 with 7,078 J/kgK is lower than EC1 with 8,723.14 J/kgK.
- The thermal conductivity value of glass wool and wood fiber board is given 0.034 and 0.046 W/mK respectively in the test conducted by Ducoulombier & Lafhaj (2017). The specific heat capacity values of these materials are 928 J/kgK for glass wool and 1515 J/kgK for wood fiber board. These values correspond to the λ and c values for tested ETIM given by the manufacturers.

In terms of hygric properties of ETIM, concluded outcomes are summarized below:

- The water vapor diffusion resistance factor indicates the materials' vapor tightness and quantification of the resistance to vapor transmission of material layer against the static air layer. Therefore, lower μ value stands for the higher permeability. All of the materials have shown values of either high or medium breathability of water vapor.
- Among all tested ETIM, lowest μ values found 2.10 and 2.14 for CC and CB, respectively. Given the static air layer vapor resistance index as 1.0 in the standards, it is seen that the resistance against water vapor of these materials is approximately double against the air layer's. This high permeability value is a strong potential for Corkoco and CelluBor.
- The value of water vapor permeability resistance being smaller than 0.14 m means the material is highly permeable. CC with 0.082 m and CB with 0.076 m stand below this number and regarded as highly permeable materials, which lets air to move through material.
- EC2 is a dense material with a very low water vapor permeability. Its s_d value of 0.433 is the highest among the tested ecological thermal insulation materials. It is above 0.14 m, meaning it has a medium permeability. Its vapor resistance index shows that its permeability 14.29 times lower than the air

layer permeability. As a limitation, Expanded Corkboard 2 (MDFacade) stands as the least breathable sample.

- According to the study conducted by Ducoulombier and Lafhaj (2017) water vapor diffusion resistance factor of GW is 2 and μ value of wood fiber board is 4. This indicates that CC and CB have shown similar resistance behavior with GW.
- The WVP values of tested ETIM are all above 10 US Perm, which indicates that all materials are found highly permeable in terms of permeance. High permeance meaning there is a strong breathing capability existing. Therefore, if the permeance of a material is high, that material tends to dry quickly or in other words shows faster drying behavior.
- According to capillary water absorption test, with the higher porosity ratio, the amount of water absorbed increases. Expectedly, CC has the highest capillary water absorption coefficient among the tested ETIM. Corkoco's capillary water absorption coefficient of 0.0462 is regarded high and therefore this material should be protected against direct water exposure or wetting through precipitation.
- Expanded Corkboard 1 has approximately one fifth of A value when compared to Corkoco. EC2 has lower A value than EC1, meaning Expanded Corkboards 2 is a denser material and more susceptible to capillary water absorption. Shortly, these materials are more applicable to be used on roofs and below the ground level on buildings and/or at area exposed to precipitation. Based on the results, EC2 with the A value of 0.0076, is the most suitable ETIM to apply, in which a case of capillary water absorption might happen.
- In the hygrothermal property comparison study conducted by Ducoulombier and Lafhaj (2017), A value for GW has been found as $0.02 \text{ kg/m}^2\text{s}^{0.5}$ and the WFB has shown an A value of $0.00153 \text{ kg/m}^2\text{s}^{0.5}$. This indicates that the wood fiber board has shown the minimum water absorption values, while

glass wool has shown a behavior more absorber than Expanded Corkboard materials but less than Corkoco.

- The water absorption tendency is a limitation of CC. The materials retain moisture, and they can be prone to mold over time. To prevent this material from water-exposed conditions, it should be protected through water barrier layers, in terms of this criterion.

Finally, overall laboratory tests on properties of ETIM are summarized below:

- The performance properties of coconut, cork and cellulose based ecological thermal insulation materials were compared and discussed. Since these materials are produced from natural resources, there is a misconception on their durability especially hygric-wise.
- Corkoco and CelluBor are noticeably better in terms of water vapor breathing criteria and thus drying behavior. The high thermal resistivity values of CelluBor should also be accentuated, yet along with Corkoco, their structure is not suitable for wetting-drying cycles, due to longer drying times and high capillary water absorption tendency.
- Expanded Corkboards are moderately porous, and light materials, that showed valuable results in terms of thermal properties, among tested materials. On the other hand, their permeability is not as good as rest of the samples, even though accepted as medium breathability.

