

**DEVELOPING ENERGY-EFFICIENT BLOCKS IN THE
FIELD USING INDIGENOUS INDUSTRIAL WASTE
MATERIALS**

BY

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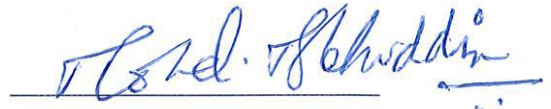
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This work is dedicated to my beloved family.

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TABLE OF CONTENTS

ACKNOWLEDGMENT	V
TABLE OF CONTENTS.....	VI
LIST OF TABLES.....	X
LIST OF FIGURES.....	XII
LIST OF ABBREVIATIONS.....	XIV
ABSTRACT	XV
ملخص الرسالة	XVIII
CHAPTER 1 INTRODUCTION.....	1
1.1 Overview	1
1.2 Thesis Objectives	3
1.3 Significance of the Study.....	4
1.4 Thesis Organization	5

CHAPTER 2 LITERATURE REVIEW	6
2.1 Replacement Materials	6
2.2 Finite Element Modelling (FEM)	13
CHAPTER 3 JOURNAL ARTICLE 1	19
3.1 Abstract	19
3.2 Introduction.....	20
3.3 Experimental Work	24
3.3.1 Materials.....	24
3.3.2 Mix Proportions	27
3.3.3 Preparation the Innovative Block Steel Mold	28
3.3.4 Mixing, Casting and Curing Specimens in the Factory	29
3.3.5 Testing Specimens	30
3.4 Results and Discussions.....	34
3.4.1 Compressive Strength.....	34
3.4.2 Oven-dry density, Unit weight and Absorption	36

3.4.3	Thermal Conductivity	39
3.4.4	Cost Analysis	43
3.4.5	Emissions of Carbon Dioxide (CO ₂) and Fuel Consumption	49
3.5	Conclusion	52
3.6	Acknowledgments	55
CHAPTER 4 JOURNAL ARTICLE 2		56
4.1	Abstract	56
4.2	Introduction	57
4.3	Experimental Research	62
4.3.1	Materials.....	62
4.3.2	Preparation of the Innovative Steel Mold	65
4.3.3	Mixing, Casting and Curing of Specimens in the Factory.....	66
4.3.4	Testing Specimens.....	68
4.4	Results and Discussions	73
4.4.1	Compressive Strength	73
4.4.2	Oven-dry density and Absorption	75

4.4.3	Thermal Conductivity	77
4.4.4	Cost Analysis	81
4.4.5	Estimated the Fuel Consumption and CO ₂ Emissions	85
4.5	Conclusions	89
4.6	Acknowledgement	91
CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS		92
5.1	Conclusions	92
5.2	Recommendations	94
REFERENCES.....		95
VITAE		114

LIST OF TABLES

Table 1: Chemical composition of expanded perlite [63].....	25
Table 2: Composition of vermiculite [65]	26
Table 3: The mix design for 1 m ³	28
Table 4: Total number of specimens and the standards applied	30
Table 5: Results of oven-dry density, unit weight, absorption, and compressive strength (at 7 and 28 days).....	36
Table 6: The average thermal conductivity and resistance of single blocks.....	41
Table 7: The average thermal conductivity and resistance of the double blocks (2-joint blocks)	42
Table 8: Cost analysis of a masonry wall for 1 m ²	44
Table 9: Evaluation of the economics of various concrete walls.....	46
Table 10: Variables used to calculate CO ₂ emission levels	50
Table 11: Chemical composition of Cement (mass%)	62
Table 12: Chemical composition of high-density polyethylene (HDPE) [99]	63
Table 13: Tires chemical composition [106]	64
Table 14: Total number of specimens and the standards applied	68
Table 15: Results of oven dry density, absorption, and compressive strength (at 7 and 28 days).....	74
Table 16: A single block's average thermal conductivity and resistance	79

