Development of Lightweight Calcium-Magnesium based Panels (LCMP) as a Thermal Insulation for Structures

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ABSTRACT

Buildings are consumers of large amounts of energy in all countries. In regions with tough climate conditions, a good percentage of the total energy consumption is due to cooling and heating of the buildings. The most important factor of saving energy in buildings is to be aware of thermal properties of the construction materials. The correct and effective use of thermal insulation in buildings contribute towards reducing the required air-conditioning or central heating system size with further reduction in the annual cost of energy. In addition, it could help in achieving thermal comfort without reliance on electrical or mechanical air-conditioning, in particular, during inter-season times. The amount of energy savings as a result of using thermal insulation differ according to the building type, the location of building (climatic conditions), and type of the insulation material used.

The objective of this research is to investigate the lightweight calcium-magnesium based panel (LCMP) as a thermal insulation in buildings and also comparing the costs of some ordinary insulation materials such as: polystyrene, polyurethane, mineral wool and etc.

Thermal resistance (R), thermal conductivity (λ), thermal conductance (1/R) and thermal transmittance (U factor) are main thermal factors of LCMP as a thermal insulation material that measured separately. Also these factors measured for a wall containing combination of LCMP and masonry materials. Experiments on fire resistance, compressive strength, water absorption and pulse velocity of LCMP were carried out.

Results show that the main thermal factors of LCMP are acceptable as per the standards and building codes. Reaction of LCMP in case of fire indicates that it is fire resistant. Water absorption of LCMP is slightly high. LCMP is also a fragile material which is not strong enough to be used as a structural material. However, it is suitable to be used as a thermal insulation for buildings. Pulse velocity test shows that LCMP samples have a good uniformity.

The cost of manufacturing LCMP is 128 \$/ m^3. When compared to other thermal insulation material prices, the price of LCMP is reasonable.

Keywords: Lightweight Calcium-Magnesium Panels, Lightweight Panels, Saving Energy, Thermal Conductivity

ÖZ

Bütün ülkelerdeli binalar büyük miktarlarda enerji tüketcileridirler. Sert ikilim şartlari olan bölgelerde, toplam enerji tüketiminin yüksek bir yüzdeliği, binaların soğutma ve ısıtmalarından kaylanmaktadır. Binaların enerji tasarufundaki en önemli faktör yapımateryallerinin termal özelliklerinin farkındalığıdır.

Binaların ısıtma sistemin boyutunun azalmasına katkıda bulunur, ilaveten, yıllık enerji maliyetinin daha da azalmasını sağlar.

Buna ek olarak, elektrik veya mekanik klimaya itimat etmeden termal rahatlığa ulaşımasında yardımcı olur, billahassa ara-sezon dönemlerinde.

Tasarruf edilen enerji miktarı, termal izolasyon kullanım sonucu, bina tipine, binanın konumuna (iklim şartlari) ve kullanılan isolasyon materyal çeşitine göre farklılık gösterir.

Bu araştırmanın amacı, binalardaki termal isolasyonlarda kullanılan hafif Kalsyum-Magnezyum Tabanlı paneli (LCMP) araştırmak ve ayrica bazı sıradan izolasyon materyallerini, örneğin: poistiren, poliüreten, amayant v.s. ile maliyetlerini kıyaslamaktır.

Termal izolasyon materyali olarak, LCMP'nin ana termal faktörleri, ısı direnci (R), ısı ilekenliği (λ), termal iletkenlik (1/R) ve ısıl geçirkenlikdir (U faktör) ki bunalar ayrı ölçülürler. Hemde bütün bu faktörler, LCMP'nin duvar içeen kombinasyon ve duvareılık materyallernde ölçülür. LCMP'nin yangın dayanımı, basinç dayanımı, su emme ve nabız hızı deneyleri uygulanmıştır.

Sonuçlar gösterirki LCMP'nin ana termal faktörleri standartlarına göre ve bina kodlarına göre kabul edilebilirdirler. LCMP yangın durumunda yangına dayanıklılık gösterir. LCMP'nin su emmesi hafifçe yüksektir. LCMP'i kırılgan bir materyaldir ki yapısal materyal olarak kullanım için yeteri kadar ğüçlü değildir. Ancak binalarda termal izolasyon malzemesi olarak kullanılmak için yugundur. Nabiz hızı testi LCMP örneklerinin iyi bir tekdüzeliğe sahip olduğunu gösterir.

LCMP'nin üretim maliyeti $128\$/m^3$. Diğer termal izolasyon materyal fiyatlariyala kıyaslandığı zaman LCMP'nin fiyat makuldur.

To My Family

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LIST OF SYMBOLS

R ……………… Thermal Resistance

U ……………... Thermal Transmittance

λ ……………… Thermal Conductivity

W …………….. Watt

K …………….. Kelvin

m …………….. Meter

dx ……………. Thickness

H …………….. Height

L ……………... Length

W …………….. Width

t ………………. Thickness

cm ……………. Centimeter

C ……..…..…… Centigrade

ft ……………… Feet

f ………………. Fahrenheit

Hz …………….. Hertz

J ……………… Joule

Kw …………… Kilowatt

LCMP ………… Light weight Calcium Magnesium based Panels

IBC …………... International Building Code

ECBC ………... Energy Conservation Building Code

BECP ………... Building Energy Code Program

IECC ………… International Energy Conservation Code

BPIE ………… Building Performance Institute Europe

NFPA ……….. National Fire Protection Association

FSI ………….. Flame Spread Index

ASTM ………. American Society for Testing Materials

DIM ………… Dynamic Insulator Materials

NIM ………… Nano Insulator Materials

USAID …….. United States Agency for International Development

ASHRAE ….. American Society of Heating Refrigerating and Air-conditioning Engineers

RAA446 …... Cyprus Building Code for Energy Purposes

IRAN Code 19 ... Iran Building Code for Energy Purposes

DIN .. Deutsches Institut für Normung, meaning German institute for standardization

EN ………… European Norms

Chapter 1

INTRODUCTION

1.1 General

Some of the most important factors for building designs are: cost, earthquake resistance, energy consumption and etc.

By considering the results of earthquake events, the importance of the usage of light-weight materials in buildings is better understood. As it is known, using lightweight materials in buildings are an important issue that causes to reduce in dead load of the structure. In the structures, reduction in dead load causes more resistance against the earthquake forces [1].

A large amount of energy consumers in all countries are buildings. In regions with tough climate conditions, a large amount of energy consumption refers to thermal conditioning of buildings [2].

The accurate uses of thermal insulation in buildings contribute in decreasing the required air-Conditioning systems size and also in decreasing the annual cost of energy. Additionally, it can help in expanding the times of thermal comfort without reliance on Electrical or mechanical air-conditioning chiefly during inter-seasons times. The amount of energy savings as a target of using thermal insulation changes according to the building type, the location of building at which climatic conditions and type of the insulation material used [2]. The most important factor of saving energy in buildings is thermal properties of used material.

Space air-conditioning may be placed as one of the greatest energy consumer in constructions.

As an instance, space heating and cooling of American's homes comprises 50–70 percent of their energy use [3].

External walls which are contacting with uncontrolled space are the most important constituent of a building. Therefore high thermal resistance of external walls brings much better comfort to a building.

In North-Cyprus saving energy is one of the most important factors that always keeps up its importance because of the costs of fuel and electricity. Energy in buildings is mainly consumed for the purpose of heating and cooling. About 45 percent of the total amount of energy is consumed for heating and cooling process in ordinary residential buildings [4].

Better insulation material having low thermal conductivity is a significant contributor for new construction and retrofitting existing buildings, when the emphasis is on energy efficiency [5].

In order to decrease the annual cost of constructions in energy section and weight of the buildings, the usage of lightweight materials with admissible thermal specifications in buildings can be helpful. Because of the importance level of this matter, this research tends to innovation a new lightweight insulation material which based on calcium and magnesium. This material has introduced in this chapter.

Some other researches about thermal insulation materials, optimum thickness of insulations, energy cost analysis and other relevant issues have been considered in this research. For more information, vide "Chapter Two" of this research.

The essential tests for accept or reject a new thermal insulation material, have done on Lightweight Calcium-Magnesium based Panels (LCMP) according to

ASTM, International Building Code (IBC), Energy Conservation Building Code (ECBC), Building Energy Code Program (BECP), International Energy Conservation Code (IECC), Iran Code 19, Building Performance Institute Europe (BPIE) and RAA 446 (Cyprus Building Code) standard and building criteria. The test procedures and results of the tests have been shown in "Chapter Three" and "Chapter Four" of this research respectively.

The results show that using the LCMP in buildings as a thermal insulation material can be permitted. In the next section, LCMP introduced briefly. More information about LCMP manufacture expressed in "METHODOLOGY" section of this research (Chapter Three).

1.2 What is the LCMP?

As mentioned before, LCMP is Lightweight Calcium Magnesium based Panels manufactured by calcium carbonate (22.5%), magnesium carbonate (22.5%), water (10%), polypropylene fibers (9 %), montmorillonite (7%), calcium sulfate (22%) and resistant carbon (7%).

Three different samples prepared with different percentages of ingredients. After measuring the coefficient of thermal conductivity by "Hot plate apparatus" test (ASTM C177), the value of that sample with calcium carbonate (22.5%), magnesium carbonate (22.5%), water (10%), polypropylene fibers (9 %), montmorillonite (7%), calcium sulfate (22%) and resistant carbon (7%) had the lowest thermal conductivity value. Therefore for other tests such as hot box test, samples with mentioned percentages have been selected. This note is important that all of the ingredients are inorganic substances which they are not poisonous or harmful for human or animal's health. More information about ingredients of LCMP has expressed in "Chapter

Three" of this research. Some of the essential tests that have been done on LCMP explained briefly in next section.

1.3 Tests on LCMP

Some essential tests according to relevant standards for considering the LCMP properties to evaluate the sufficiency of this material as a thermal insulation for structures have been done. These tests show that using of LCMP as a thermal insulation material in terms of thermal properties, cost and safety is reasonable.

1.3.1 Guarded Hot Plate

Testing with Guarded Hot Plate Apparatus is an accurate test method to estimate coefficient of thermal conductivity of some materials. Guarded Hot Plate Apparatus is a utensil for determination of heat conductance - in steady-state - properties, thermal resistance and thermal conductivity, of slab specimens in accordance with International Standards ISO 8302, DIN EN 12667, ASTM C-177.

Guarded hot plate apparatus have been designed for using in laboratories, making steps and finally quality control process for a wide range of materials with low and intermediate thermal conductivities. Some of the materials with low and/or intermediate thermal conductivities are: rubber, cellular rubber, plastics, polystyrene, mineral fibers, polyurethane, glass fibers and etc. Since sample size is small – compared to one section of a building such as wall – for constructional researches, it is one of the best choices for homogenous materials.

1.3.2 Guarded Hot Box

Guarded hotbox apparatus used to evaluate the thermal conductivity coefficient of construction materials in large scales (e.g. 1200 × 1200 mm). For vertical specimen such as walls, measurement of heat-flow will be in horizontal dimension in this test.

On the other hand measurement of heat-flow in vertical dimension is related to horizontal samples such as ceiling.

Guarded hotbox test is suitable for homogenous or non-homogenous materials, but for homogenous materials, using hot plate (ASTM C 177) should be more suitable.

This method of test applies for steady-state testing and it does not establish criteria or procedure for doing dynamic tests for dynamic data analysis. However some type of hotbox apparatus designed for dynamic tests. This test process is intended for use at normal conditions of construction applications. The natural conditions of outside in temperature zones range from (approximately) -47 to 84˚C and the inside temperature for normal conditions of residential buildings is 21˚C.

1.3.3 Fire Test

ASTM standards introduced some criteria for fire test of materials. Fire testing of materials is a widespread topic in Materials science. ASTM's standards for flammability and fire are including evaluation and testing the ignition, burning or flaming of certain materials. Majority of these standards refer to exterior or interior parts of constructions as well as commercial and household furniture. Some standards for fire test in order to different purposes are: ASTM E2707 - 09 Standard Test Method for Determining Fire Penetration of Exterior Wall Assemblies Using a Direct Flame Impingement Exposure, ASTM E119 - 12a Standard Test Methods for Fire Tests of Building Construction and Materials and ASTM E84-06 Standard Test Method for Surface Burning Characteristics of Building Materials. Surface burning method used in this research to evaluation of LCMP's characteristics.

1.3.4 Pulse Velocity

The Pulse velocity test is an ultra-sonic test to evaluate the density, homogeneity, uniformity and etc. of concrete and/or similar-concrete materials. The higher value of this test shows better homogeneity and compaction of sample.

Pulse velocity apparatus essentially includes: two transducers, one amplifier, one electrical generator and one electronic timing instrument to assessing the time interim between pulse generator transducer and pulse receiver transducer.

Pulse velocity test has been done on LCMP samples to evaluate compaction and uniformity of them. High value of pulse velocity presents better homogeneity, uniformity and density, and also it shows better cohesion.

Pulse velocity test usually applied to determine the approximate strength of concrete as an assessing concrete quality, determination of Poisson's ratio and modulus of elasticity of concrete, and determination of the uniformity and interior changes of concrete members occurring with the time.

All test procedures expressed in "Chapter Three" of this research.

1.3.5 Compressive Strength Test

The compressive strength test in accordance with EN-826 has been done on LCMP samples. EN-826 mainly is related to compressive strength of thermal insulation materials.

Six samples with 50 x 50 x 24 mm of LCMP placed between the jaws of device, 4 KN force applied to samples within about three minutes. The results shown that LCMP samples compared to some other insulations such as EPS (Expanded Polystyrene) have better compressive strength, but generally their compressive strength is not enough for using as structural material.

1.3.6 Water Absorption

In this test four samples of LCMP with sizes of 50 x 50 x 25 mm were tested. Samples were placed into oven (temperature 105°C) during 48 hours to make oven-dry samples (stable weight). Then the samples (oven-dry) were weighed and recorded as an initial weight (oven-dry weight). Afterwards, samples were placed completely into the water during 24 hours. Finally samples were taken out from water and weighted to obtain the saturated weight of LCMP samples.

Test procedures details and results expressed in chapter three and chapter four, respectively.

1.4 Summary

Results show that main thermal factors of LCMP according to standard and building codes are acceptable. Reaction of LCMP in face of fire shows that LCMP is fire resistant. LCMP is fragile material and it is not strong enough for using as a structural or masonry material, and because of high water absorption of LCMP, it is suitable just for using as a thermal insulation in interior face of external walls of buildings. However in order to use of LCMP in exterior face of walls or in high humid places – such as bathroom – using water insulation as a protector on LCMP is necessary.

Pulse velocity test shows that LCMP samples have a good uniformity.

In summary the usage of LCMP as a thermal insulation material in term of thermal properties is acceptable by standards and building codes. And in other terms such as cost and safety can be reasonable.

Chapter 2

LITERATURE REVIEW

2.1 General

Thermal insulation material is either a single material or a combination of more than one material. When applied correctly, it reduces the rate of heat flow by radiation, conduction and convection. Because of its high thermal resistance, the heat flowing between controlled and uncontrolled spaces in buildings will retard or even completely stop.

It is clear that better insulation materials are those that have lower thermal conductivity than the others. One of the most important rules for insulation is energy conservation for cooling and heating of buildings. Therefore, selection of suitable insulation materials and their optimum thickness is very important for building insulation. As the thickness of the insulation material increase the rate of heat-transmission will continue to decrease. However, increasing the thickness of insulation may lead to increase in cost. So it is essential to know the cost parameters and insulation properties for better estimation of the insulation cost and thickness [6]. A good point to consider when deciding on the right thickness for insulation is that as the thickness of insulation increase so does the cost and this relationship is linear [6]. Therefore, proper selection of the type of thermal insulation and its thickness uplifts thermal comfort by minimum cost.