5.2 Statements of Reliability of Test Methods Conducted in Laboratory

The laboratory tests have been conducted according to international standards. Regarding finding of thermal qualification related values, a calibrated system setup has been prepared which is given almost the same results with the hot and cold plate method described in the standards. Eventually the equipment used during the laboratory tests is calibrated and therefore, the results might have been different to some extent rather than expectations gained through data sheets.

Results gained with laboratory tests for materials' thermal properties are found to be exaggerated. There are several reasons behind the results that exceed acceptable range limits of specific heat and thermal conductivity coefficient. The first of them is the non-achieved steady-state temperature which is eventually caused by the high energy flow from the heater. It is a consequence of the power of the heater. Another reason is the lack of rapid heat flux. The lack of planar heat flux sensor is also affected the results since the measurements of materials' surface are taken from single points.

Different methods have been tried during the calibration including restricting the amount of energy given, restricting the time of energy given, modifying the heating power of the source, and adjusting the ratio of material surface area to heater surface area. Eventually the data obtained with calibrated system were in the range of values obtained by the method given in the standards, yet higher than the ones given by the manufacturers. Calibrated system is thought to be one of the reasons behind the wide range of thermal property values between laboratory tests and manufacturers' data sheets.

Another reason along with the calibrated equipment behind the higher values obtained is the ambient conditions. The ambient conditions, where the laboratory tests have been conducted, was between 26 and 27°C and 34 to 40% RH. It is known that the thermal conductivity values rise with the higher temperatures and humidity. That is why the λ and c values of ETIM found were higher than the values given in the manufacturers data sheets.

Another remark about the property values is that the specimens with different physical properties such as bulk density and apparent porosity are not expected to show same properties to those given in the data sheets. Ultimately, the batch qualities during the mass production of a bio-based material might change and therefore differences might happen in the material properties.

There has been data provided in the literature through former research and international standards regarding the terminology, production process, and performance characteristics of selected thermal insulation materials. However, information obtained through the literature review and laboratory tests shows that regarding the standards of TIM for each analysis and quantitative data especially on the hygric performance qualification evaluation found lacking. In terms of the test standards outside of thermal properties, standards of test methods given for the water absorption coefficient and the moisture content are described to be applied on structural building elements rather than thermal insulation materials. Since the hygroscopic behavior of tested materials are different from the ones described in the standards, there has been an ambiguity in terms of test durations, acceptable ranges of parameters for subjected materials, and the test setups at some situations.

5.3 Evaluation of Energy and Hygrothermal Performance of Timber Frame Building

The total data gathered through WUFI Plus simulation on the case of timber frame buildings designed with previously tested ETIM are discussed to figure out the building components' hygrothermal activity and subsequently compared with each other. Thermal transmittance value, and energy performance index provide an insight on the thermal behavior of building components in timber frame buildings. Ultimately, the hygric behavior of the timber frame building envelope components as water content and relative humidity, which includes researched ETIM, is presented. The results achieved with HAM simulation are shown in Table 5.2.

Table 5.2. The compiled data of energy properties on hygrothermal performance of buildings with ETIM.

Sample Name	U_F	U_E	U_R	Total	EPI	WC_{maxF}	WC_{maxE}	WC_{maxR}
				Energy Need				
	W/m ² K	W/m ² K	W/m ² K	kWh	kWh/m ² /year	kg/m ²	kg/m ²	kg/m ²
CC	0.506	0.386	0.318	8,700.1	38.84	0.27	2.74	0.35
EC1	0.473	0.367	0.296	8,367.6	37.36	1.76	2.87	1.75
EC2	0.514	0.391	0.323	8,748.9	39.06	1.69	2.74	1.67
CB	0.456	0.357	0.285	8,098.3	36.15	1.71	2.91	1.71

In terms of energy and hygrothermal performance related values of building components with selected ETIM on the timber frame building case, concluded outcomes are summarized below:

- All of the thermal transmittance values for components with selected ETIM are found under the reference values given in the TS 825:2013 as the maximum 0.570 W/m²K for external walls and floors and 0.380 W/m²K for the roof. This means all of the ETIM provides good insulation performance.
- In order to minimize the thermal energy loss, the components with the lower U values should be preferred. The lowest U_F , U_E , U_R values are found in the components used CB with 0.456 W/m²K, 0.357 W/m²K, and 0.285 W/m²K respectively. Therefore, CB is the best option with respect to insulation properties. Second best option is EC1 while EC2 stands as the least preferred insulation material in terms of thermal transmittance capability.
- It is seen that the type of ETIM affects the energy consumption values of the timber frame building. Since the coldest month in İstanbul is January, monthly energy demand of January is the highest. In winter, CelluBor requires the least amount of energy, yet during summer, the building with CelluBor needs higher energy. The overall energy need of the case building

is the lowest with CelluBor with 8,098.3 kWh. As can be expected, the energy need of the building has a direct relationship with the thermal conductivity values of the TIM used.

- It is known that there is a correlation between the annual energy demand of building with EPI. The maximum value found through TS 825:2015 was 38.56 for the case timber frame building. The simulation verified and fine-tuned the information by the standard. The EPI values for case buildings are all found fluctuating around 38.56 kWh/m²/year.
- Timber frame building with CelluBor has the lowest EPI, as well as the MDFacade, which is the under the value calculated through formula in the standards. This value is found 36.15 for CelluBor, while it is the highest with 39.06 for Expanded Corkboard 2. Low EPI means that the lower amount of heating/cooling energy needed per square meter to keep the building's interior temperature between the control values.
- All ETIM have shown good performance values in terms of thermal energy related qualifications. However, in order to decrease the energy requirement and increase the thermal performance of the building, CB stands as the most effective ETIM among the tested materials. It is followed by EC1 as the second-best option.
- Expectedly, the ETIM has shown a decrease in the temperature on component layers analysis in Figures 4.12., 4.13. and 4.14. The change of RH can be seen in those figures with layers analysis as well. Generally, the RH of ETIM have shown a decrease through their layers. Yet in some time slots it is seen that ETIM on roof layers was incapable to lower the RH, in other terms, an increase has been seen. Therefore, it is thought that ETIM on the roof tends to grow mold because of increasing humidity.
- According to the hygrothermal simulation results, RH levels of EC1 and EC2 have seen similar behavior in all three components. The RH within the

building components researched, entire element of these component has a rate lower RH than 90%. Meaning that there is more of moisture that can be stored in vapor or water form in the components. The WC in simulated building components have indicated supportive results with the RH graphs and no condensation occurred.

- The RH analysis on roof components shows that the vapor barrier has a higher RH meaning that it has an appropriate capacity of regulating the water vapor transportation between layers. However, the RH values of ETIM in roof structures during summer are higher than. Since in higher temperatures the RH is expected to be lower, this is an unwanted situation which is caused by the location of the vapor barrier. This might be also caused by the outdoor RH levels, as seen in Figure 3.14., which are between 65 and 90% during the summer. It points out that the humidity is constantly fluctuating between the days and overall, it is a very humid environment.
- The total water content of floor and external wall components have been seen increased during the simulation period. The increase in the TWC in the long run may result as humidity and condensation problems in the materials of those components. On the other hand, the roof structure showed lower TWC in summer expectedly and continuity in the yearly cycle.
- RH and WC graphs of CC indicated that the short cycles of increase and decrease might cause a problem on the durability of this material. Eventually, it may result in Corkoco to be prone to problems related to wet and dry cycles. Likewise, the graphs of CB on its water content and RH draw attention with respect to the rapid cycles of wetness and dryness.
- In the graphs presenting the WC of ETIM in building components, it is noticed that EC1 has the highest ratios of water content. Higher WC in materials is undesirable since it is known that the thermal conductivity capacity of the thermal insulation materials increases with the increase of the water content.

- CC draws attention with its lowest water content in floor and roof sections. This might be a result related to the application direction of the material since its water content of exterior wall section are high. Nonetheless, during the laboratory tests conducted, it has been determined that the CC and CB has poor hygric behavior despite the higher water vapor permeability.