Table 17: The average thermal conductivity and resistance of the double blocks (2-joint blocks)	80
Table 18: Cost estimation for a meter square of a masonry wall system	82
Table 19: The parameters used in CO ₂ emission calculation [86], [87]	86

LIST OF FIGURES

Figure 1: Volcanic Scoria Coarse aggregate (a) VS (# 3/8 in) (9.52mm); (b) VS (# 3/16 in) (4.76mm).....	26
Figure 2: Shape and average sizes in mm of (a) Perlite; (b) Vermiculite; (c) Polystyrene	27
Figure 3: Geometry and dimensions of the fabricated blocks	29
Figure 4: Manufacturing process (a) blocks making machine; (b) blocks covered with burlaps and polyethene sheets	30
Figure 5: Capping specimens for compressing test	31
Figure 6: (a) Immersed weight (W_i); (b) Saturated weight (W_s); (c) Oven-dry weight (W_d).....	32
Figure 7: (a) FOX600 instrument setup; (c) Tested specimens; (b) Samples preparation	34
Figure 8: Compressive strength of the produced blocks at 7- and 28-days curing period	36
Figure 9: Oven-Dry densities for the blocks (kg/m^3).....	38
Figure 10: Absorption of the produced blocks per cubic meter.....	39
Figure 11: Weigh of the individual blocks	39
Figure 12: Thermal conductivity of the single and double blocks.....	42
Figure 13: Thermal resistance of the single and double blocks.....	43
Figure 14: Annual energy consumption and cost for the developed masonry walls	48
Figure 15: Net present value using different masonry wall	48

Figure 16: Annual fuel consumption with various wall types	51
Figure 17: CO ₂ emissions with different thermal insulation walls	52
Figure 18: Shape and average sizes in mm of (a) HDPE; (b) LDPE; (c) CR	65
Figure 19: Geometry and detailed dimensions of the fabricated blocks.....	66
Figure 20: Manufacturing process at the factory: (a) blocks making machine; (b) forklift equipped with a hooper; (c) tray of hollow concrete blocks; (d) curing process.....	67
Figure 21: (a) Matest compression test machine; (b) capping specimens before testing .	69
Figure 22: (a) Configuration of the FOX600 heat flow meter device; (b) Samples preparation; (c) Design of HFM apparatus	72
Figure 23: Compressive strength of the produced blocks at 7-and 28-days curing period	75
Figure 24: Oven-Dry densities for the blocks	77
Figure 25: Absorption of the produced blocks	77
Figure 26: Thermal conductivity of the single and double blocks.....	80
Figure 27: Thermal resistance of the single and double blocks.....	81
Figure 28: Annual energy consumption for cooling system when using different masonry walls	84
Figure 29: Annual energy cost and saving.....	85
Figure 30: Annual fuel usage as a result of various wall types	88
Figure 31: CO ₂ emissions linked to varied thermal insulating walls.....	89

LIST OF ABBREVIATIONS

HCB	:	Hollow Concrete Block
HFM	:	Heat Flow Meter
HDPE	:	High-Density Polyethylene
LDPE	:	Low-Density Polyethylene
EPS	:	Expanded Polystyrene
CR	:	Crumb Rubber
VL	:	Vermiculite
Wd	:	Dry weight, g
Ws	:	Saturated Weight, g
Wi	:	submerged Weight, g
W/C	:	Water to cement ratio

ABSTRACT

Full Name : Saeed Mubarak Al-Tarbi
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The necessity for eco-friendly green buildings will continue to raise answering the climatic change challenges while the need for energy saving is vital to protect the natural environments. The energy consumption for both domestic and industrial buildings has gradually increased in developed countries. Since the building envelope plays a critical role in energy conservation where the greatest heat and energy loss always exists, the physical and thermo-mechanical efficiency of these envelopes must be assessed in terms of energy performance to mitigate the effect of climatic change.