In some buildings, especially residential buildings, making airtight space is important. Applying insulation materials can have significant effect when cracks and small openings covered by insulations.

2.1.1 Function of Thermal Insulation

There are three modes of heat transfer: convection, radiation and conduction. In this study, heat transfer by conduction mode is more important than the other modes. So the thermal insulation by using conduction mode will be explained in this section.

In some thermal insulation materials too much air cells entrapped. Therefore, resistance to heat flow relates to the air cells, not the material. Increasing the cell sizes will decrease the density of material and on the other hand decreasing cell sizes lead to increasing density of material. Conduction usually decreases as the density decreases [7, 8, 9].

Many types of insulation materials, such as plastic foams (e.g. polyurethane and polystyrene), have other types of gases within the material instead of air. It leads to increasing conduction resistance (R value) when compared to air based insulation materials. In other types of materials, air cells and/or gas cells do not play an important role. However, thermal resistance of these materials relates to the content of insulation material.

Some common types of materials are described in the following sections.

2.1.2 Advantages of Using Thermal Insulations

i. **Matter of principle:** The accurate uses of thermal insulation in buildings contribute towards decreasing the size of air-conditioning units required and also decreases the annual cost of energy. Additionally, it can help in achieving thermal comfort without reliance on electrical or mechanical air-conditioning chiefly during inter-season times. Reducing energy consumption can save energy resources and this should be the responsibility of everybody to save energy resources [8].

ii. **Economic Benefits:** The correct use of the thermal insulation of buildings contributes to the reduction of the size of air conditioning systems as required and reducing the annual energy cost. By applying about five to eight per-cent of total building cost for insulation, the initial cost will be paid back between 3.5 to 8.8 years according to the amount of energy saving [8, 7].

iii. **Environmental Benefits:** The use of thermal insulation in buildings not only save cost of energy but it also results in saving energy sources and preventing emissions of hazardous gases because of using fossil fuels.

iv. **Thermally Comfortable Buildings:** Thermal comfort is very important factor in buildings. So selection of proper thermal insulation in buildings, especially public buildings (e.g. airports), can make large spaces thermally comfortable. In general, insulation can help in expanding the times of thermal comfort without reliance on electrical or mechanical air-conditioning mainly during inter-seasons times. Thermal comfort is described in the following sections.

v. **Reducing Noise levels:** Usually the thermal insulations may reduce disturbing noises from outside of buildings.

vi. **Fire Protection:** If the selected insulation materials are not flammable then in case of fire this will not help the spread of fire to different parts of buildings. Therefore, the ingredients of insulations should be non-flammable to preclude the spread of fire. So selecting and installing suitable insulation for buildings is very important.

vii. **Structural Integrity of Buildings:** Temperature changes can cause thermal movements which are not desirable. So using thermal insulations can reduce or even prevent these movements and keep integrity of building by tolerating the changes of temperature.

viii. **Customer Satisfaction:** increase in the use of thermal insulation will lead to decrease in peoples or customer's cost, making more energy available to others, saving energy sources for future generations and providing better service with lower costs [8].

2.2 Insulation's Definitions

There are some terms relating to, such as, thermal insulations, thermal conductance, thermal transmittance, thermal conductivity and thermal comfort. These terms are explained in the following sections.

2.2.1 Thermal Insulations

Thermal insulation is a material or combination of materials. When these materials applied correctly they reduce the rate of heat flow by radiation, conduction and convection. Because of their high thermal resistance, heat flowing between controlled and uncontrolled spaces in buildings will retard [10].

2.2.2 Thermal Conductivity

Thermal conductivity is the time rate of steady state heat flow (W) through isothermal planes of a unit area of 1m thick homogeneous material in an upright direction when there is one unit (1˚K) difference of temperature along the sample.

Thermal conductivity or K-value has been expressed in W/m˚K or Btu/h.ft˚F or (Btu-in/hr.ft^2 ˚F). Generally, thermal conductivity is measurement of the influences of a material in heat transmission through conduction [8].

2.2.3 Thermal Resistance

According to ASTM C 168, thermal resistance can be defined as the quantity of resistance that is measured by the temperature difference between two sides of a certain material that induces a unit heat flow – in steady state – trough a unit surface area. It is expressed as a function that depends on thermal conductivity of material, thickness of material and density. Thermal resistance or R-value is defined in $m^{2}{}^{\circ}K/W$ or ($h.ft^{2}\ {}^{\circ}F/Btu$) [11].

2.2.4 Thermal Conductance

It is the heat flow rate of a material due to one unit of temperature difference (˚K) between two sides of a material trough the surface area of the element or material. Thermal conductance is like thermal conductivity but thermal conductance directly refers to the thickness of element [8].

Thermal conductance is the reverse of the sum of the thermal resistance of layers, except outside and inside air film resistance. The unit of Thermal conductance – C value – is $W/m^{2}\ {}^{\circ}K$ or ($Btu/h.ft^{2}.{}^{\circ}F$).

2.2.5 Thermal Transmittance

It is the heat flow rate (W) of a certain material due to one unit of temperature difference (K) between two sides of a material, trough the surface area of the element or material.

Thermal transmittance is the reverse of the sum of the thermal resistance of layers, including outside and inside air film resistance. The unit of thermal transmittance – U value – is $W/m^{2}{}^{\circ}K$ or ($Btu/h.ft^{2}\ {}^{\circ}F$). It is often called: overall heat transfer coefficient [8].

2.2.6 Thermal Comfort

Thermal comfort is the specific temperature or state that in this state the body can adopts itself to existing area by minimum amount of energy conservation.

The main factors of thermal comfort can be divided into two parts as subjective factors, such as: age, body shape, gender, thermal insulation of the clothes, etc., objective factors, such as: air temperature, humidity, air swiftness, etc. [12].

2.3 Background of Research on Thermal Insulations

During the last two decades the need for thermal insulation for constructions has increased. One of the main reasons of this increase is the reduction of renewable energy resources that energy resources are decreasing day to day. On the other hand the usage of energy resources is increasing because of the population growth.

Energy consumption in addition to decreasing energy resources caused global warming and pollution emission.

S.Al-homoud (2005), researched on energy consumption in building section. He mentioned that in all countries, the main energy consumption relates to building section. Especially in some countries with harsh climate conditions, a large amount of energy spends for ventilation, heating and/or cooling the buildings.

The main objective of his research was to express the basic principles of insulation and assess the insulation materials that are commonly used in constructions. Different types of insulations have been presented, such as: organic/inorganic materials, rigid panel or boards, mineral fibers and foams. This research introduced R values (Thermal resistance) of some of these materials. However, other researchers have expressed these R values with some tolerance due to using different methods of evaluation, shape and purity of materials and facilities used by evaluator.

The following figure shows the R-values for 5cm thick materials, which are commonly used in constructions.

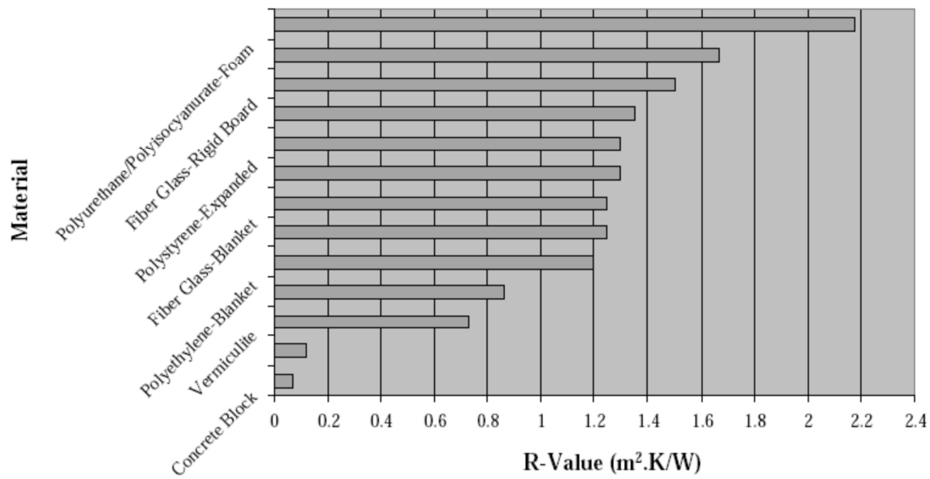

Figure 2.1: Thermal Resistance of Some Materials Based on Al-homoud (2005)

L.F.Cabeza et al. (2010) have researched on usage of insulations in Mediterranean climate. They built four boxes with 2.4 x 2.4 x 2.4 m in dimensions at Mediterranean conditions. They compared three different insulation materials, polyurethane, mineral wool and polystyrene over a period of time. They used common hollow bricks and cement mortar as structural materials and mineral wool, polyurethane and polystyrene as thermal insulations. Figure 2.2 shows the boxes that made for this research.

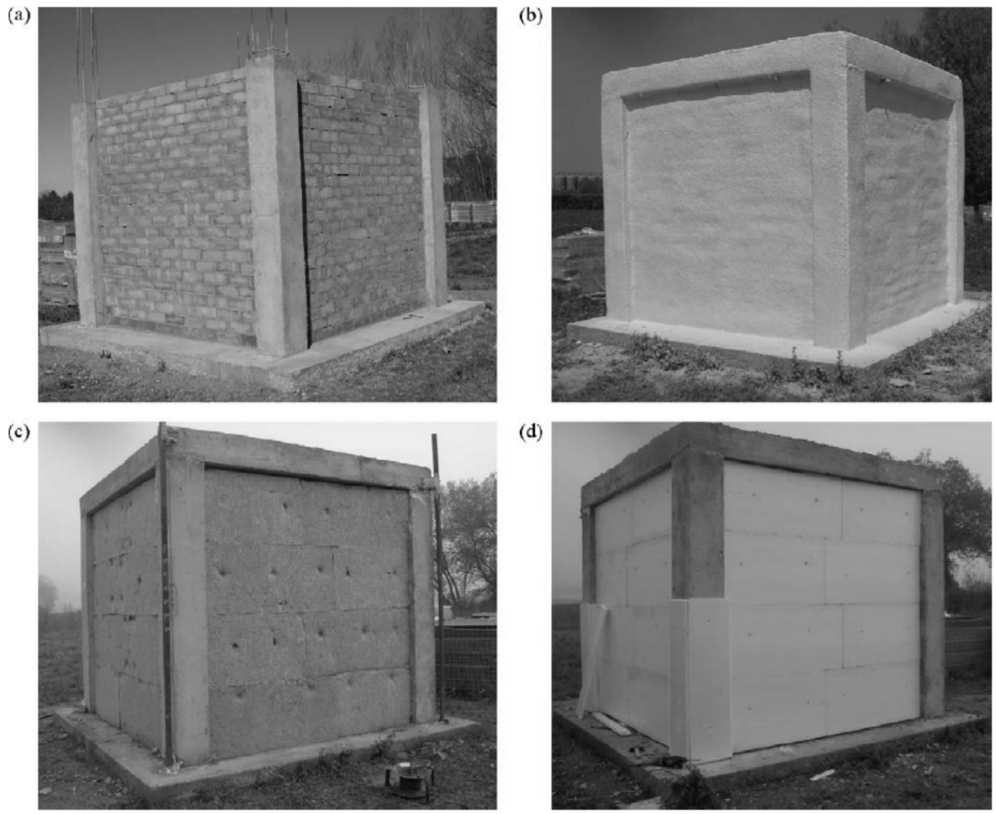

Figure 2.2: Construction Process of the Cubicles. (a) Reference cubicle; (b) cubicle during construction: cubicle insulated with PUR; (c) insulated with mineral wool; (d) cubicle during construction: cubicle insulated with polystyrene according to L.F.Cabeza et al. (2010) research

The properties of insulation materials were according to Spanish building code and they can be found in Table 2.1.

As explained before, thermal resistance depends on thickness of material. So, the material type, thicknesses of materials and their thermal conductivity used in this study are given in Table 2.1.

Table 2.1: Thermal Conductivity of Some Materials based on L.F Cabeza et al., (2010) research

Material	Thickness (cm)	Thermal conductivity (W/m˚K)
Cement mortar	1	0.700
Hollow brick	7	0.375
Polyurethane	5	0.028
Mineral wool	5	0.040
Polystyrene	5	0.034
Perforated brick	14	0.543
Plastering	1	0.570
Concrete precast beam	25	0.472
Concrete	5	1.650
Double asphalt membrane	1	0.700
Crashed stone	10	2.000

The results show that using insulations in buildings lead to decrease in energy demand during summer months by up to 64 percent and during winter months up to 37 percent. Also the study reveals that the highest decrease in energy demand is achieved when polyurethane was used.

B. Odeniz et al. (2005) carried out research for suitable roof materials for warm climates, such as Famagusta (North Cyprus).

Famagusta is a city in North Cyprus with climate changing between hot-humid and composite climate.

They compared some different types of roofs in Famagusta, with and without thermal insulations, and found out that for any type of roof, using thermal insulation can reduce the energy consumption and annual costs. The roofs with timber lath (2.5 cm thick) and soft glass wool insulation (4 cm thick) have the best results in achieving thermal comfort when insulation is applied near the exterior surface.

Bjørn Petter Jelle (2011) focused on properties, possibilities and requirements of traditional and future conceptual thermal insulators. He compared thermal properties of different insulations, such as: polystyrene, polyurethane, mineral woll, etc.. However, other important properties, such as: durability, fire resistance, water resistance, freezing/thawing resistance, cost, environement impact, mechanical strength and ease of performance of traditional and propable future materials, must also be considered.

As a conclusions, he mentioned that there is no single material which satisfies whole of the critical requirements as an insulation material. Also he observed that choosing a suitale material from existing ones and improving existing materials through continious research are important actions which can be instrumental for future research. Finally he named some materials as conceptual future materials, uch as: Dynamic Insulator Material (DIM), Nano Insulator Materials (NIM) and load-bearin insulator materials.

Osman Ilter (2010) carried out research on the effects of using pumices in mortars on the thermal conductivity of mortar as part of a wall. He used two different types of mortar, one made of limestone and the other one with pumice. The results have shown that the mortar made with pumice had better results in thermal conductivity than the other one. He also found that usually lightweight materials have lower thermal conductivity. According to this research, using pumice-blocks and mortar as thermal insulator can reduce energy consumption between 35–45 percent in residential buildings.

The following table shows the results of thermal conductivity test.

Table 2.2: Details of Walls Which Were in Osman Ilter's thesis (2010)

Wall Type	Block Dimensions (LxHxT) cm	λ	Wall Type	Block Dimensions (LxHxT) cm	λ
Wall 1 (pumice mortar)	39×18.5×15 (cm) t=15	0.2642	Wall 1 (limestone mortar)	39×18.5×15 (Cm) t=15	0.3021
Wall 2 (pumice mortar)	39×18.5×19 (Cm) t=19	0.2219	Wall 2 (limestone mortar)	39×18.5×19 (Cm) t=19	0.2655
Wall 3 (pumice mortar)	39×18.5×25 (Cm) t=25	0.2084	Wall 3 (limestone mortar)	39×18.5×25 (Cm) t=25	0.2422

According to Table 2.2, the walls which were made by using pumice mortars have lower conductivity coefficient than the other types of walls. These results will be discussed in the next chapter according to the requirements of the Iranian Code, RAA446/2009.

Altug Saygılı, et al. (2011) worked on new methods to improve the properties of thermal insulation of fly ash. They mixed various percentage of snow with fly ash and investigated the thermal properties of the mixture. The thermal conductivity tests had shown that adding 20 per cent snow to fly ash shows the best effect on thermal conductivity of fly ash. The higher percentage of snow leads to decreasing thermal conductivity.

Adding snow to fly ash leads to decrease in the unit weight, increase in the void ratio and improved shear strength of fly ash.

They also presented the conductivity coefficient of their material mixture and some other materials. Table 2.3 shows thermal conductivity of some common materials and Table 2.4 shows thermal conductivity of fly ash bricks which are mixed with different percentages of snow.