The overall simulation results on building with researched ETIM are summarized below:

- All the tested ecological thermal insulation materials have shown satisfactory energy consumption values according to the Turkish Standard of thermal insulation requirements on buildings.
- The thermal characteristics of CB has been found outstanding. Nevertheless, the hygric properties of CB is recorded as poor compared to other ETIM researched.
- According to the results obtained, hygrothermal performance of EC1 is the outstanding between tested ETIMs by taking its both thermal and hygric values into account.

CHAPTER 6

CONCLUSION

This study is focused on the material characteristics of ecological thermal insulation materials and their hygrothermal performance for used in timber framed buildings. Since the usage of conventional thermal insulation materials results in toxicity through chemical and physical dispersion, usage of natural substitutes are necessary.

Natural materials providing the satisfactory energy efficiency values should be used which is avoiding polluting the environment, harm ecosystems and/or endanger human health by maintaining the reduced energy consumption in construction field. Hence, the evaluation of ecological thermal insulation materials is critical.

In this study, the efficiency and durability of coconut fiber added corkboard, expanded corkboard, and boron added cellulose is examined in laboratory. The ecological thermal insulation materials used in the case timber framed building is analysed through WUFI Plus heat, air, and moisture simulation to present their hygrothermal performances in the construction.

Laboratory analyses were conducted to exhibit their physical, thermal, and hygric properties of selected ecological thermal insulation materials. Obtained results are discussed with respect to their limits and potentials.

In answer to the first research question regarding the hygric behavior of ETIM with respect to water and vapor related properties it can be said that the ETIM were found to be porous and lightweight materials that showed satisfactory thermal properties according to the laboratory tests conducted. However, there were some differences within tested ETIM in hygric performances, e.g., Expanded corkboards are indicated as the materials that are durable against water, yet their vapor permeability values are not as high as coconut fiber added corkboards and boron added cellulose.

Regarding the research question on the ability of ETIMs to prevent heat loss in buildings, this research highlights the potential of the tested materials and encourages the use of Expanded Insulation Corkboard EC1 as an acceptable natural thermal insulation material that can be used with confidence in building envelopes.

In explanation to the third research question regarding the energy demand and thermal properties of ETIM in timber frame constructions, the findings in this research underline the suitability of using ecological thermal insulation materials in the timber frame building design in similar climate conditions to İstanbul and provide an insight to choose the correct ETIM. HAM simulation conducted with WUFI Plus presented that the energy demand of the buildings with ETIM are within the acceptable range defined by the Turkish Standards for selected region. CelluBor has shown outstanding thermal characteristics.

Yet, it is needed to improve the hygric performance of cellulose, especially on external wall sections. It is found that simulated timber-frame floors and roof show better results with Corkoco. Finally, results have shown that hygrothermal performance of Expanded Insulation Corkboard is the outstanding one to be applied on all components between tested ETIMs by taking both thermal and hygric values into account.

On the subject of replacing thermal insulation material with ecological substitutes, it can be claimed that selected ETIM especially Corkoco and Expanded Corkboard perform no different than mineral wool-based ones like glass wool and rock wool. Since Expanded Corkboard has been observed to perform better in terms of water content. In terms of water absorption properties, it is observed that Expanded Corkboard has even better performance characteristics. Therefore, these materials might be encouraged to be used in the cases where rock wool is used timber frame buildings by designers and practitioners.

One thing to acknowledge is that a considerable number of timber framed structures in Turkey use the Baghdadi system. Considering that the *Bağdadi* system is not a standard production method, the use of on-site productions such as *Bağdadi* and adobe was avoided in this study. It should be noted that testing of ecological thermal insulation materials in timber framed structures with non-standardized manufacturing has not been considered as the subject of this study. However, it is worth mentioning that this study may have an important place to use natural thermal insulation materials in the restoration projects of timber framed structures.

Another reason why on-site productions such as *Bağdadi* and adobe were not considered as part of this study is that the required standardized materials' inputs for simulation could not be found.

There are several delimitations set during the research. The first one of them is regarding the traditional timber frame buildings. Even though researched ETIM are found compatible to work with timber frame buildings, the use of ETIM on historical timber frame buildings is left out of this study, since the historical buildings are not generic and should be handled with singularity. However, it is possible to conduct energy and hygrothermal simulation for already existing historical buildings with *Hımsı* or *Bağdadi* systems, by collecting case-related data with sensors and additional atmospheric data. As a result, this study focused on the use of industrialized and standardized materials and providing the necessary energy and humidity conditions to the building.