In Saudi Arabia, the need for energy efficiency is becoming more and more important to the public and principals due to the steady growth of population and increasing demand for energy. To regulate and minimize the consumption of energy, the Saudi Energy Efficiency Center (known in Arabic as KAFAA) has recently been established. Three-quarters of all the electricity generated within the country is used by the buildings sector. Specifically, air

conditioning accounts for almost three-quarters of the electricity consumption in residential buildings.

Since much of the thermal load is transmitted via building walls, the use of ideal building materials in building walls may greatly minimize the load of thermal transmission in order to use less energy to cool buildings. The hollow concrete blocks are the most common building material used in wall construction in Saudi Arabia. Therefore, new blocks were developed in this study to reduce the thermal conductivity so that the energy consumption for both domestic and industrial buildings will be less.

The primary objective of this study was to explore the use of locally-sourced indigenous industrial waste and by-product materials such as perlite, rubber, high density polyethylene, low density polyethene, expanded polystyrene beads, vermiculite and volcanic scoria aggregate for the development of new low-thermal conductivity lightweight concrete blocks in the field and to assess the effectiveness of such concrete blocks by comparing their thermal conductivity with those available in the local market.

The experimental results were based on the compressive strength (ASTM C129), Density and Absorption (ASTM C 140), and Thermal conductivity (ASTM C177 and C518). In addition, based on the experimentally measured thermal resistance, the economic feasibility, fuel energy usage, and CO₂ emissions were calculated.

The results proved that all the newly developed blocks (perlite, vermiculite, scoria, and polystyrene, high density polyethylene, low density polyethylene) fulfilled the standard requirement by ASTM C129 for non-load bearing blocks for both compressive strength of 4.14 MPa whereas blocks made with crumb rubber failed to meet the requirement. In addition, the perlite and scoria blocks are categorized as light-weight concrete blocks as they had the lightest weight of (15.19 kg) and (17.07kg), which were lower by 25% and 15%, respectively, contrasted with the block controls (without insulation materials). Also, the new design of the control blocks had the largest influence on the thermal conductivity as it reduced by 54% while scoria and perlite had the highest reduction of thermal conductivity of almost 60% compared to that of the commercially produced in the market. Furthermore, a cost analysis found that the scoria block is the most affordable as it had the lowest unit price. In terms of energy consumption, the new design of control blocks reduced the energy consumption of the market block wall by roughly 53%, which saves annually around 3.95 \$/m². Whereas using scoria blocks save 68.81 kWh/m² and \$4.6/m² annually. The Scoria-wall may reduce CO₂ emissions by a factor of 2.4 when compared to a commercial concrete block.

ملخص الرسالة

الاسم الكامل: سعيد مبارك سعيد التاربي

عنوان الرسالة: إنشاء وتطوير طوب البناء المجوف موفرا للطاقة في المصنع باستخدام النفايات الصناعية والمواد العازلة للحرارة.

التخصص: هندسة مدنية وبيئية

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ستستمر الحاجة إلى المباني الخضراء الصديقة للبيئة في زيادة استجابة لتحديات التغير المناخي بينما تعد الحاجة إلى توفير الطاقة أمراً حيوياً لحماية البيئة الطبيعية. ازداد استهلاك الطاقة لكل من المباني السكنية والصناعية تدريجياً في البلدان المتقدمة مثل المملكة العربية السعودية التي أصبحت بحاجة أكثر الى ترشيد الطاقة بسبب زيارة في الكثافة السكانية والرغبة في الحفاظ على الموارد الطبيعية. استناداً لذلك تم فرض العديد من القوانين والانظمة لترشيد الاستهلاك الكهربائي من خلال إنشاء المركز السعودي لكفاءة الطاقة المعروف بكفاءة. ونظراً لأن الكثير من الحمل الحراري ينتقل عبر جدران المبنى ، فإن استخدام مواد البناء المثالية في جدران المباني قد يقلل إلى حد كبير من حمل النقل الحراري من أجل استخدام طاقة أقل لتبريد المباني.