Table 2.3: Thermal Conductivity of Some Materials based on the research carried out by Altug Saygılı, et al. (2011)

Material	Thermal conductivity (W/m°K)
Fire brick	1.000
Brick, solid or perforated lightweight	0.410
Concrete block, hollow medium weight	0.850
Concrete block, hollow lightweight	0.570
Concrete lightweight solid blocks	0.430
Concrete lightweight solid blocks	0.630
Masonry, light concrete air bricks	0.560
Masonry, light concrete air bricks	0.910
Fly ash brick (FA) (at optimum moisture content)	0.392

Table 2.4: Thermal Conductivity of Fly Ash Bricks based on the research carried out by Altug Saygılı, et al. (2011)

Material	Thermal conductivity (W/m°K)
10% snow added fly ash brick (FI10) (over optimum moisture content)	0.284
20% snow added fly ash brick (FI20) (over optimum moisture content)	0.255
30% snow added fly ash brick (FI30) (over optimum moisture content)	0.272

Researched on the impacts of thermal insulations of walls and roofs on the thermal comfort inside the buildings was carried out by Ashok Kumar, et al. (2012).

Roofs and walls are the main parts of buildings that play an important role in heat transfer between inside and outside of buildings.

According to Energy Conservation Building Code (ECBC) explained in the following sections and considering the insulation materials available in India, such as: Expanded Polystyrene, Polyurethane and Elastospray, using either of the following: 5 cm elastospray, 6 cm polyurethane, 7 cm expanded polystyrene, 8 cm fiber glass,15 cm Foam concrete, would comply with the ECBC requirements for building walls. Similarly to comply with the requirements of building roofs either of the following can be used: 5cm elastospray, 5.5 cm polyurethane, 7 cm expanded polystyrene, 8 cm Fiber glass, 14 cm Foam concrete.

2.3.1 Optimum Thickness of Insulations

The optimum thickness of thermal insulation is the specific thickness of insulation in which insulations have maximum efficiency. Lower thickness leads to decrease in the efficiency of insulations and higher thickness will lead to increase in the building costs.

The schematic monograph of optimum thickness based on cost shown as follow.

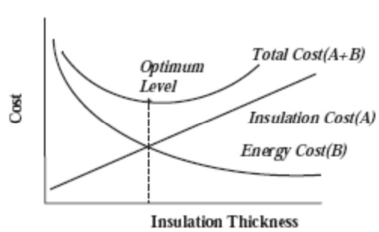

Figure 2.3: Schematic Nomograph of Optimum Thickness based on Meral Ozel (2012) research

According to figure 2.3, by increasing insulation thickness the insulation costs will increase as well. But energy costs decrease by increasing insulation thickness.

There are two lines related to energy cost and insulation cost. The optimum thickness exists in the junction point.

Meral Ozel (2012) researched on optimum thickness of thermal insulations in constructions. She focused on climate conditions in Elaziğ (Turkey) and calculated the optimum thickness by Life-Cycle-Cost-Analysis over 20 years of life time. She has shown that the optimum thickness of insulation varies between 5.4 and 19.2 cm and the energy saving varies between 86.26 and 146.05 $/ m^2 with a period of payback between 3.56 and 8.85 years. These results refer to various types of insulations. She has also investigated the impact of using optimum thickness of insulation on the environment. Results indicate that by applying optimum thickness of insulations one can reduce the emissions and fuel consumption 68 to 89.5 percent depending on the type of insulation. Extruded polystyrene, glass wool, expanded polystyrene and rock wool was used in her research as thermal insulators.

In another study by Meral Ozel (2011), extruded polystyrene and expanded polystyrene were used as insulation materials for buildings with different wall materials, such as: concrete, briquette, autoclaved aerated concrete, bimblock and bricks. The results showed that 2 to 2.8 cm thickness of insulation can increase energy saving between 2.78 and 102.16 \$/m^2 and the period of payback is 1.32 to 10.33 years depending on the wall material and type of insulation.

2.4 Standards for Building Insulation

The energy standards and codes for building design have been introduced and used in some countries in order to help in building design and promote energy efficiency in construction sector.

Nowadays, applying standards and codes in building sector is an essential matter. Therefore, regular update and revision of standards and codes is very important. Using a practical approach like performance-approach would make standards more efficient than the theoretical standards.

Some countries such as: New Zealand, Sweden, Australia, Canada, USA, France and UK have chosen the performance-approach in their standards [13].

Commercial and residential constructions in U.S use approximately 39–40 percent of energy. The high energy consumption of residential buildings is a critical part of energy problem. This can mainly be resolved by using energy codes [14].

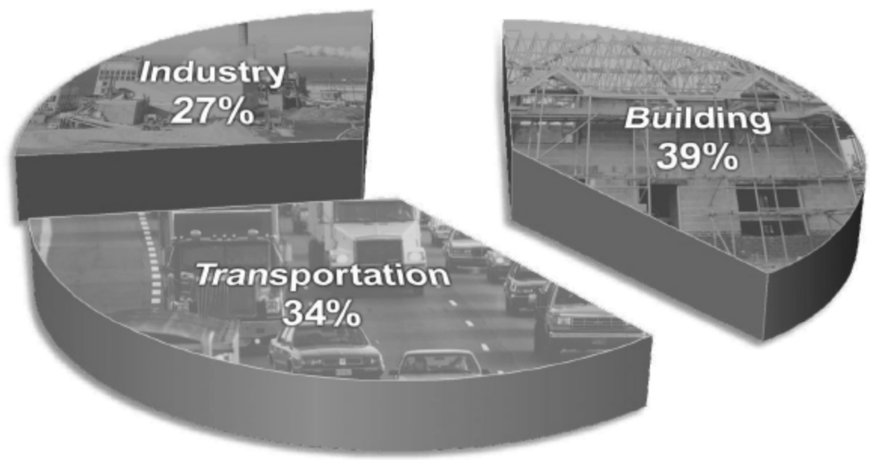

Figure 2.4: Percentage of Energy Consumption by Different Sections of Society according to ECBC statistics

2.4.1 Energy Conservation Building Code (ECBC)

The ministry of power of India's Government introduced ECBC in 2007. It was the first step towards increasing energy efficiency in construction division. Bureau of energy efficiency of India developed ECBC with guidance and support from United States Agency for International Development (USAID) [15].

ECBC provides some methods for design: building envelope, water pumping and heating systems, electrical systems, lighting systems and heating and ventilation air conditioning systems.

The perspective design method of ECBC concerning U-values and R-values of walls, roofs and windows in construction based on five different climatic zones.

According to ECBC the insulation materials must have higher R-value than the minimum specific R-values in the perspective design method or combination of insulation material and structural materials must have lower U-value than maximum specified U-values [16].

Table 2.5 is retrieved from ECBC envelope requirements and it indicates the minimum R-values of insulation and maximum U-values of wall.

Table 2.5: Maximum U-factor and Minimum R-value for Wall and Insulations which Recommended by ECBC

Climatic zones	Hospital, Hotel, Call centers (24 Hours)		Other building type (Day time)	
	Maximum U-factor of overall assembly ($W/m^2.K$)	Minimum R-value of insulation alone ($m^2.K/W$)	Maximum U-factor of overall assembly ($W/m^2.K$)	Minimum R-value of insulation alone ($m^2.K/W$)
Composite	0.44	2.1	0.44	2.1
Hot and Dry	0.44	2.1	0.44	2.1
Warm and Humid	0.44	2.1	0.44	2.1
Moderate	0.44	2.1	0.44	2.1
Cold	0.369	2.2	0.352	2.35

2.4.2 Building Energy Code Program (BECP)

Building Energy Code Program that was established in 1991 is an annual energy code that is publishing by U.S department of energy every year. It supports more energy efficiency for residential and commercial buildings in America.

BECP improves the energy efficiency of buildings by reducing the energy consumption of buildings in America, which reduces the cost for consumers and reduces the air pollution by minimizing emissions of carbon dioxide.

2.4.3 IECC and ASHRAE 90.1

The International Energy Conservation Code (IECC) is one of the two essential baseline energy codes for buildings and the other one is the ASHRAE/ANSI/IESNA standard 90.1 for constructions except low-rise residential buildings.

The IECC is concerned about commercial and residential construction. It is updated approximately once in every three years. The last available version is 2009. On the other hand ASHRAE 90.1 is only concerned about commercial buildings. It is also updated once in every three years like IECC [17].

2.4.3.1 Effects of Energy Codes on Building Design

The IECC, SHRAE 90.1 and generally all standards and codes for buildings, abode energy efficiency demands for the materials, equipment and design employed in all new buildings, renovations, additions and building proficiencies. They reduce the energy consumption to maintain a healthy cooling or heating for functioning buildings. The codes and energy standards for buildings apply to: walls, floors and ceilings of constructions. Also they apply for vitreous or non-glass windows and doors. The codes also can apply to electrical and mechanical systems and equipment in buildings such as: water heating system, lighting system and heating and cooling systems [17].

2.4.4 Iran Code 19

In 1992, the Council of Ministers had chosen a code for buildings to dictate energy preservation in construction, depending on their usage and type.

Code 19 was based on German standards and codes. This code does not consider the climatic factors. The main factor or parameter of this code is the level of energy preservation of construction. There are four groups of constructions defined; with very low and/or low, moderate and high energy preservation [13].

Iran code 19 compulsory U factor for any elements of building such as: wall, roof, window, etc. is specified. Also specified in the code is G value for any group as a whole [13]. Using U factor for elements is perspective design and the other one is a simplified performance system method.

In 1994, a new draft version of code 19, based on ASHRAE, containing details of U factor was provided but it was not complete.

Building and Housing Research Center prepared a new more systematic version of the code in 1995. It was based on French Th-B and Th-G standards. In 1996, recommendations were prepared for technical solutions. Finally in 2000, the new code was accepted and replaced the old one as a mandatory code [13].

2.4.4.1 Basic Definitions of Iran Code 19

There are some basic definitions that are essential to be able to understand the code. These definitions are similar to those definitions that are present in most of the codes all around the world.

1- Living spaces: Daily required spaces of people for working, living, etc.

2- Controlled spaces: Some spaces in buildings including living spaces and non-living spaces that must have a temperature between comfort zone ranges.

3- Comfort zone: The specific conditions of humidity and temperature that more than 80 percent of the people feel comfortable in that condition.

4- Uncontrolled spaces: Other spaces in buildings that are not controlled spaces, such as parking and stairs.

5- Physical envelope: Any walls, floors, ceilings and openings that surrounded the building and set between outdoor and controlled/uncontrolled spaces.

6- Building envelope: Any walls, floors, ceiling and openings that are surrouning the building and set between outdoor or uncontrolled spaces and controlled spaces.

The difference between building envelope and physical envelope is the possibility of presence of uncontrolled spaces in physical envelope.

7- Thermal bridge: Some points of building that have high heat flow because of the heterogeneous insulation material or lack of continuity of insulation in building envelope.

2.4.4.2 Material Properties of Thermal Insulation, According to Iran Code 19

The materials acceptable as thermal insulation in constructions must have thermal conductivity less than or equal to 0.065 W/m˚K and also they must have thermal resistance more than or equal to 0.5 m^2 ˚K/W.

According to Iran Code 19, thermal conductivity of some materials is shown in table 2.6. Based on this table, expanded polyurethane blocks have the lowest thermal conductivity (0.03) and concrete have the highest thermal conductivity (1.75).

Table 2.6: Thermal Conductivity of Some Materials According to Iran Code 19

Material	Thermal conductivity (W/m˚K)
Concrete with mineral sand	1.400
Concrete with no additives	1.750
Pumice	1.100
Brick	1.000 to 1.350
Cement mortar	1.150
Plastering	0.500
Expanded polystyrene	0.058
Expanded polyurethane blocks	0.030

2.4.4.3 Building Classification Based on Occupancy

According to Iran Code 19, the buildings are classified into four types, based on their occupancy. This classification based on the following three factors.

1- Continuity of usage of buildings during the day and night in a period of year
2- The intensity of the temperature difference between the inside and outside
3- The importance of stabilizing the temperature of indoor spaces

These classifications are further expanded as four types of buildings, as follows:

Type A: Residential buildings, hospitals, hotels, inns, sanitariums, laboratories, research centers, dormitories, maternity and fridge buildings.

Type B: Radio and TV stations, major and/or minor communication center, banks, control center and main station of metro, administrative section of industrial buildings, educational buildings, fire stations, police buildings, post office buildings, libraries, shopping centers and self-services.

Type C: Tourism camps, memorial constructions, international or domestic airport buildings, covered stadiums, workshops, cinema, theater buildings, sporting clubs, factories (except vehicle and metal production factories) and exhibitions.

Type D: Storehouses, vehicle and metal production factories, grain depots, transport buildings, minor train stations, shelters and slaughterhouses.

2.4.4.4 Building Classification Based On Location of Building and Energy Requirement

According to the building location, and based on their energy demand, there are three different groups of constructions.

Group A: Low annual energy requirement

Group B: Medium annual energy requirement

Group C: High annual energy requirement

There is a chart in Code 19 that includes the name of each city and its relevant group. As mentioned before this code does not consider the climatic factors. The main factor or parameter of this code is the level of energy preservation of construction.

2.4.4.5 City Classification Based on the Population

Based on the population of the cities, there are two types of cities:

Big cities: With more than 1,000,000 populations

Small cities: With less than 1,000,000 populations

2.4.4.6 Building Classification Based on Energy Saving

There are four groups of buildings according to their energy conservation.

Group 1: Buildings with high energy conservation

Group 2: Buildings with medium energy conservation

Group 3: Buildings with low energy conservation

Group 4: Buildings with no energy conservation

The following table shows the number of group according to their location, city, infrastructure area and their annual energy demand.

Table 2.7 : Building Classification Based on Energy Saving According to Iran Code 19

Small cities		Big cities		Energy requirement	Building types based on their occupancy
Living space		Living space			
>1000 m^2	< 1000 m^2	>1000 m^2	< 1000 m^2		
Group 2	Group 2	Group 1	Group 1	High	Type A
Group 3	Group 3	Group 2	Group 2	Medium	
Group 4	Group 4	Group 3	Group 3	Low	
Group 2	Group 2	Group 1	Group 2	High	Type B
Group 3	Group 3	Group 2	Group 3	Medium	
Group 4	Group 4	Group 3	Group 4	Low	
Group 2	Group 2	Group 2	Group 2	High	Type C
Group 3	Group 3	Group 3	Group 3	Medium	
Group 4	Group 4	Group 4	Group 4	Low	
Group 4	Group 4	Group 4	Group 4	High	Type D
Group 4	Group 4	Group 4	Group 4	Medium	
Group 4	Group 4	Group 4	Group 4	Low	

2.4.4.7 Design Methods

Iran Code 19 has two different methods for building envelope design: perspective design method and simplified performance method.

2.4.4.7.1 Performance Design Method

This method is applicable in any situations. It is based on total annual energy requirement. This method is based on using specified compulsory U factor for all elements of building such as: wall, roof, window and etc. and specified G (for glassy elements) value for any group as a whole.

This method calculates reference heat transfer coefficient of buildings by using the heat coefficients of whole elements that are specified according to the building location, occupancy, etc. and shown in some of the tables. The result of comparing the design heat transfer coefficient and reference heat transfer coefficient of buildings can result in the efficiency of insulation.

2.4.4.7.2 Perspective Method

Perspective method is a simplified method which is applicable for villas, residential buildings, units of apartments with less than 1,000 m^2 living space and third group of buildings according to their energy saving.

According to energy saving, the designer must reduce the area of glassy openings to 1/12 of total living space so that he can use single skinned glassy windows in first group of buildings. Otherwise designer should use performance design method.

Since the performance method is a complex method and also in some cases using this method is not economic and practical then perspective method is recommended. Table 2.8 shows the minimum R-values (thermal resistance) of non-glassy elements.