Nonetheless, this study might be beneficial for the selection of thermal insulation materials in restoration of fired-clay brick infill in timber frame buildings. The applicability and compatibility of ecological thermal insulation materials to restoration projects and traditional timber structures containing other infill materials need to be clarified in other studies.

Another delimitation is on the selected ecological thermal insulation materials' position among the building industry. Their availability and easy achievability in the

market, as well as the cost effect is left out of research. Another point that is eliminated on ETIMs' properties are the fire resistance classification. Therefore, without defining some of these properties, it is abstained to label ETIM as advantageous or disadvantageous from some aspects.

There are certain aspects left unexplained in this research. Therefore, in further studies:

- the hygrothermal behavior of ETIM on traditional Turkish timber frame structures may be examined.
- In enhanced laboratory conditions, the hygric behavior tests on CelluBor may be tested.
- Materials with high water content may need to be specifically tested for mold growth.

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APPENDICES

A. Raw Data from Laboratory Experiments

Density

Sample	Mdry (kg)	Msat (kg)	Surface Area (m ²)	Thickness (m)	Volume (m ³)	Density (kg/m ³)	Av. (kg/m ³)
CC.r.1	0.048	0.099	0.011	0.042	0.00044095	108.23	99.96
CC.r.2	0.039	0.077	0.010	0.040	0.00040735	95.10	
CC.r.3	0.041	0.098	0.011	0.039	0.00042664	96.55	
EC1.r.1	0.020	0.046	0.007	0.030	0.00020357	96.87	97.87
EC1.r.2	0.019	0.047	0.007	0.030	0.00020208	95.45	
EC1.r.3	0.020	0.045	0.007	0.030	0.00020126	101.29	
EC2.1	0.033	0.033	0.010	0.031	0.00029574	111.99	114.39
EC2.2	0.035	0.031	0.010	0.031	0.00029879	118.49	
EC2.3	0.034	0.031	0.010	0.031	0.00030351	112.69	
CB1	0.016	-	0.005	0.037	0.00020181	80.17	90.88
CB2	0.018	-	0.005	0.035	0.00017691	100.60	
CB3	0.014	-	0.005	0.033	0.00015385	91.89	

Porosity

Sample	Mdry (kg)	Msat (kg)	Volume (m ³)	Vwater (m ³)	Porosity (%)	Av. (%)
CC.r.1	0.048	0.099	0.00044095	0.00006664	15.11	14.35
CC.r.2	0.039	0.077	0.00040735	0.00005292	12.99	
CC.r.3	0.041	0.098	0.00042664	0.00006382	14.96	
EC1.r.1	0.020	0.046	0.00020357	0.00001357	6.66	7.05
EC1.r.2	0.019	0.047	0.00020208	0.00001535	7.60	
EC1.r.3	0.020	0.045	0.00020126	0.00001384	6.88	
EC2.1	0.033	0.033	0.00029574	0.00003465	11.72	11.60
EC2.2	0.035	0.031	0.00029879	0.00004020	13.46	
EC2.3	0.034	0.031	0.00030351	0.00002921	9.62	
CB1	0.016	-	0.00020181	-	-	-
CB2	0.018	-	0.00017691	-	-	
CB3	0.014	-	0.00015385	-	-	
Water Density in 24°C = 997.32 kg/m ³						