تعتبر البلك الخرسانية المفرغة من أكثر مواد البناء شيوعاً في تشييد الجدران في المملكة العربية السعودية. لذلك، تم تطوير طوب جديدا في هذه الدراسة باستخدام انواع مختلفة من المواد العازلة مثل البيرلايت، الفيرموكلايت، والصخر البركاني، وكذلك مواد بلاستيكية ونفايات مضرّة بالبيئة مثل البولي إيثيلين عالي ومنخفض الكثافة والمطاط من اطارات السيارات وحبيبات البوليسترين لتقليل التوصيل الحراري بحيث يكون استهلاك الطاقة لكل من المباني السكنية والصناعية اقل و الحفاظ على البيئة و الموارد الطبيعية.

أثبتت النتائج أن جميع الطوب المطورة حديثاً في هذه التجربة (البيرلايت والفيرميكولايت والسكريا والبوليسترين والبولي إيثيلين عالي الكثافة والبولي إيثيلين منخفض الكثافة) تفي بالمتطلبات القياسية من قبل ASTM C129 للجدران

غير الحاملة لكل من مقاومة الانضغاط البالغة 4.14 ميجا باسكال بينما الطوب المصنوعة من المطاط فشلت في تلبية المتطلبات. بالإضافة إلى ذلك ، يتم تصنيف الطوب المصنوع من البيرلايت والصخر البركاني على أنها بلك خرسانية خفيفة الوزن حيث أنها كانت أخف وزنًا (15.19 كجم) و (17.07 كجم) ، والتي كانت أقل بنسبة 25٪ و 15٪ على التوالي ، مقارنةً بالبلوك المنتج بدون مواد عازلة. أيضًا ، كان للتصميم الجديد للطوب (بدون مواد عازلة) التحكم التأثير الأكبر على الموصلية الحرارية حيث انخفض بنسبة 54٪ بينما كان للصخر البركاني والبيرلايت أعلى انخفاض في التوصيل الحراري بنسبة 60٪ تقريبًا مقارنةً بالمنتج التجاري في السوق. علاوة على ذلك ، وجد تحليل التكلفة أن الجدار البركاني هي الأقل تكلفة لأنها تحتوي على أقل سعر للوحدة. وفيما يتعلق باستهلاك الطاقة ، قلل التصميم الجديد للطوب (بدون مواد عازلة) التحكم من استهلاك الطاقة بحوالي 53٪ ، مما يوفر سنويًا حوالي 3.95 دولار للمتر المربع. في حين أن استخدام الطوب البركاني يوفر 68.81 كيلو واط ساعة للمتر المربع مايعادل 4.6 دولار سنويًا. وكما يقلل الجدار المصنوع من الصخر البركاني من انبعاثات ثاني أكسيد الكربون بمعامل 2.4 مقارنةً بالطوب الخرساني المتوفر في السوق.

CHAPTER 1

INTRODUCTION

1.1 Overview

The use of air conditioning is irreplaceable in Saudi Arabia due to the hot and arid climate which could reach 45 °C during the summer months [1]. Therefore, buildings in Dammam city alone utilize 74% of Saudi Arabia's power, while air conditioning accounts for 67% of that city's total building electrical usage.[2]. Further, the air conditioning absorbs around 71% of the total electricity in the hot climate like Jeddah while it accounts about 40% for the milder climate like Abha [2]. Other major factors are known as minor factors to contribute for energy dissipation, such as growing income, population growth and energy efficiency [3]. Therefore, the consumption of electricity will be increased in order to provide a convenient indoor environment.