Table 2.8: Recommended R-values by Iran Code 19

Group 3	Group 2	Group 1	Building group (based on energy saving)	
1.5	2.1	2.8	Light	Wall
1.0	1.4	1.9	Heavy	
0.8	1.1	1.5	Close to uncontrolled spaces	
2.7	3.7	5.0	Light	Ceiling
2.2	3.0	4.0	Heavy	
1.7	2.3	3.1	Close to uncontrolled spaces	
1.6	2.2	3.0	Light	Floor
1.3	1.8	2.4	Heavy	
1.0	1.3	1.8	Close to uncontrolled spaces	
2.0	2.7	3.7	Envelope insulation	Base floor (on the soil)
0.9	1.3	1.7	Insulation below the surface	

Thermal resistance of elements and walls can be calculated by equations (1) and (2).

$$R_i = dx_i/\lambda_i \tag{1}$$

$$R = \sum R_i \tag{2}$$

Where:

dx_i = Thickness of element i (m)

R_i = Thermal resistance of element i (m^2 °K/W)

λ_i = Coefficient of thermal conductivity of element i (W/m °K or W/m °C)

R = Total thermal resistance of wall, ceiling and/or roof (m^2 °K/W)

Example: For normal Concrete with assumptive $\lambda = 1.4$ and thickness = 20 cm, Plaster with assumptive $\lambda = 0.5$ and thickness = 2 cm and insulation material with assumptive $\lambda = 0.067$ and thickness = 3.5 cm, Total wall thermal resistance will be:

$R = [(0.20/1.4)+(0.02/0.5)+(0.035/0.067)] \approx 0.705\ m^2$ °K/W.

2.4.5 Building Performance Institute Europe (BPIE)

The Building Performance Institute Europe (BPIE) carries out procedure analysis, advice and performance support. The main duty of this institute is publishing in the area of energy implementation in buildings.

Since February 2010, this institute became the European partner of the global building implementation network. It is based in Brussels. Improving the energy performance in construction is the main mission of BPIE. BPIE focuses on the efficient performance of the European guidance related to construction sector. It is the great project of BPIE to analyze and recommend regulatory appraisals and financial incentives, which can lead to the construction of very low-energy buildings. One of the complements of institute's approach is the procedure analysis and it offers to conquer the barriers of Europe for the renovation of the buildings in Europe.

The BPIE shares fact-based knowledge and analyses through the GBPN (Global Building Performance Network) and cooperates with scientific centers in US, China and India. BPIE is an open share data without any access limitation [18].

2.4.6 RAA 446

The ministry of commerce, industry and tourism in Republic of Cyprus (south side of Cyprus) is overall responsible for the construction energy conservation code in Cyprus. A code in field of construction energy conservation has been submitted by Energy service of the same ministry in 2007. It has been revised in 2009. The name of this building code in English is: Ministerial order regulating the minimum energy performance requirements (RAA446/2009). This code concerned with all kinds of buildings, for example: single occupancy family houses, multi-occupancy family houses, offices, educational buildings, hospitals, hotel and restaurants, wholesale and retail trade and sport facilities [18].

2.4.6.1 RAA Certificates Overview

Building authorities, municipalities, direct administration offices are responsible organizations which are in charge of performance. So they have to collect the energy operation certificates and energy saving calculations upon the receipt of an application for a building permit.

The responsibility of energy service section of ministry of commerce, industry and tourism enrolls the energy operation certificate of construction and the qualified proficient issuing of the certificates of building energy operation [18].

2.4.6.2 Which Buildings These Certificates Are Applicable

These certificates are applicable for every new construction and/or renovation private residential and private non-residential types of buildings.

2.5 Cyprus Statistics

According to BPIE announcement, there is some information about residential, non-residential buildings, population distribution, climatic zones, etc. as follows.

2.5.1 Climatic Zones

In Cyprus there are four different climatic zones [18].

Zone 1: Seaside (e.g. Famagusta and Polis)

Zone 2: Plains (e.g. Lefkosa/Nicosia and Athalassa)

Zone 3: Semi-mountain area (e.g. Lefkara in south Cyprus)

Zone 4: Mountain area (e.g. Aminados in south Cyprus)

2.5.2 Breakdown of the Constructions by Types

The BPIE estimated statistics of breakdown of the constructions by their types. Figure 2.5 shows that the highest percentage of buildings are residential houses followed by transportation facilities.

As explained before, according to the statistics that are published by different organizations, between 39 - 40 percent of energy consumption relates to the buildings and remarkable percentage of the buildings relates to residential buildings. Therefore, considering the energy consumption of residential buildings should be more important than the other types of buildings.

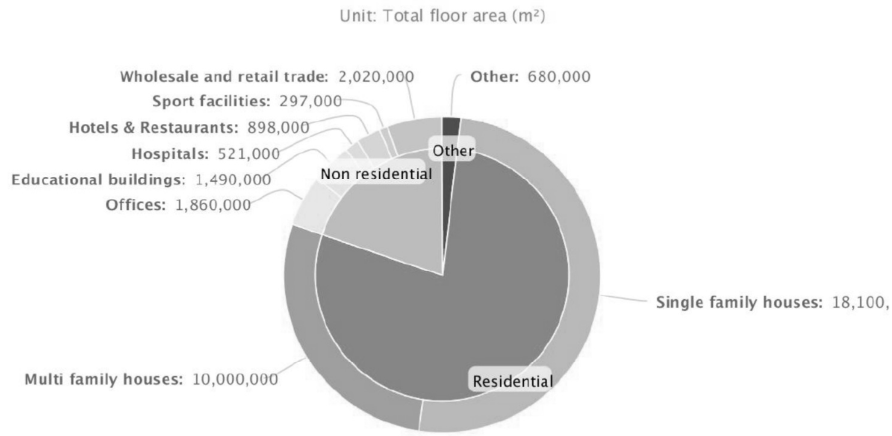

Figure 2.5: Breakdown of the Building Construction in Cyprus According to Their Type

2.5.3 Breakdown of the Residential Buildings by Location

According to BPIE data collection between the years 1980–2009, 63.1 percent of residential buildings dwelled in urban areas and 36.9 percent of residential buildings dwelled in rural zone.

The breakdown of residential buildings by their location has shown in Figure 2.6.

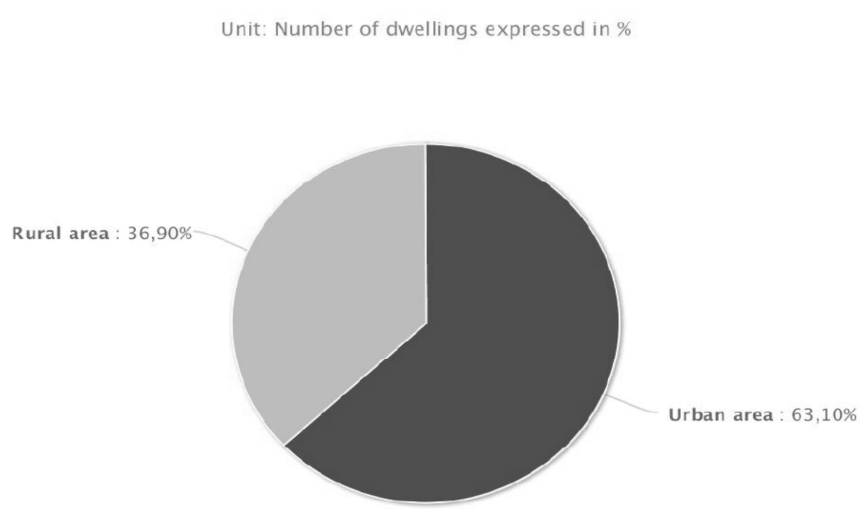

Figure 2.6: Breakdown of the Residential Buildings in Cyprus by Location

2.6 Design Criteria Based on RAA446/2009 Code

RAA446/2009 code is concerned with the primary energy consumption in construction section in Cyprus. According to this code U-factor of each element such as: wall, roof, window and floor should be less than the thermal protection required (U-factor) that is introduced in RAA446/2009 code.

According to RAA446/2009 Table 2.9 introduces maximum U-factors for different elements of building for all types of buildings including residential and non-residential buildings. Table 2.9 shows the maximum U-value for each element of construction.

Table 2.9: Recommended Maximum U-value by RAA446/2009

Roofs	0.85
Walls	0.85
Floors	2.0
Windows	3.8

According to Table 2.9, for proper selection of insulation, U-value of insulation plus U-values of structural materials must be less than the values given in the table. In other words overall U-value of building envelope components such as walls, floor and roofs must be lower than recommended maximum U-values in Table 2.9.

Chapter 3

METHODOLOGY

3.1 General

In this chapter the method of preparing Lightweight Calcium-Magnesium based panels (LCMP), tests carried out, such as: pulse velocity, fire resistance, thermal conductivity of insulation, water absorption for wall and wall plus LCMP, are explained.

The main ingredients of LCMP are: calcium carbonate, magnesium carbonate, montmorinollite powder or kaolinite powder, polypropylene fibers, calcium sulfate, water and resistant carbon. Three samples were prepared with different percentage of ingredients and conductivity coefficient of samples was measured by guarded hot plate apparatus (according to ASTM C 177) as thermal conductivity of LCMP. The sample with lowest conductivity coefficient was selected and tested with guarded hot box apparatus (according to ASTM C 1363) for conductivity coefficient of wall together with insulation panel. Also the pulse velocity, water absorption and fire tests were carried out on selected samples and the results of these tests are given in the next chapter.

3.2 Preparation of LCMP

As mentioned in the previous section three samples with different percentage of ingredients were prepared for conductivity coefficient tests. Prior to giving the preparation procedure of samples it is necessary to introduce the materials used for the samples, such as: calcium carbonate, magnesium carbonate, calcium sulfate, kaolinite and polypropylene fibers.

3.2.1 Calcium Carbonate

Calcium carbonate is known as a chemical compound. Its formula is $CaCO_3$. This substance is a common substance and it is available in rocks all around the world. Calcium carbonate is the main constituent of pearls, snails, eggshells, coal balls and shells of marine organisms. This is the main cause of hard water and also calcium carbonate is the active component in agricultural lime. This substance is odorless, white in color and acid soluble. Density of calcium carbonate is 2.71 g/cm^3. Pure calcium carbonate is used for medical purposes. The main source of some industrial materials, such as: limestone, chalk and travertine, is calcium carbonate. Calcium carbonate is not poisonous so it is not dangerous for health. Figure 3.1 shows the calcium carbonate powder.

Figure 3.1: Calcium Carbonate Powder

3.2.2 Magnesium Carbonate

Magnesium carbonate is solid, white in color, odorless, acid soluble and non-toxic. Density of magnesium carbonate tri-hydrate is: 1.83 g/cm^3. Melting point of tri-hydrate magnesium carbonate is about 170 ˚C.

Magnesium carbonate commonly obtained by mining of the magnesite. The tri-hydrate salt, ($MgCO_3 \cdot 3H_2O$), can be produced by mixing magnesium solutions and carbonate ions under an atmosphere of carbon dioxide.

Magnesium carbonate sometimes used in flooring, fire extinguishing, fireproofing, dusting powder, compositions, toothpaste and cosmetics. Figure 3.2 shows the magnesium carbonate powder.

Figure 3.2: Magnesium Carbonate Powder

3.2.3 Calcium Sulfate

Naturally calcium sulfate (or calcium sulphate) is white, translucent and crystalline rock. This is odorless and non-toxic substance. In the form of anhydrous it is usually used as desiccants. By impregnating with other substances like Cobalt (II) chloride, pink or blue color of this substance will be produced.

The hemihydrate form ($CaSO_4$ + 0.5 H_2O) of calcium sulfate is known as plaster of Paris and also dehydrate form ($CaSO_4$ + 2 H_2O) of this material is known as gypsum.

Anhydrites and gypsum which are produced in many locations all around the world are the main sources of this material. The world annual production of gypsum is 127,000,000 tons. In addition to natural resources, calcium sulfate is also produced by industrial process. Figures 3.3 and 3.4 show the gypsum and calcium sulfate, respectively.


Figure 3.3: Gypsum


Figure 3.4: Calcium Sulfate

3.2.4 Kaolinite Powder

Kaolinite is a clay mineral with the formula: $Al_2Si_2O_5\,(OH)_4$. Kaolinite is part of an industrial mineral group. It is a soft material and non-toxic. The color of kaolinite is white, but sometimes it is available in brown, red, pink, orange or blue depending on its purity. China clay or kaolin is the rock that is rich in kaolinite. The origin of this name is from Chinese (Kao-Ling), a village near “Jingdezhen” China. In 1727 kaolinite introduced to English from French version “kaolin”. This material is available in many countries such as: France, Iran, Germany, India, United Kingdom, United States, Vietnam, Bulgaria, Czech Republic and Brazil.

The kaolinite clay is most found in soils in moist climate zones (e.g. tropical rainforest). The percentage of kaolinite decreases in drier or cooler climates but other clay proportions, such as: illite and smectite, increases in cooler and drier climates, respectively. The most usage of kaolinite is in paper production. However, in recent years kaolinite is researched as an additive agent to structural materials, such as concrete, for improving some properties.

Figure 3.5 shows the kaolinite clay.

Figure 3.5: Kaolinite Clay

3.2.5 Polypropylene Fibers

Polypropylene or polypropene is a kind of thermoplastic polymer. It is used for different industrial purposes, such as: packing, textiles, labeling, carpets and thermal under wears. Some reusable plastic forms are used for preparing laboratory equipment, banknotes, loudspeakers and automotive components.

Polypropylene is flexible and rough. Melting point of polypropylene is approximately 175 ˚C.

Generally there are three different types of polypropylene. 1- homo polymer 2- random copolymer 3- block copolymer. Ethylene typically used with co-monomer. Ethylene-propylene rubber (EPDM) when added to polypropylene-monomer increases the strength of low temperature impact. Polypropylene has high strength against fatigue stress and also it is heat resistant.

Polypropylene is classified as low to medium hazard material by Environmental Working Group (EWG).

Nowadays polypropylene fibers are used in some structural materials like cementitious mortars to improve some properties, such as creep and heat transfer. Figure 3.6 shows a kind of polypropylene fiber.

Figure 3.6: Polypropylene Fibers

3.2.6 Preparation Method

Three different samples prepared with different percentage, by weight, of ingredients. Table 3.1 illustrated the percentage of each ingredients of each sample.

Table 3. 1: Percentages of Ingredients for Different Samples

Sample No.	Calcium carbonate	Magnesium carbonate	Water	Fibers	kaolin	carbon	Calcium sulfate
No.1	15	30	10	9	7	7	22
No.2	30	15	10	9	7	7	22
No.3	22.5	22.5	10	9	7	7	22

Polypropylene fibers must float on water at ambient conditions, 22˚C temperature, for 3 hours to expansion.

Calcium carbonate, calcium sulfate and magnesium carbonate mixed together and added to 47˚C water and blending continued until mixture reached to 77˚C temperature. The temperature must remain at 77˚C for 15 minutes while stirring.

Resistant carbon and montmorinollite or kaolin powder added to mixture after 15 minutes while mixture losing its temperature. Polypropylene fibers added to mixture when the mixture temperature was about 50-55 ˚C.

The mixture decanted in square molds with 30 x 30 x 4 cm dimensions. After 72 hours, panels removed from molds and placed in furnace for 108-110 hours at 148-160 ˚C temperature.

The samples tested with guarded hot plate apparatus for measuring conductivity coefficient.

Sample No.3 had the lowest coefficient. Therefore, sample No.3 was selected for other tests, such as conductivity coefficient test for the complete wall (wall blocks, insulation panel and plastering) with guarded hotbox apparatus, pulse velocity test and the others that explained in the following sections. The results of each test are given in chapter 4.