Thermal Conductivity Test

Sample	Area (cm ²)	Area (m ²)	dAV (cm)	dAV (m)	Q (kWh)	Qend (Wh)	tHeat (h)	Qend (W)	dT (K)	Ktuned (W/mK)	AV (W/mK)
CC.r.1	96.08	0.009608	3.91	0.03913	0.009	3.523	0.483	7.290	33.348	0.2287	0.232
CC.r.2	101.80	0.010180	4.01	0.04010	0.010	4.148	0.450	9.217	39.385	0.2338	
CC.r.3	97.22	0.009722	4.03	0.04030	0.009	3.565	0.467	7.639	32.948	0.2329	
EC1.r.1	101.00	0.010100	2.99	0.02988	0.009	3.704	0.433	8.547	39.914	0.1780	0.173
EC1.r.2	99.93	0.009993	2.98	0.02980	0.010	4.071	0.400	10.179	42.654	0.1721	
EC1.r.3	98.95	0.009895	2.98	0.02980	0.010	4.032	0.383	10.517	42.230	0.1700	
EC2.1	89.40	0.008940	3.03	0.03030	0.009	3.278	0.483	6.782	31.761	0.1750	0.177
EC2.2	88.83	0.008883	3.02	0.03018	0.009	3.257	0.533	6.107	31.965	0.1791	
EC2.3	89.48	0.008948	3.02	0.03020	0.009	3.281	0.483	6.789	32.844	0.1759	
CB1	107.3276	0.010733	2.765	0.02765	0.009	3.936	0.300	13.119	53.401	0.1614	0.150
CB2	107.3276	0.010733	2.39	0.02390	0.010	4.373	0.300	14.576	52.644	0.1356	
CB3	107.3276	0.010733	2.645	0.02645	0.008	3.498	0.267	13.119	50.225	0.1521	

Specific Heat Capacity Test

Sample	MDRY (kg)	dT (K)	Qcalc. (W)	time (sec)	Q (j)	c (J/kgK)	cAV (J/kgK)
CC.r.1	0.0387	42.97	251.5215	100	9851.594	5924.758	5,390.24
CC.r.2	0.0508	30.65	244.1711	70	7092.691	4559.535	
CC.r.3	0.0405	30.20	250.9528	70	6962.033	5686.422	
EC1.r.1	0.0315	23.99	243.482	70	7017.222	9284.068	8,723.14
EC1.r.2	0.0307	23.99	251.9809	70	7185.192	9750.785	
EC1.r.3	0.0322	42.59	242.3878	100	9777.13	7134.58	
EC2.1	0.0322	30.08	242.053	80	7056.609	7285.761	7,078.51
EC2.2	0.0298	35.85	245.1217	80	7100.621	6650.799	
EC2.3	0.0311	20.10	249.828	50	4556.328	7298.973	
CB1	0.0308	37.14	242.0874	90	9532.494	8341.745	8,035.44
CB2	0.0290	33.32	250.6455	70	7676.262	7945.719	
CB3	0.0321	30.59	250.4936	70	7671.61	7818.852	

Water Vapor Permeability Test

Sample Name	μ	μ	sd	sd	WVTR	WVTR	Permeance	Permeance	Permeance	Permeance
	(unitless)	(unitless)	(m)	(m)	(g/hm ²)	(g/hm ²)	g/Pasm ²	g/Pasm ²	Metric Perm	Metric Perm
CC.s.1	2.31	2.10	0.090	0.082	19.08	20.73	0.0000035548	0.0000038611	41	44
CC.s.2	2.12		0.083		20.37		0.0000037934		44	
CC.s.3	1.87		0.072		22.74		0.0000042352		49	
EC1.s.1	8.23	10.96	0.244	0.326	7.94	6.69	0.0000010875	0.0000011159	13	13
EC1.s.2	16.59		0.493		4.08		0.0000007607		9	
EC1.s.3	8.07		0.240		8.05		0.0000014995		17	
EC2.1	11.72	14.29	0.357	0.433	5.56	4.71	0.0000007618	0.0000007851	9	9
EC2.2	14.60		0.444		4.52		0.0000008423		10	
EC2.3	16.55		0.500		4.03		0.0000007513		9	
CB1	1.97	1.90	0.073	0.067	22.62	25.00	0.0000030985	0.0000042843	36	40
CB2	2.31		0.080		20.92		0.0000038961		45	
CB3	1.43		0.047		31.45		0.0000058582		40	

1 US Perm = 1.74784×10^7 g/Pasm² (ASTM E96/E96M-22).

1 Metric Perm = 1.15191×10^7 g/Pasm²

Capillary Water Absorption

Water absorption per unit area (kg/m ²) & square root time (s ^{0.5})							
Sample	Time						
	1 min	3 min	5 min	10 min	15 min	30 min	1 h
	60	180	300	600	900	1800	3600
	7.75	13.42	17.32	24.49	30.00	42.43	60.00
CC	0.379411	0.547020	0.784846	0.880079	1.188405	1.935498	2.744638
EC1	0.066643	0.177283	0.234052	0.283382	0.357588	0.460089	0.618018
EC2	0.148777	0.186353	0.262623	0.295527	0.361168	0.445375	0.543292