Saudi Arabia's population is rising rapidly, as in many other countries around the world, and the demand for energy is increasing. KSA recorded a dramatic rise in electricity consumption between 2000 and 2020 because of rapid economic development. The peak demand for electricity jumped from 50 GW to 60 GW during time from 2012 to 2017, and by 2020 it is forecast to reach 70 GW [4]. During 2009-2017, the Saudi Electric Company invested at least SR 380 billion to satisfy this need [5]. There is also a critical need to establish policies for the use of resources that would promote sustainable growth. The Saudi Energy Efficiency Center (known in Arabic as KAFAA) has been established with the main objective of controlling energy usage in response to

the increased concern about excessive power consumption in KSA. As a result of stringent enforcement of energy efficiency standards, the estimated power consumption might be reduced by 5 to 10 %, resulting in an increased capacity of 3 to 6 GW and a savings of \$1.5 to 3.0 billion over the next 20 years. Reducing demand for air conditioning and adopting energy-saving techniques might save the government as much as \$0.25 billion annually, according to the estimations presented in this paper [6].

The economy of KSA is heavily reliant on fossil fuel supplies, namely oil reservoirs, the decline of which would adversely affect the country's future growth. The overall demand of energy is rising annually by about 5-8 percent, which will result in the production of oil and oil demand being equal in 2035. Therefore, residential buildings need to be more assessed in comparison to their actual energy use [2]. By limiting the use of air-conditioning systems, energy consumption may be minimized by reducing heat flow through the buildings envelope. The brick walls are the surfaces that are most frequently exposed to the elements, including temperature and solar radiation. The reduction in the thermal conductivity of these components may then contribute to a decrease in the temperature of the inner surfaces thereby leading to long-term advantages, including decreases in both cooling costs and emissions of the atmosphere due to reduced fossil fuel utilization[7]. Researchers noted that heating and air-conditioning loads can be reduced by many ways, but especially by a smart choice of the building envelope design and materials[8]. It was reported that, depending on the type of building, the surrounding environment and the insulating material used in the construction, the importance of energy savings consumed in the buildings would differ.

Hollow or solid concrete blocks are the most prevalent material used in the wall building construction in Saudi Arabia. Attributed its low thermal conductive and material usage, hollow concrete block is considered to be a preferable choice from

economic and environmental perspective for making concrete walls in predominant hot and arid climate. However, casting hollow concrete blocks is more challenging than casting solid ones and the implementation of air holes using lightweight aggregates is a more cost-effective method of minimizing the thermal conductivity of concrete blocks [9]. It is possible to manufacture lightweight aggregates from recycled natural materials, recycled by-products, or unprocessed materials. The resulting blocks are less compact and provide better thermal insulation when lightweight aggregates are used to produce lightweight concrete, but they also display weak mechanical properties [10].

The main objective of this study is to use new cost-effective and energy-saving building materials in the manufacture of normal or lightweight concrete blocks in the field, including locally sourced waste and by-product materials such as perlite, rubber, polyethylene, extended polystyrene beads, vermiculite, and volcanic scoria aggregate as aggregates. The development of newly renovated masonry blocks will be of value to Saudi Arabia 's building and manufacturing industries and will lead to national "strategic" attempts to minimize energy consumption more effectively across the region.

1.2 Thesis Objectives

The main objective of this research is to investigate the ability of developing new lightweight hollow concrete blocks in the field utilizing indigenous industrial waste and by-product materials with low thermal conductivity and low weight and satisfying the mechanical properties of the standard blocks in Saudi Arabia. The specific objectives of the proposed research project are as follows:

1. Select the optimum dosage of the insulated materials (perlite, vermiculite, rubber, expanded polystyrene beads, high density polyethylene, volcanic scoria aggregate, and low-density polyethylene) that have a potentially good thermal resistance to be included in concrete blocks of relatively low density.
2. Fabricate a new block using the best insulation materials and the optimum hole arrangement to arrive at the highest "optimum" thermal resistance.
3. Measure the thermal resistance and the mechanical properties experimentally of the fabricated blocks that will be cast in the field and compare the results with the standards.
4. Perform an economic analysis to assess the cost-effectiveness of the developed blocks in energy saving.