3.3 Tests on LCMP

In this section some physical tests carried on LCMP samples to find thermal conductivity modulus, reaction of LCMP against fire and pulse velocity test are briefly explained.

3.3.1 Guarded Hot Plate Test (ASTM C 177)

Testing with Guarded Hot Plate Apparatus is one of the most accurate test methods to estimate the coefficient of thermal conductivity of some materials. Guarded Hot Plate Apparatus is a utensil for determination of heat conductance properties in steady-state, thermal resistance and thermal conductivity, of slab specimens in accordance with International standards ISO 8302, ASTM C-177.

Guarded hot plate apparatus was designed for laboratory use, making steps and finally quality control process for a wide range of materials with low and intermediate thermal conductivities. Some of materials with low and/or intermediate thermal conductivities are: rubber, cellular rubber, plastics, polystyrene, mineral fibers, polyurethane, glass fibers and etc. Since sample size is small when compared to a section of a wall for constructional researches, guarded hot plate apparatus is one of the best choice for homogenous materials.

The hot plate apparatus comprised of the following parts:

1- Hot plate in bottom and cold plates in upper, sample size 100x100 mm, 200x200 mm or 300x300 mm.
2- Guarded hot plate on each side.
3- Cooling plate.
4- Electrically heating system
5- Sensors for measuring the temperature of guarded hot plate, cooling plate and Central Hot-plate.

6- Ambient temperature range: 200 ˚C up to 300 ˚C.

7- Computer unit.

Device works with 220/240 Volts, AC, 50 Hz.

Three different LCMP specimens (300 x 300 x 25 mm) were tested by Guarded Hot Plate Apparatus, and the best result obtained by sample No.3. Therefore, sample No.3 was selected to be used for other tests, such as Guarded Hot Box Apparatus.

Figures 3.7 and 3.8 show Guarded Hot Plate Apparatus.

Figure 3.7: Guarded Hot Plate Apparatus

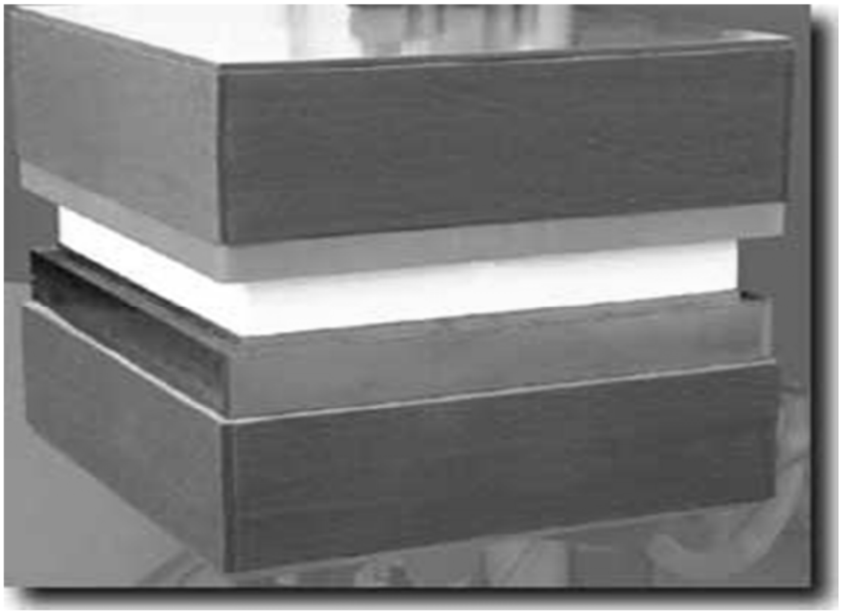
Figure 3.8: Plates of Guarded Hot Plate Apparatus

Three more tests on No.3 samples of LCMP have been done by another type of hotplate apparatus with 120x80x25 mm specimen dimensions. The results of all tests are shown in chapter four.

3.3.2 Pulse Velocity Test (ASTM C597)

The Pulse velocity test is an ultra-sonic test to evaluate the density, homogeneity, uniformity and etc. of concrete and/or similar-concrete materials. The higher value obtained from this test indicates better homogeneity and compaction of sample.

According to figure 3.9 pulse velocity apparatus essentially includes: two transducers, one amplifier, one electrical generator and one electronic timing instrument to assess the time interval between pulse generator transducer and pulse receiver transducer.

Figure 3.9: Pulse Velocity Device

The quality of concrete in terms of presence of cracks, segregation, presence of internal defects, etc. can be evaluated by using Table 3.1.

Table 3.2: Correlation Between Concrete Quality and Pulse Velocity

Pulse Velocity (km/second)	Concrete quality (Grading)
Above 4.5	Excellent
3.5 to 4.5	Good
3.0 to 3.5	Medium
Below 3.0	Doubtful

Pulse velocity test has been done on LCMP samples to evaluate their compaction and uniformity. High value of pulse velocity presents better homogeneity, uniformity and density and also it shows better cohesion.

Pulse velocity test usually applied to determine the approximate strength of concrete as an assessment of concrete quality, determination of Poisson's ratio and modulus of elasticity of concrete, determination of the uniformity and interior changes of concrete members occurring by time.

3.3.2.1 Test Procedure

"TRAN" and "REC" transducers must be connected to velocity meter (V meter). V meter should be turned on by using AC line or battery.

The instrument must check zero by reference bar which provided for this target. Before placing transducers on the ends of the bar, faces of transducers should be smeared by grease. "SET REF" control should be adjusted until the instrument reads transit time from reference bar.

For 400 mm or less length of path, using 0.1 microsecond range recommended for the maximum accuracy.

A couple of suitable points by specific length "L" on the material must be selected for doing the test. Transducer's faces have to be pressed hard on surfaces of material without any movement during the test to prevent any probable errors. The test continues until a consistent value appears on the monitor. The value shows the time of pulses which passed through the L. The mean value of the readings can be taken when recorded values are between the two values.

The pulse velocity value will be achieved by the following formula:

$$\text{Pulse velocity} = (\text{Length of path}/\text{Transit time}) \tag{3}$$

When measurement of transit time is ongoing, keeping transducers away from each other is essential to note because by approaching each one to another one, the receiver transducer may record unwanted signals and this would result in an improper travel (transit) time.

In order to get better results the temperature must be between 10 ˚C and 30 ˚C. One should keep in mind that the moisture has significant effect on the test. According to ASTM C 597; length of path should be between approximately 50 mm to 15 m depending on intensity and frequency of the generated signals.

According to ASTM C 597: "The results obtained by the use of this test method are not to be considered as a means of measuring strength nor as an adequate test for establishing compliance of the modulus of elasticity of field concrete with that assumed in the design."

Three samples of LCMP prepared for this test. Each sample tested with two different length of path. By using direct measurement between two sides of sample, the length of path will be the thickness of sample. And also by using indirect measurement, the length of path must be calculated.

Since LCMP samples have 26 ± 2 mm thickness, length of path in direct measurement is 24 to 28 mm, depending on the accurate sample size.

Figure 3.10 shows the pulse velocity test on a LCMP sample.

Figure 3.10: Pulse Velocity Test

The results of this test expressed in chapter four.

3.3.3 Fire Test

ASTM standards introduced some criteria for fire test of materials. Fire testing of materials is a widespread topic in materials science. ASTM's standards for flammability and fire are including evaluation and testing the ignition, burning or flaming of certain materials. Majority of these standards refer to exterior or interior parts of constructions as well as commercial and household furniture. Some of the standards for fire test are: ASTM E2707 - 09 Standard Test Method for Determining Fire Penetration of Exterior Wall Assemblies Using a Direct Flame Impingement Exposure, ASTM E119 - 12a Standard Test Methods for Fire Tests of Building Construction and Materials and ASTM E84-06 Standard Test Method for Surface Burning Characteristics of Building Materials. Surface burning method used in this research to evaluation of LCMP’s characteristics. There is a classification according to International Building Code (IBC), which has three different classes including A, B and C. This classification based on Flame Spread Index (FSI) of material.

This method evaluates the flame growth on the bottom side of specimen when fixed horizontally. Flame Spread Index (FSI) can be obtained by this method. FSI is a non-dimensional number that should be placed on a relative scale between 0 and 100. FSI of asbestos-cement board is 0 and red oak has value of 100. Figure 3.11 shows fire test according to ASTM E 84.

Figure 3.11: Fire Test (ASTM E 84)

3.3.3.1 ASTM E 84, Scope

1- This fire test method is accountable of standard for comparative surface flaming behavior of construction materials such as wall and ceilings. The material shall be stable enough to be fixed in the ceiling position during the test.

2- The main objective of this test is evaluating relative flame spread and smoke emission of specimen. However, there is not necessarily a relationship between these two parameters.

3- The use of some materials as a support on the bottom side of sample can reduce FSI from those which do not have such support. These results (results of testing with supports) do not relate to indices obtained by fire testing without any kind of supporting materials.

4- The standard values in this test are in pound-inch units.

5- The text of standard, footnotes, notes and references, except tables and figures, which provide explanatory information, shall not considered as standard's requirements.

6- This standard just used to evaluate and describe the reaction of materials, assemblies or products to fire and flame in controlled conditions, it does not incorporate whole factors required for fire risk and/or fire hazard assessments of the products, materials or assemblies by itself under the real conditions.

7- This standard does not directly relate to low-flame-spread indices of materials that drip or melt during the test to those indices of materials which do not drip or melt during the test [19].

3.3.3.2 Classification of Materials According to ASTM E-84

International Building Code (IBC) classified building materials according to ASTM E 84 fire test. According to IBC's Table 3.2, materials with different FSI value and smoke emission are classified into three, namely A (I), B (II) and C (III). Inorganic materials such as bricks and tiles are classified in class A (I).

Generally, materials with maximum FSI value of 200 and smoke emission of 450 are acceptable by National Fire Protection Association Life Safety Code, NFPA No. 101.

NFPA 101 primarily applies this classification to interior wall and ceiling finish materials. Roof coverings must meet a different set of criteria.

Classifications of some common materials are given in Table 3.3.

Table 3.3: Classification of Materials by NFPA 101 and IBC

NFPA	IBC	Rate of flame spread (FSI)
A	A (I)	0 - 25
B	B (II)	26 - 75
C	C (III)	76 - 200
D	-	201 - 500
E	-	Over 500

Table 3.4: Classification of Some Common Materials

Material	Rate of flame spread	Classification
Birch, Yellow	80	C (III)
Brick	0	A (I)
Cedar, Western Red	69	B (II)
Douglas-fir	90	C (III)
Fiberboard, Medium Density	167	C (III)
Gypsum Wallboard	10-15	A (I)
Gypsum Sheathing	15-20	A (I)
fiber-cement exterior materials	0	A (I)
Hemlock, West Coast	73	B (II)
Idaho white pine	82	C (III)
Inorganic reinforced cement board	0	A (I)
Maple	104	C (III)
Masonite	<200	C (III)
Oak, Red or White	100	C (III)
Oriented Strand Board (OSB)	150	C (III)
Particle Board	116-178	C (III)
Pine, Lodgepole	98	C (III)
Pine, Ponderosa	115	C (III)
Plywood, Fire-retardant-treated construction	0-25	A (I)
Plywood, Oak	125-185	C (III)

3.3.3.3 Test Process

One sample of LCMP (300 x 300 x 25 mm) is fixed horizontally on a metallic base. A torch fixed under the specimen. The timing started when the torch lit up. The total time of test was 10 minutes (According to ASTM E 84). During the test, spreading of smoke emission and flame was observed and recorded. The detailed results of this test are available in chapter four.

3.3.4 Guarded Hotbox Test (ASTM C 1363)

Guarded hotbox apparatus used to evaluate the conductivity coefficient of construction materials in large scales (e.g. 1200 × 1200 mm). For vertical specimen such as walls, measurement of heat-flow will be in horizontal dimension in this test. On the other hand, measurement of heat-flow in vertical dimension is related to horizontal samples, such as ceiling.

Guarded hotbox test is suitable for homogenous or non-homogenous materials, but for homogenous materials, using hot plate (ASTM C 177) is more suitable.
This method of test applies for steady-state testing and it does not establish criteria or procedure for doing dynamic tests for dynamic data analysis. However some types of hotbox apparatus designed for dynamic tests. This test process is intended for use at normal conditions of construction applications. The natural conditions of outside temperature zones range from (approximately) -47 to 84 ˚C and the inside temperature for normal conditions of residential buildings is 21 ˚C.

Specimen size depends on hotbox apparatus design. According to design of existing apparatus, a sample (wall) with 1200 × 1200 mm size has been used in this study. Figures 3.12, 3.13 show the hotbox apparatus and schematic presentation of hotbox device, respectively.

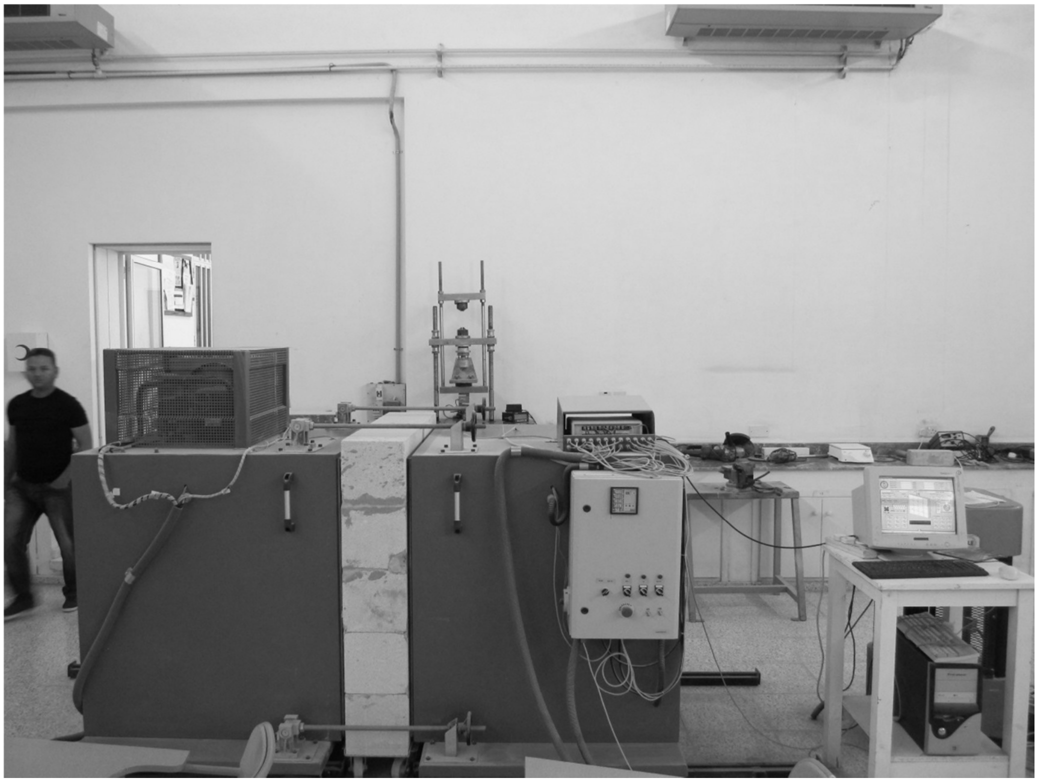

Figure 3.12: Hotbox Apparatus

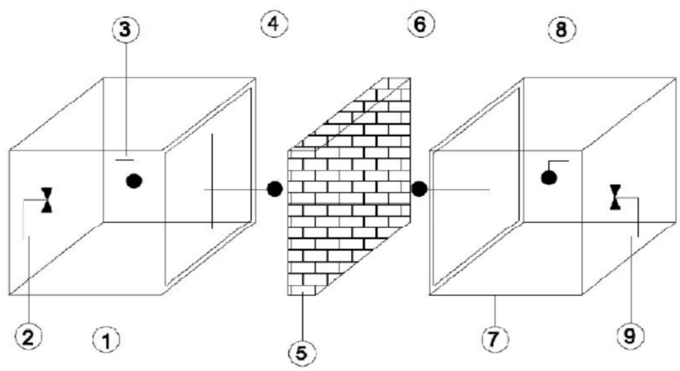

Figure 3.13: Schematic Presentation of Hotbox Device

Where:

1. Cold chamber
2. Freezer fan
3. Thermo-couples (3 unit) to measure the ambient temperature of cold chamber

4. Thermo-couples (9 unit) to measure the surface temperature of wall sample in cold side
5. Wall specimen 1200 x 1200 mm
6. Thermo-couples (9 unit) to measure the surface temperature of wall sample in warm side
7. Hot chamber
8. Thermo-couples (3 unit) to measure the ambient temperature of warm chamber
9. Heater fan

3.3.4.1 Test process

Three different type of walls – type I, type II and type III– were built for testing. The difference between these walls refers to their brick characteristics, such as weight, dimensions and price.