Water absorption per unit area (kg/m ²) & square root time (s ^{0.5})							
Sample	8 h	12 h	24 h	48 h	72 h	96 h	120 h
	28800	43200	86400	172800	259200	345600	432000
	169.71	207.85	293.94	415.69	509.12	587.88	657.27
CC	3.606078	3.784255	3.987292	4.055253			
EC1	0.880939	0.896162	1.056623	1.254262	1.347327		
EC2	0.807654	0.872471	1.017387	1.145194	1.241015	1.303186	1.389025

B. Data from WUFI Simulation

Thermal Transmittance Values

	U_f (W/m ² K)	Heat Transfer Coefficient Convective external	HTC Radiant External	HTC Convective internal	HTC radiant internal	Rse	Rsi	Absorption/Emission
		W/m2K	W/m2K	W/m2K	W/m2K			
CC	0.506	18.5	6.5	2.5	3.38235	0.04	0.17	0.4/0.9
EC1	0.473							
EC2	0.514							
CB	0.456							
	U_e (W/m ² K)	Heat Transfer Coefficient Convective external	HTC Radiant External	HTC Convective internal	HTC radiant internal	Rse	Rsi	Absorption/Emission
		W/m2K	W/m2K	W/m2K	W/m2K			
CC	0.386	18.5	6.5	3.19231	4.5	0.04	0.13	0.4/0.9
EC1	0.367							
EC2	0.391							
CB	0.357							
	U_r (W/m ² K)	Heat Transfer Coefficient Convective external	HTC Radiant External	HTC Convective internal	HTC radiant internal	Rse	Rsi	Absorption/Emission
		W/m2K	W/m2K	W/m2K	W/m2K			
CC	0.318	18.5	6.5	5.5	4.5	0.04	0.1	0.68/0.9
EC1	0.296							
EC2	0.323							
CB	0.285							

Energy Demand

	Heating Energy	Cooling Energy	Total Energy	Area	Volume	EPI
	(kWh)	(kWh)	(kWh)	m ²	m ³	kWh/m ²
CC	7,599.90	1,100.20	8,700.10	224	1344	38.84
EC1	7,275.00	1,092.60	8,367.60			37.36
EC2	7,674.80	1,074.10	8,748.90			39.06
CB	6,952.90	1,145.40	8,098.30			36.15

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Monthly energy	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
CC	1748.22	1654.6	1401.77	422.999	146.682	12.3316	0	0	0	0	680.83	1528.34
	0	0	0	0	0	93.3955	373.801	371.352	238.866	12.5044	0	0
	1748.22	1654.6	1401.77	422.999	146.682	105.7271	373.801	371.352	238.866	12.5044	680.83	1528.34
EC1	1682.039	1590.038	1344.896	397.4786	132.4649	12.13783	0	0	0	0	647.4197	1464.618
	0	0	0	0	0	91.0659	365.02	365.417	238.208	12.7896	0	0
	1682.039	1590.038	1344.896	397.4786	132.4649	103.20373	365.02	365.417	238.208	12.7896	647.4197	1464.618
EC2	1760.87	1673.239	1418.784	428.4621	147.9922	12.91877	0	0	0	0	687.4039	1540.959
	0	0	0	0	0	88.2052	360.348	362.394	233.223	11.5036	0	0
	1760.87	1673.239	1418.784	428.4621	147.9922	101.12397	360.348	362.394	233.223	11.5036	687.4039	1540.959
CB	1613.183	1539.142	1288.863	368.6297	113.308	10.73626	0	0	0	0	610.2113	1404.057
	0	0	0	0	0	98.9423	378.851	373.971	252.537	16.8407	0	0
	1613.183	1539.142	1288.863	368.6297	113.308	109.67856	378.851	373.971	252.537	16.8407	610.2113	1404.057

Figure, showing the monthly energy consumption needs for buildings designed with selected ETIM