1.3 Significance of the Study

The increasing use of electricity has been a big concern for both governments and the public. The government is worried about the unsustainable use of oil in energy generation and, as a result, the carbon footprint continues to rise. Since air conditioning absorbs a significant proportion of electrical energy, it accounts for about 74% of the overall electricity used in residential buildings [2], it would be reasonable to reduce this aspect as far as possible by the usage of industrial waste and by-product materials which offers an additional advantage by ensuring that these products are disposed of without environmental damage. The findings of this research work will be the basis for developing guidelines for the use of waste materials in the manufacture of lightweight concrete blocks used in Saudi Arabia for building construction.

1.4 Thesis Organization

The main body of the MS thesis contains five chapters which constructed as follows: CHAPTER 1 introduced with an overview of the topic, the main objectives and finally the significance of the study. The second chapter (CHAPTER 2) presents a comprehensive literature review about the materials used to produce concrete blocks and any research relate to the work. CHAPTER 3 contains a full published journal article about the development of energy-efficient hollow concrete blocks in the field using perlite, vermiculite, volcanic scoria, and expanded Polystyrene, while CHAPTER 4 presents another journal article regarding development of eco-friendly hollow concrete blocks in the field using wasted high-density polyethylene, low-density polyethylene, and crumb tire rubber. CHAPTER 5 of the thesis finishes with a summary of the key findings and recommendations for future research in the field of construction and building materials.

CHAPTER 2

LITERATURE REVIEW

2.1 Replacement Materials

Researchers conducted extensive research on materials that can be used as a replacement of aggregates to improve the thermal insulation of concrete blocks. For instance, scoria from a quarry in Harrat Rahat, western Saudi Arabia, was investigated by Moufti et al, [11] for industrial utilization. Different percentages of scoria as (coarse and fined aggregates) were utilized to produce cubes with different concrete mixes. ASTM (1995) for compressive strength requirement was achieved and hence, scoria was ideally suited for structural concrete and building blocks due to its potential high thermal resistivity.

Budaiwi et al. [12] examined the thermal resistance of different insulation materials utilize in Saudi Arabia and its correlation with temperature. Their results indicated that the type of insulation materials tend to affect the envelope cooling loads in a way that the materials subjected to high temperature have higher thermal conductivity. Polyethylene was the most sensitive material for temperature while polystyrene was the least. In Dhahran, during the hot months, polyethylene exhibited 83% reduction in thermal resistivity.

Yasar et al.[13] carried out laboratory tests on structural lightweight concrete (SLWC) by replacing the aggregate with basaltic pumice (scoria) and fly ash as replacement of mineral admixture. 20% of fly ash was used by weight with lightweight basaltic pumice (scoria) and normal Portland cement (NPC) to produce the control mixture. The results

showed that scoria could be used to produce SLWC whereas the use of fly ash is preferable to lower the cost and the environmental impact effects. Using fly ash in SLWC promoted the compressive and tensile strengths in contrast to the control SLWC.

Yang et al [14] tried to develop a new type of compound blocks which has capability to reduce the permeability and thermal conductivity of the walls. Load-bearing layer, heat insulation layer, and decoration layer were the three layers of the compound concrete block. The load-bearing layer was made of heavyweight materials. Lightweight materials were used for the heat insulation layer and called CPS with polystyrene or CPI with perlite expansion. The results showed CPS blocks were better than the clay bricks whereas the CPI blocks were as good as the clay bricks from thermal perspective.

Cairns et al.[15] examined the usage of tire rubber in concrete masonry bricks. With a water-to-cement ratio of 0.87, they used three proportions of rubber (10, 25 and 50 percent). The results showed that after 28 days of curing, the compressive strength decreased by 22, 23 and 41% as the percentage of rubber increased. The authors also observed a minor improvement in the strength when the rubber chips coated with cement paste to raise the rubber -cement interaction force.