Type I: AKG (Aerated Blocks) with dimensions of 600 x 250 x 250 mm. Figures 3.14 and 3.15 illustrates the AKG block and wall type I respectively.

Type II: BIM Blocks with dimensions of 330 x 200 x 250 mm. Figures 3.16 and 3.17 illustrates the BIM block and wall type II respectively.

Type III: Hollow Clay bricks with dimensions of 300 x 100 x 240 mm. Figures 3.18 and 3.19 illustrated the clay brick and wall type III respectively.

Note1: All kinds of brick and blocks mentioned are commonly used for constructions in North Cyprus.

Note 2: Every type of walls has 1200 x 1200 x (250 mm for type I,II and 240 mm for type III) dimensions.

Figure 3.14: Schematic Shape of AKG Block (600 x 250 x 250 mm)

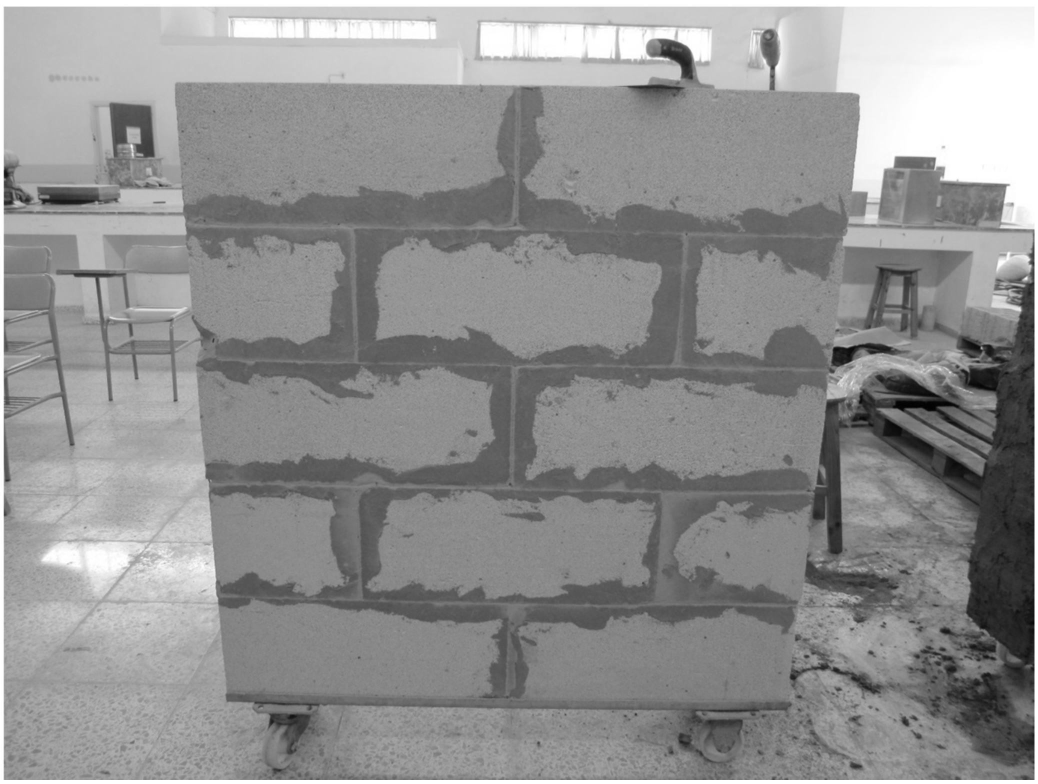

Figure 3.15: Wall Type I

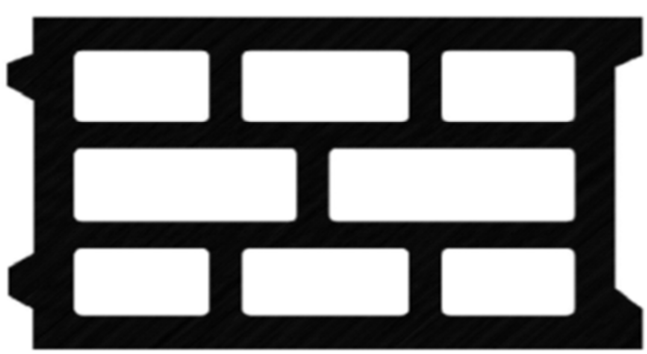

Figure 3.16: Schematic Shape of BIM Block (330 x 200 x 250 mm)

Figure 3.17: Wall Type II

Figure 3.18: Schematic Shape of Clay Brick (300 x 100 x 240 mm)

Figure 3.19: Wall Type III

ABS Deco-wall is an ordinary gypsum plaster – Figure 3.20 – which is mostly used for construction plastering in North Cyprus. Therefore, estimating the thermal conductivity coefficient of ABS gypsum plaster could be important. So after measuring the thermal conductivity of wall type I, 10 mm of gypsum plaster applied on the wall and the test repeated to estimate the thermal conductivity coefficient of gypsum plaster (Figure 3.21).

Figure 3.20: Preparing Gypsum Plaster with ABS Deco-Wall and Water


Figure 3.21: 10 mm of Gypsum Plaster Applied on the Wall Specimen

LCMP can be attached to the wall with adhesive, such as, wallpaper or tile adhesive.

16 samples of LCMP needed for doing hotbox test. The samples attached to the wall type II with 1 mm tile adhesive (figure 3.22). 1mm thick ABS gypsum plaster was applied on the surface (figure 3.23). Figure 3.24 illustrates the wall type II which is insulated with LCMP.

After hardening period – five days – it was ready for test. The sample placed in the hotbox apparatus and fixed vertically. Hotbox test usually takes about seven hours. Hotbox apparatus has two different thermal zones – cold and warm sides – and twelve sensors in each side which collect heat flow data every one minute. Temperature is between 4.5 and 8.5˚c and humidity is 70% with ±0.6 at the cold side and the warm side temperature is between 37.5 and 42.5˚c and the humidity is 40%

with ±0.6 tolerance. Figure 3.25 shows the display unit of hotbox device during the test.

Figure 3.22: The Samples Attached to the Wall Type II with 1 mm Tile Glue

Figure 3.23: 1mm Thick of ABS Gypsum Plaster was Applied on the Surface of LCMP Samples

Figure 3.24: Insulated Wall with LCMP

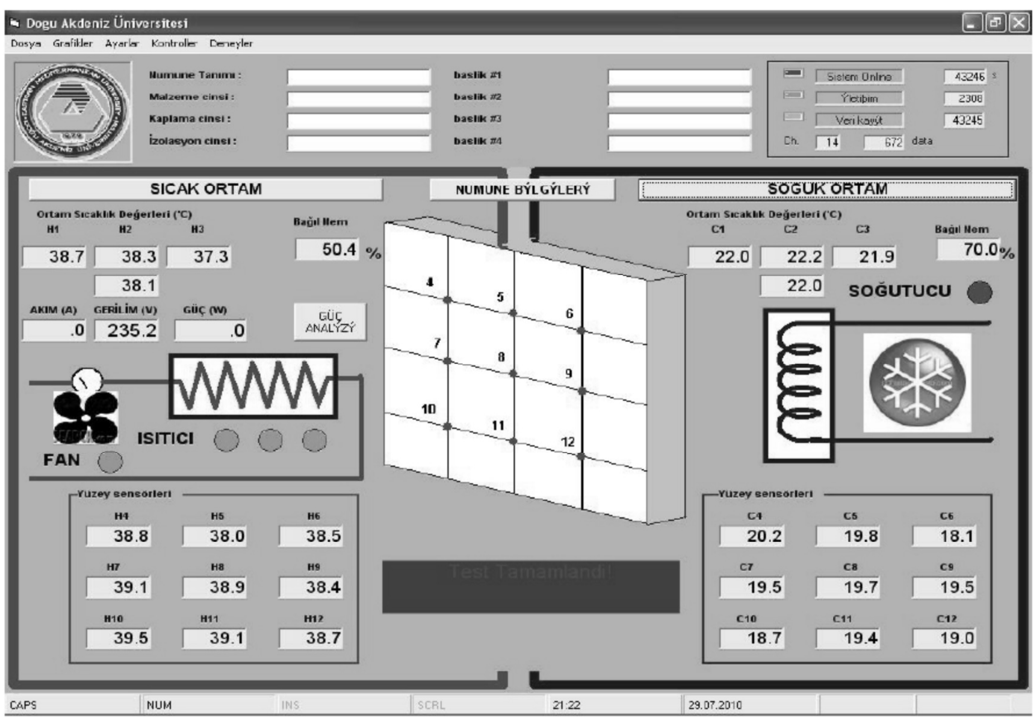

Figure 3.25: Display Unit of Hot-Box Apparatus

The results obtained from the tests are given in chapter four.

3.3.5 Compressive Strength Test (EN-826)

The compressive strength test, according to EN-826, is a specific method to evaluate the compressive behavior of thermal insulation materials. This standard specifies a testing method and equipment to evaluate the compressive strength of thermal-insulation material which are explained in detail in the following sections.

3.3.5.1 Test Process

The testing machine has two parallel plates which have various dimensions depending on the size of samples. Specimen sizes can be 50 x 50 mm, 100 x 100 mm, 150 x 150 mm, 200 x 200 mm and 300 x 300 mm.

In this research, six specimens with 50 x 50 x 24 mm are selected for compressive strength test.

EN-826 states that compression speed rate shall be d/10 minute with ± 25 % tolerance. where “d” is the thickness of sample.

LCMP specimens placed centrally between the jaws of the machine.

The compressive force with a rate of 0.02 MPa per second was applied on the specimen within 1.8 (± 0.1) minutes. Test continued until the specimen failed.

Figure 3.26 and 3.27 show the compressive strength test of LCMP.

Figure 3.26: Compressive Strength Test on LCMP

Figure 3.27: Failure of LCMP in Compressive Strength Test

The results of this test are given in chapter four.

3.3.6 Water Absorption Test

In this test four samples of LCMP with approximate sizes of 50 x 50 x 25 mm were tested.

Samples were placed into the oven (temperature 105°C) for a period of 48 hours to make oven-dry samples (stable weight). Then the samples (oven-dry) were weighed and recorded as an initial weight (oven-dry weight). Afterwards, samples were placed completely into the water for a period of 24 hours. Finally samples were taken out from the water and weighted to obtain the saturated weight of LCMP samples.

Percentage of water absorption of samples was calculated by using equation (4). Figure 3.28 illustrates the LCMP samples which are sank in the water for water absorption test.

Figure 3.28: LCMP Samples which are Sank in the Water

Percentage of water absorption (%) = [[Saturated Weight- Oven Dry Weight (initial)] / [Oven Dry Weight (initial)]] X 100 (4)

The results of this test are discussed in chapter four.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 General

This chapter illustrates results of the tests which were carried out on LCMP samples such as thermal conductivity test, fire test, pulse velocity test, compressive strength test and water absorption test.

The results of pulse velocity test, thermal conductivity test, compressive strength test and water absorption test are numeric and they are illustrated with graphs and/or tables. Fire test process was recorded with camera. The result of this test is included in this chapter and the recording of the test is available in compact disc (CD) enclosed in this thesis.

4.2 Thermal Conductivity Test

One of the main objectives of this research was estimating the thermal properties of LCMP. Since LCMP will be introduced as a thermal insulation, the most important property of insulation material is thermal conductivity coefficient in addition to other properties such as safety, cost, mechanical properties, weight, etc. Because of the importance of this matter, two different types of tests were carried out on the LCMP samples to find its thermal conductivity coefficient. As mentioned before, Hot-Plate and Hot-Box tests applied for LCMP samples. Hot-Plate test shows the thermal conductivity coefficient of LCMP sample with 300 x 300 x 25 mm dimensions and Hot-Box test shows the thermal conductivity coefficient of LCMP samples when they are applied side by side on a wall with dimensions of 1200 x 1200 x 250 mm.

Although the results obtained from each were acceptable results. The Hot-Box test results might be more suitable for engineers and designers in construction field. Because using insulation panels like LCMP or any other type of panels in unified form on the walls with large dimensions is not possible. Therefore, estimating the thermal conductivity coefficient of combination of panels might be more applicable. The results of each test are given in the following sections.

4.2.1 Hot-Plate Apparatus Test Results

Three samples of LCMP with different percentages of ingredients were tested by Hot-Plate apparatus and sample No.3 had the best results. Therefore, sixteen panels of sample No.3 were prepared for Hot-Box apparatus test.

Table 4.1 shows the conductivity coefficient, thermal resistance and thermal conductance of LCMP samples No.1, No.2 and No.3. Time taken for this test was approximately 156 minutes.

Table 4.1: Thermal Conductivity Coefficient of LCMP Samples by Hot-Plate Apparatus Test

Sample Number	Weight (g)	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m^2)	Thermal conductivity (W/m°K)	Thermal resistance (m^2°K/W)
#1	702.8	300	300	25	258.6	0.05488	0.547
#2	705.5	300	300	25	256.4	0.05417	0.553
#3	703.4	300	300	25	252.3	0.05379	0.558

According to Table 4.1 sample No.3 has the lowest thermal conductivity and density. On the other hand, it has the highest thermal resistance because of its ingredients percentage. According to these results, a component with 22.5 percent of calcium carbonate, 22.5 percent of magnesium carbonate, 10 percent of water, 9 percent of polypropylene fiber, 7 percent of montmorillonite or kaolin powder,7 percent of resistance carbon and 22 percent of calcium sulfate has the best results in thermal conductivity coefficient. Therefore, preparing this sample for hot-box apparatus test and other tests is reasonable.

The results of other tests on sample No.3 of LCMP are illustrated in the following sections.

4.2.2 Hot-Box Apparatus Test Results

As mentioned in chapter three, three different wall types prepared for hot-box apparatus test to evaluate the thermal conductivity coefficient of three different types of commercial block and/or bricks, LCMP samples and gypsum plaster.

Type 1 includes: AKG (aerated gas blocks) with dimensions of 600 x 250 x 250 mm and 34 $/m^2 (only for 1 m^2 of blocks without labour and mortar costs).

Type 2 includes: BIM blocks with dimensions of 330 x 200 x 250 mm and 22 $/m^2 (only for 1 m^2 of bricks without labour and mortar costs).

Type 3 includes: Clay bricks with dimensions of 300 x 100 x 250 mm and 20 $/m^2 (only for 1 m^2 of bricks without labour and mortar costs).

All of the wall sample dimensions are: 1200 x 1200 x (250 mm for type 1, 2 and 200 mm for type 3).

Figures 4.1 to 4.3 show the changes of thermal conductivity coefficient (W/m˚K) of type 1, type 2 and type 3 walls versus time (in minute) respectively. Time taken for this test was approximately seven hours.

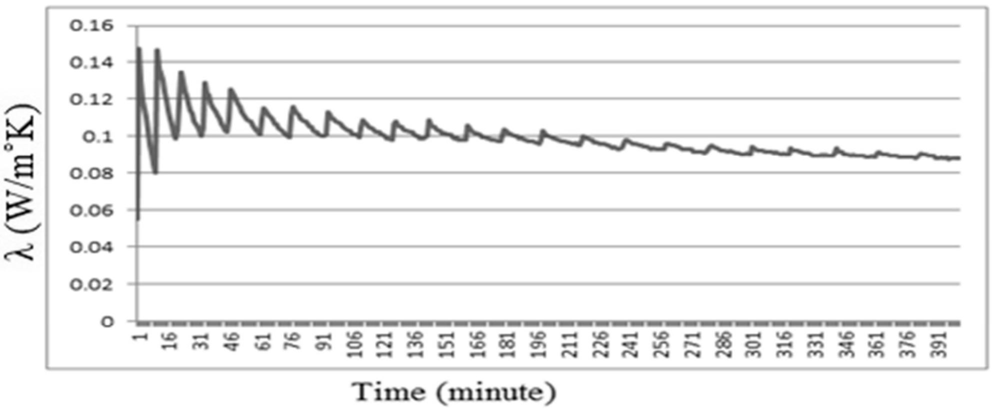

Figure 4.1: The Changing of Thermal Conductivity Coefficient (W/m˚K) of AKGs Versus Time (minute) for Wall Type 1

The mean value of thermal conductivity in Figure 4.1 is 0.09 W/m˚K.

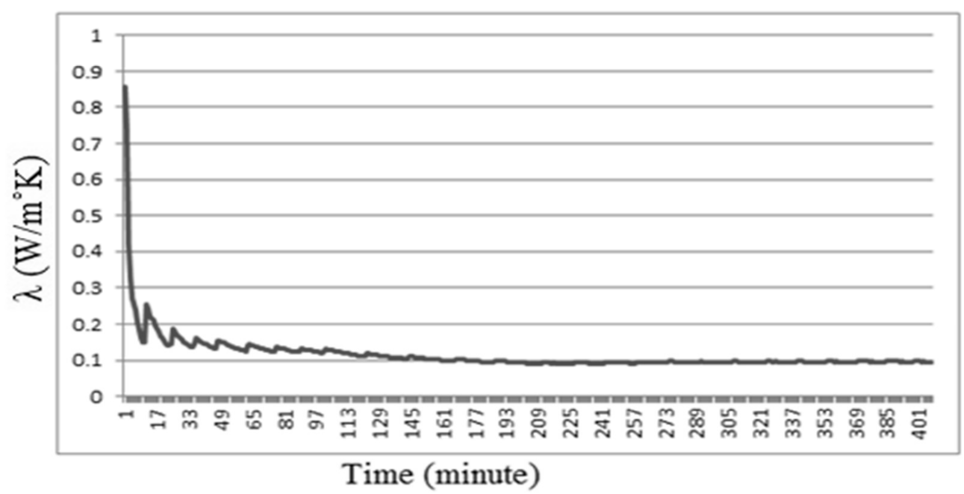

Figure 4.2: The Changing of Thermal Conductivity Coefficient (W/m˚K) of BIMs Versus Time (minute) for Wall Type 2

The mean value of thermal conductivity in Figure 4.2 is 0.1146 W/m˚K.

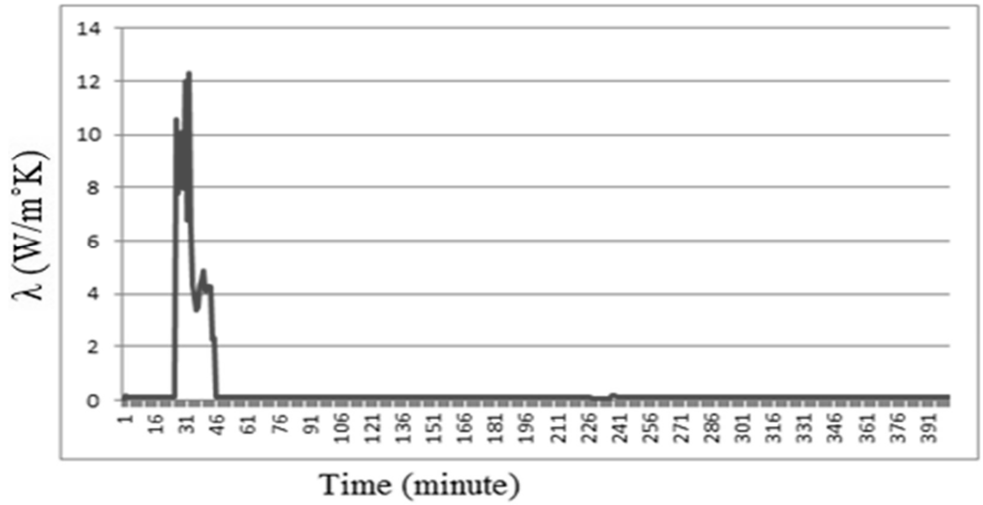

Figure 4.3: The Changing of Thermal Conductivity Coefficient (W/m˚K) of Clay Bricks Versus Time (minute) for Wall Type 3

The mean value of thermal conductivity in figure 4.3 is: 0.40378 W/m˚K.

According to figure 4.1 to 4.3 the changing of thermal conductivity coefficient versus time is decreasing by passing the time. It seems that these changes are because of the establishing of equivalence between two sides, but these changes are a part of results and they cannot be ignored because the mean value of those values is reasonable and acceptable which based on all the changes of thermal conductivity coefficient versus time. The mean values of thermal conductivity coefficient of BIM, AKG and clay brick walls which obtained by this method was equal to their thermal conductivity coefficients which introduced by their companies.

Figures 4.4 to 4.6 illustrate the changes of thermal resistance ($m^{2\circ}K/W$) of type 1, type 2 and type 3 walls versus time (in minutes) respectively.

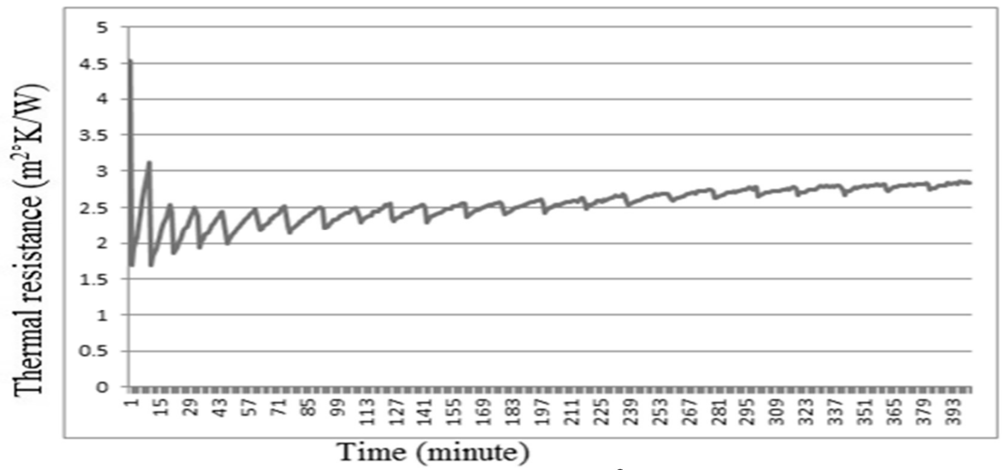

Figure 4.4: The Changes of Thermal Resistance (m^2°K/W) of Wall Type 1 Versus Time (minute)

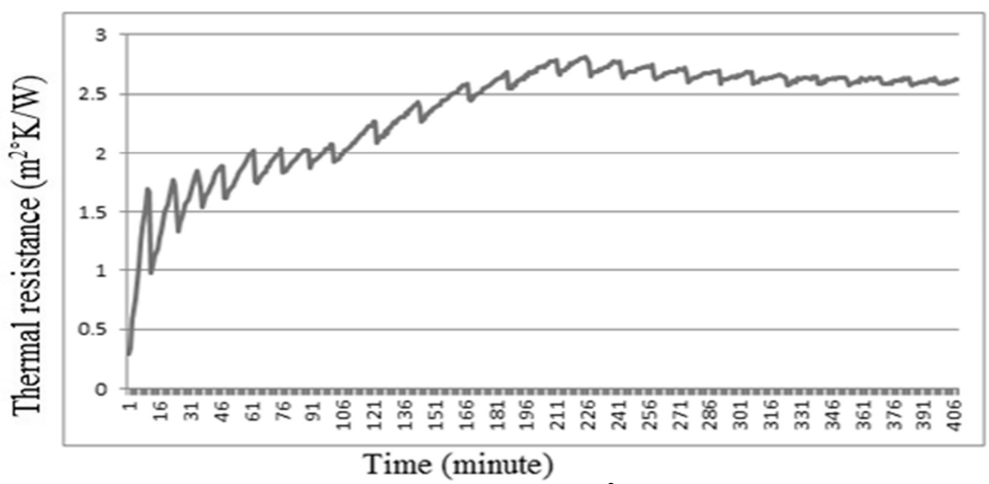

Figure 4.5: The Changes of Thermal Resistance (m^2°K/W) of Wall Type 2 Versus Time (minute)

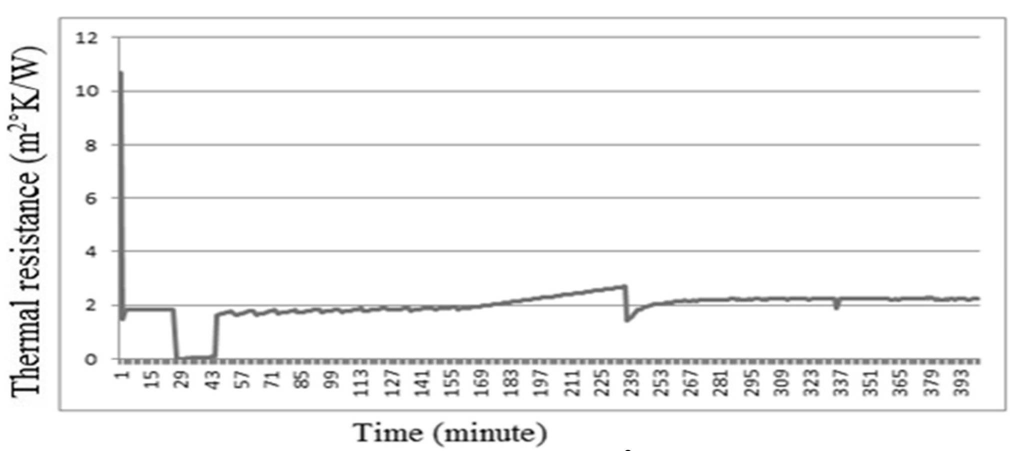

Figure 4.6: The Changes of Thermal Resistance (m^2°K/W) of Wall Type 3 Versus Time (minute)

Thermal conductivity coefficient of ABS Deco-wall gypsum plaster which applied to the wall type 1 with 10 mm of thickness, evaluated by hot box apparatus. This value is 0.23480 W/m˚K.

LCMP samples attached to wall type 2, 1mm of tile adhesive applied for attaching the panels and 1 mm of gypsum plaster applied on the surface.

Thermal conductivity coefficients of LCMP samples were evaluated indirectly by using hot-box apparatus test and the following formula.

$$R = \sum Ri \tag{5}$$

where R is total thermal resistance of a wall and Ri is thermal resistance of each element of the wall.

$$R = \Delta x/\lambda \tag{6}$$

where R is thermal resistance, Δx is thickness and λ is thermal conductivity of material.

Therefore, the thermal conductivity coefficient of LCMP samples when they are applied on a wall with gypsum plaster and tile glue can be determined by finding the thermal resistance of gypsum plaster, tile glue and wall type 2 separately and then adding them together. Thermal resistance of tile glue with the same thickness is approximately equal to thermal resistance of gypsum plaster. Since the thickness of tile adhesive and gypsum plaster which applied on the wall are about 2 mm, any probable difference between thermal resistance values between them is not much effective on estimating the thermal resistance of LCMP.

Figure 4.7 illustrates the changes of thermal resistance (m^2°K/W) of wall type 3 – including LCMP samples, 1 mm of tile adhesive and 1 mm of gypsum plaster – versus time (minute).

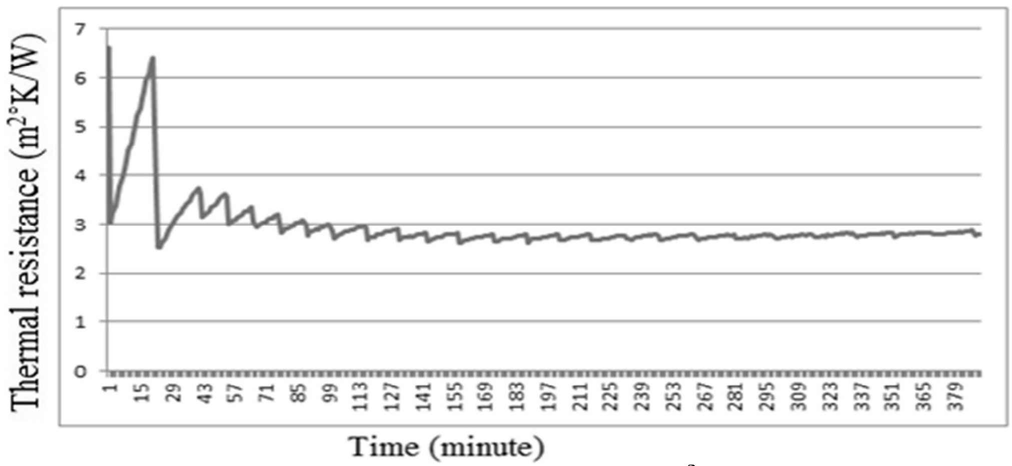

Figure 4.7: The Changes of Thermal Resistance ($m^{2\circ}K/W$) of Wall Type 3 – Including LCMP Samples, 1 mm of Tile Adhesive and 1 mm of Gypsum Plaster – Versus Time (minute)

The mean value of thermal resistance in Figure 4.7 is 2.947315 $m^{2\circ}K/W$.

Thermal resistance of 1 mm of gypsum plaster and 1 mm of tile adhesive can be calculated by (1) formula which expressed in chapter two as follows:

Thermal resistance of 2 mm of gypsum plaster and tile adhesive = 0.002/0.2348 => R is 0.008518 $m^{2\circ}K/W$.

Also thermal resistance of wall type 2 is 2.339923 $m^{2\circ}K/W$.

Therefore thermal resistance of LCMP can be calculated by (5) formula as follows:

Thermal resistance of LCMP = 2.947315 – 2.339923 – 0.008515

Thermal resistance of LCMP = 0.598873 $m^{2\circ}K/W$.

Figure 4.8 illustrated the changes of thermal resistance of LCMP ($m^{2\circ}K/W$) versus time (Minute)

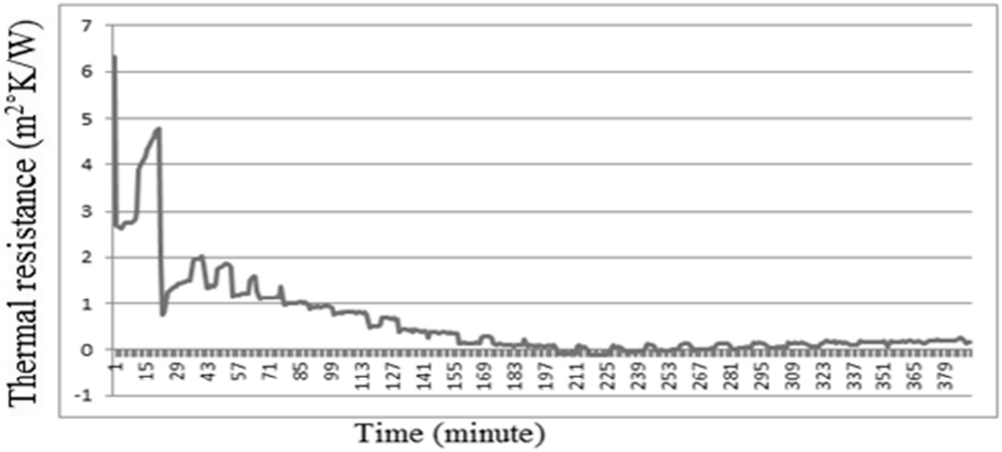

Figure 4.8: The Changes of Thermal Resistance of LCMP (m^{2}°K/W) Versus Time (Minute)

Thermal conductivity coefficient of LCMP can be calculated by using (6) formula as follows:

Thermal conductivity coefficient of LCMP = 0.024/0.598873

Thermal conductivity coefficient of LCMP = 0.04007 W/m°K.