Crumb rubber was used by Sukontasukkul & Chaikaew [16] to replace fine and coarse aggregates in pedestrian blocks. Two dosages (10 and 20% by weight) of rubber were used with two different sizes (No. 6 and No. 20). Content and the size of rubber were the most effective factors of the strength. They found that the strength was reduced by almost 45 and 85% for the 10 and 20%, respectively, as compared to the control mix.

Hossain [17] examined the use of volcanic scoria as a cement additive on the potential industrial utilization. Also, the possibility of using scoria as coarse and fine aggregates

in lightweight concrete was assessed by conducting a series of tests on its density, air content, workability, strength, water permeability, and drying shrinkage. The results proved that scoria fulfilled the required strength and density by ASTM standards. Likewise, scoria could be used as heat-insulating material in building construction as it had a low thermal conductivity between 0.15 to 0.4 W/m.K.

Ünal et al [18] utilized various aggregate sizes of diatomite with several quantity of cement contents to produced masonry unit blocks. Various physical and mechanical properties tests were conducted on the formed blocks, such as compressive strength, thermal conductivity and bulk density. Its compressive strength ranged from 2.5 to 8 MPa while the best thermal conductivity was 0.23 W/m.K, therefore, diatomite could be utilized to provide a significant degree of thermal insulation in concrete structures.

Topçu & Işıkdağ [19] studied the effect of using perlite as a lightweight aggregate in clay bricks. The mixture consists of binding materials such as cement, bitumen, gypsum lime, clay and perlite with various ratios (5 to 50%. by total volume). It was concluded that with a reduction in the replacement ratio of perlite, the compressive strength increases while the thermal resistance of perlite brick decreases. Also, 30% of perlite was found to be the most suitable ratio as it reduces the thermal conductivity to 0.215 W/m.K as contrasted to control bricks with 0.465 W/m.K.

Al-Jabri et al [10] evaluated the viability of producing concrete blocks in the hot climate region using vermiculite and polystyrene as lightweight aggregates and cement kiln dust (CKD). The results suggested that vermiculite is not viable to produce concrete blocks due its low compressive strength while the Polystyrene is an effective material for producing lightweight concrete block to be utilized in non-load bearing walls with

a low thermal conductivity. Furthermore, adding up to 15% of CKD had a minimal impact on the compressive strength.

Two types of concrete blocks and nine types of clay bricks in Saudi Arabia was assessed by Al-Hadhrami & Ahmad [20]. The study was for thermal performance efficiency of the ability to add insulation materials like polystyrene, perlite and mineral wool inside the holes. The results proved that filling the insulation materials inside the cavities or mix it within the masonry brick decreased the thermal conductivity significantly. Also, concrete bricks were found less thermally effective than red clay bricks. The thermal resistivity increased by around 50% by adding perlite into the holes of concrete blocks, while for clay bricks it was reduced by 10%.

T. C. Ling [21] studied the impact of adding waste rubber by volume with 5 to 50% as the replacement of fine aggregate and with 0.45-0.5 water/cement ratio while keeping a 5.6 ratio of aggregate/cement fixed in all mixes. The results suggested that the content of rubber should not exceed 40% for non-structural and 10% for structural applications.

I. H. Ling & Teo [22] remarked the potency of using waste rice husk ash (RHA) and expanded polystyrene beads (EPS) in concrete blocks. Part of aggregate was replaced by EPS while waste rice husk ash (RHA) was used as a cementitious pozzolanic material with different dosages of (5, 10, 15, 20% by volume) to produce 21.5×10.25×6.5 cm solid bricks. The results showed a major increase around 25% of compressive strength which was obtained by 10% RHA as compared to the reference mix.