4.3 Compressive Strength Test Results

Six specimens with 50 x 50 x 24 mm selected and placed between the jaws of machine centrally for compressive strength.

The compressive force with rate of 0.02 MPa per second applied on specimen within 1.8 (± 0.1) minutes. Test continued until the specimen yielded.

Figure 4.9 illustrates the compressive strength (MPa) of LCMP samples.

The vertical axis shows the sample number and the horizontal axis shows the compressive strength in MPa.

As mentioned before, loading rate was 0.02 MPa/s and the numbers displayed on the testing unit of machine were: 1.52, 1.45, 1.47, 1.57, 1.47 and 1.50 respectively.

Since the sample sizes were 50 x 50 mm, the compressive strength in MPa will be calculated by following equation.

$$\sigma = P/A \quad (7)$$

Where: σ is compressive strength (MPa), P is force (N) and A is cross sectional area of sample (mm^2). Therefore, the compressive strength of samples are: 0.61, 0.58, 0.59, 0.63, 0.59 and 0.60 MPa respectively.

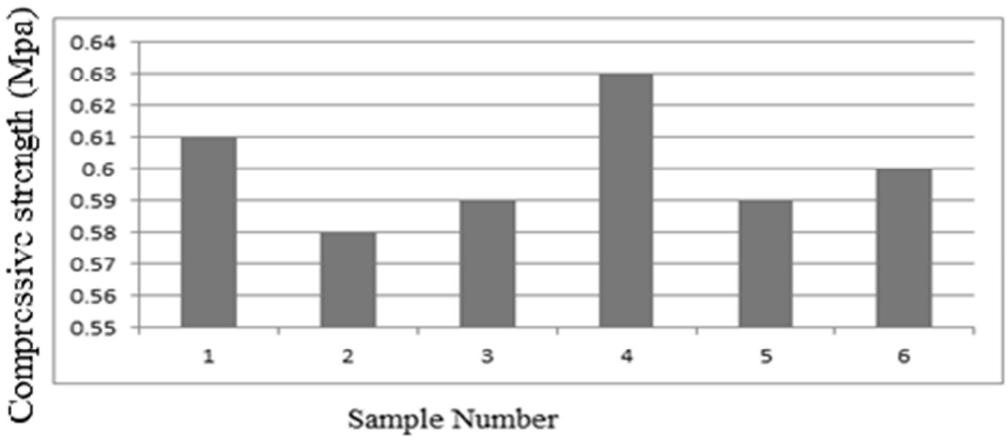

Figure 4.9: Compressive Strength (MPa) of LCMP Samples

According to Figure 4.9, the mean value of LCMP compressive strength is 0.6 MPa. Therefore, compressive strength of LCMP compared to structural materials – such as bricks – is not high, but this value of strength is acceptable for non-structural insulation materials. This value is high compared to other types of insulation materials such as expanded polystyrene. The main reason of this value is calcium sulfate and calcium carbonate that used in LCMP. The difference between the values – less than 8 percent – may be refers to the uniformity of ingredient of samples.

4.4 Pulse Velocity Test Results

Three samples of LCMP prepared for this test. Each sample tested with two different length of path. By using direct measurement between two sides of sample, the length of path will be the thickness of sample. By using indirect measurement, the length of path must be calculated.

Since LCMP samples have 26 ± 2 mm thickness, length of path in direct measurement is 24 to 28 mm, depending on the accurate sample size.

Samples 1, 2 and 3 have 26, 28 and 27 mm of thickness respectively. Therefore length of path for direct measurement will be 26, 28 and 27 mm for sample 1, 2 and 3 respectively.

For indirect measurement, the length of path for samples 1, 2 and 3 were selected as 105.3, 227.7 and 229.6 mm respectively.

Table 4.2 illustrates the length of paths and transmission times for each sample.

Table 4.2: Transmission Time and Length of Path for Each Sample

Sample number	Length of path (mm)		Time of transmission (μs)		Pulse velocity (km/s)	
	Direct method	Indirect method	Direct method	Indirect method	Direct method	Indirect method
# 1	26	105.5	32.4	23.9	0.80	4.41
# 2	28	227.7	40.8	52.9	0.69	4.30
# 3	27	229.6	22.9	49.5	1.17	4.64

It is important to note that, according to ASTM C 597, the length of path should be between approximately 50 mm to 15 m depending on intensity and frequency of the generated signals.

Therefore, the mean value of pulse velocity is 4.45.

According to Table 3.1 in chapter three, LCMP has a "good" uniformity.

Lack of the air bubbles in the samples and adaptation of ingredients with each other should be the main cause of high pulse velocity value.

4.5 Fire Test Results

One LCMP sample placed horizontally (simulating the use for a ceiling) above the burner (Figure 3.11 chapter three). The test started when the burner lit up and it continued for a period of ten minutes.

This test repeated two times with different burner elevation.

Since this test is a visual evaluation, the test process recorded by camera. And film of the fire test process has been enclosed in this thesis.

The Flame Spread Index (FSI) and smoke emission of LCMP sample was about zero. Therefore the reaction of LCMP against fire shows that LCMP is non-flammable.

According to tables 3.2 and 3.3 in chapter three and the test evaluations, The LCMP can be classified as A (I) and A in IBC and NFPA standards respectively.

Since any ingredients of LCMP are non-flammable materials – except polypropylene fiber which used in low percentage – the combination of them would be non-flammable.

4.6 Water Absorption Test Results

Four samples of LCMP were used for this test. Samples were placed into oven (temperature 105°C) for a period of 48 hours to make oven-dry samples (stable weight). Then the samples (oven-dry) were weighed and recorded as an initial weight (oven-dry weight). Afterwards, samples were placed completely into water for a period of 24 hours. Finally samples were taken out from water and weighed to obtain the saturated weight of LCMP samples.

Table 4.3 gives the weights of samples for oven dry and saturated surface dry situation and the percentage of the water absorption is calculated by using equation (4) in chapter three.

Table 4.3: Weights of Samples for Oven Dry and Saturated Surface Dry Situation and the Percentage of Water Absorption

Sample number	Weight of sample (g)		Percentage of water absorption
	Over dry	Saturated surface dry	
# 1	12.0	69.1	475.8
# 2	15.2	87.1	473.0
# 3	10.5	60.8	479.0
# 4	09.2	52.5	470.7

Mean value of the percentage of water absorption is: 474.64 percent

Results show that percentage of water absorption of LCMP is too high (about four time of its weight)/ Therefore LCMP must have water insulation as a protection in humid places.

Water absorption of calcium sulfate and calcium carbonate is high. Therefore, the high percentage of water absorption of LCMP may be affected by the high percentage of water absorption of calcium sulfate and calcium carbonate.

Chapter 5

CONCLUSIONS

5.1 General

The results obtained from each test and their comparison with the standards and building codes are presented in this chapter together with their conclusions and recommendations for future work.

Generally one of the most important factors of saving energy in buildings is thermal properties of used material. External walls which are contacting with uncontrolled space are the most important constituent of a building. Therefore, high thermal resistance of external walls brings better comfort to a building.

A material with lower thermal conductivity has better thermal properties when it is used as a thermal insulation. Also, the lightweight materials that are used in buildings can reduce the dead load of the structure. Therefore, this research intended to find a new material with acceptable thermal properties, weight, cost and safety.

A new material is manufactured through this study which is named as LCMP and the tests necessary to estimate the sufficiency of LCMP, as a thermal insulation material, have been done.

The results – according to ASTM, ICBC, IECC and etc. standard and codes – show that the usage of LCMP as a thermal insulation in terms of price, weigh, safety and thermal specifications is acceptable. However, because of the high water absorption and fragile form of LCMP, it is not suitable to be used in humid place or used as a structural material. LCMP should have water insulation before being suitable to be used in high humid places.

5.2 Conclusions and Recommendations

LCMP samples have been tested by hotplate apparatus and hotbox apparatus to estimate the conductivity coefficient. And also other tests such as fire test and pulse velocity test were carried out on numerous samples.

Ratifications by standards and/or building codes, comparison with other insulation materials in terms of cost and weight and also the advantages and disadvantages of using LCMP in buildings are expressed in this section.

5.2.1 Ratifications by Standards and/or Building Codes

The results of thermal conductivity tests – hot plate and hot box tests – indicated that the LCMP samples have low thermal conductivity – 0.05379 and 0.04007 with hot plate and hot box tests respectively – therefore, it can be used as a thermal insulation material. According to different building criteria, standards and codes – which are given in detailed in chapter two – depending on the type of wall used, the thickness required for LCMP will be different.

The following examples give the necessary thickness of LCMP that should be applied on a 25 cm thickness of clay brick wall with 2 cm thickness of cement mortar plastering on the exterior side of the wall and 1 cm thickness of Deco-wall gypsum plastering in interior side of the wall to comply RAA 446 (Cyprus criteria), ECBC and Iran Code 19 for residential building by using tables of 2.1, 2.5, 2.8 and 2.9 from chapter two and figure 4.7 from chapter four.

According to Iran Code 19:

Minimum R factor required by Iran code 19 for third group of buildings with light walls is 1.5.

R value of 1 cm gypsum plaster is 0.0426 $m^{2}°K/W$

R value of 2 cm cement mortar plastering is 0.0286 $m^{2}°K/W$

R value of 25 cm of thickness of clay bricks is 0.6191 $m^{2}°K/W$

Total R value of the wall except LCMP insulation is 0.6903 $m^{2}°K/W$

Therefore, by substituting 3.3 cm of LCMP in equation (1) and (2) R value of 0.823 $m^{2}°K/W$ can be obtained. Adding this to the R value of wall adequate R value required by Iran Code 19 can be obtained.

According to RAA 446 (Cyprus criteria):

Maximum required U factor is 0.85 $W/m^{2}°K$

Total R value of the wall with insulation must be 1.176 $m^{2}°K/W$

The R values of inside air film and outside air film are 0.68 and 0.17 $m^{2}°K/W$, respectively. Therefore, there is no need to use thermal insulation.

According to ECBC:

Maximum required U factor is: 0.44 $W/m^{2}°K$

Total R value of the wall with LCMP must be 2.27 m2˚K/W

The R values of inside air film and outside air film are 0.68 and 0.17 $m^{2}°K/W$, respectively. Therefore, minimum 3.0 cm of LCMP should be used to achieve the required U value by ECBC criteria.

This research proves that the walls which are made by 25 cm thick BIM and AKG blocks with plastering do not need any insulation material according to RAA 446, ECBC and Iran Code 19.

The other types of bricks and/or blocks may require insulation.

Fire test result shows that LCMP is non-flammable material which can be classified as A (I) and A in IBC and NFPA standard classifications respectively. LCMP complies with the safety factor required in case of fire. Therefore, when compared with some other insulation materials, such as polystyrene, in case of fire LCMP is a safer material.

Compressive strength test indicated that LCMP has approximately 0.6 MPa compressive strength, which is a bit on the high side for a non-structural insulation material.

Water absorption test showed that the LCMP samples have high water absorption which is a weak point for use in humid places. Therefore, when used without water insulation, LCMP is most suited to be used on the interior side of external walls. Otherwise they should be protected by a kind of water insulation.

The high pulse velocity number achieved from the pulse velocity test that despite LCMP is a light-weight material, it has a good uniformity and density.

5.2.2 General Comparison with Other Insulation materials

Some characteristics of the insulation materials, AKG blocks, BIMs and clay bricks compared with LCMP in this section. Table 5.1 illustrates the comparison of LCMP with other insulation and structural materials used in this study.

Although BIM and AKG blocks do not need any thermal insulation they are also considered in table 5.1. It is clear that in terms of cost and weight it is more reasonable to use clay bricks with LCMP instead of AKG or BIM blocks.

Table 5.1: The Comparison of Some Characteristic of LCMP with Few Other Materials

Name of the material	λ (W/m°K)	Weight (Kg/ m³)	Cost (\$/m²)	Compressive strength (Mpa)	Water absorption (%)	Flammability index
LCMP	0.0401	252	3.19 t=2.5cm	0.6	≈ 474	A (I)
Mineral wool	0.0405	133	20.4 t=4cm	0.1 – 0.15	1.5	A (I)
EPS	0.0380	100 - 200	27 t=2.5cm	0.1 – 0.3	3.5	A (1) – B (II)
Polyurethane foam	0.0287	85-150	≈ 36.5 t=3cm	0.2	5-7	A (II)
AKG	0.0990	700-800	34 t=25cm	12 - 20	10	A (I)
BIM	0.1146	900-1000	22 t=25cm	16 - 18	17 - 19	A (I)
Clay brick	0.4037	700-800	20 t=25cm	10 - 15	17 - 24	A (I)
Concrete	1.7500	2150-2250	18 t=25cm	10 - 45	4.35	A (I)
Gypsum plastering	0.2348	1000-1200	23.5 t=2.5cm	13.8	18-28	A (I)

5.2.3 Advantages

The advantages of using LCMP as a thermal insulation material in constructions can be listed as follows:

1- Decreasing dead load in structures (by unit weight of 252 Kg/ m³)

2- Saving annual energy costs

3- Saving energy resources

4- Easy and fast to cut and apply

5- Safe for health

6- Reduce noise levels

7- Low price (3.19\$/m² for 2.5cm thickness)

8- Durable and non-flammable

9- Environmentally friendly

10- The compressive strength of LCMP is higher than other non-structural insulation materials, such as polystyrene.

11- Decrease the thickness of the walls

5.2.4 Disadvantages

Disadvantages of LCMP can be listed as follows:

1- LCMP is a fragile material so it can brake easily during the transportation or application.

2- LCMP has high water absorption; therefore it is more suitable to be used on the inner side of walls and it must be protected by using water insulation in humid places.

3- The compressive strength of LCMP is lower than structural materials.

4- Since the LCMP is a rigid panel, it is not easy to apply on walls with curved surfaces.

5- LCMP must be applied with the wall with a kind of adhesive, such as tile adhesive.

5.3 Recommendations

In this section there are some general recommendations and a recommendation for future studies which are given as follow:

According to RAA446 for most of the type of materials that are commonly used and are available in Cyprus, there is no need to use thermal insulation for constructions. On the other hand, based on some studies which mentioned in chapter two, the usage of thermal insulation may increase the energy saving and reduce the annual costs of buildings especially in winter and summer seasons for Mediterranean climate conditions. Therefore RAA446 should be revised to approach better energy efficiency in Cyprus.

Using thermal insulations without any seam or gap may give better results than using panels or blocks with some gap or seam between panels. Therefore using thermal insulation with some characteristics like LCMP in terms of thermal properties, price, safety and weight in a mortar form is recommended for future studies. On the other hand, the transportation and applying the mortar form of insulations is much easier than the panel form of insulations.

5.4 Overall Conclusion

Nowadays researches carried out on energy conservation became one of the most important matters. Therefore, finding suitable way to save energy resources and decrease energy consumption is also a very important issue. So this research was aimed at contributing the recent research trend on energy conservation through introducing a new insulation material. Since the test results on LCMP complied with standards and codes relating to energy conservation then LCMP can be a suitable choice for contractors, engineers and researchers.

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