Sengul et al. [23] provided more details about the influence of perlite on the lightweight concrete thermal conductivity and mechanical properties. Perlite with various dosage from 20% to 100% replaced natural aggregate and mixed with superplasticizer and air

entraining admixture. The results proved that substitution of 60% of perlite decreased the thermal conductivity and strength by 42% and 84%.

Xu et al. [24] used expanded polystyrene beads (EPS) to produce lightweight hollow concrete blocks. Three dosages of 15, 20, and 25% by volume of EPS were prepared to examine its effects on density and compressive strength. The results showed that the most critical parameters for determination density and strength were EPS dosages and water to cement ratio and as the mentioned parameters increased, the density decreased as well as the compressive strength.

Celik et al. [25] chose colemanite to be added to perlite, coal dust, water, Carboxymethylcellulose (CMC) and sand for producing lightweight solid bricks (50×100×100 mm). 0–20% (by mass) colemanite was added with different temperatures (200–400 °C) to be studied. They found that the optimum brick obtained at 10% colemanite heated up to 400 °C, which had the best physico-mechanical properties and the lowest thermal conductivity coefficient with 0.12 W/m.K compared to other commercial bricks (normal brick, pumice block, gas concrete and sandwich brick) with 0.54, 0.54, 0.2, 0.18 W/m.K, respectively.

Al-Aqeeli et al. [26] invented a new type of masonry by replacing fine aggregate with crumb tire rubber. Fine and coarse crumb rubber particles were utilized to cast three different types of blocks, each with a different combination of fine and coarse rubber. The strength of blocks made with coarser rubber increased by almost 50% while other mixes of the blocks nearly satisfying the ASTM C129 requirement for compressive strength with 3.5 MPa. Therefore, there was a 21 percent increase in thermal conductivity when utilizing coarse rubber blocks, but the least amount of conductivity was obtained when using fine and both rubber sizes.

Sodupe-Ortega et al. [27] examined the inclusion of crumb rubber (CR) as aggregate to produce bricks and long hollow blocks using automated machine in the field. The content of CR was on the range of 10 to 40% by weight with multiple w/c ratios (0.7 to 0.9) in masonry blocks. The outcomes proved that using CR with percentages greater than 20% became unrecommended and affect the compressive strength of the blocks severely. Further, the increase in the w/c ratios reduced the strength.

Safinia and Alkalbani [28] studied the ability of using plastic bottles inside the masonry unit blocks. 500-ml plastic bottles were placed inside the blocks (8 bottles per block) to be tested for compressive strength. 57% higher strength of the plastic bottles compared to Oman's market hollow concrete blocks was showed by the results. Similarly, Wonderlich et al. [29] proved that the recycled plastic bottles boosted the masonry unit's compressive strength. Harder plastic bottles exerted an internal stress on the face shells, which pushed them outward, reducing the amount of space available for compressing. Furthermore, because the bottles had a larger diameter, there was less net surface area available for compressive force.

Mathew et al. [30] applied the use of low-density polyethylene in solid concrete blocks. 5 to 30% by volume of waste plastic (LDPE) used to replace the coarse aggregates with the same sizes. The results revealed that 15% was the Optimum percentage of replacement which would give the maximum compressive strength of the plastic blocks.

Sayadi et al. [31] tested the influence of expanded polystyrene (EPS) on the density, compressive strength and thermal conductivity of foamed concrete. EPS was added in the range of 0-82% and with w/c ratio of 0.33 to produce expanded polystyrene foamed concrete (PFC) with densities of 400 kg/m³ to 150 kg/m³. Results showed that

significant reduction in the density, compressive strength and thermal conductivity of 150 kg/m³, 0.08 MPA and 0.0848 W/m.K, ,respectively, obtained by increasing the volume of EPS up to 82%.

Lu et al. [32] studied the viability of using recycled glass aggregates (WGA) and incinerated sewage sludge ash (ISSA) to develop a green concrete block. Mechanical properties such as density, compressive strength and thermal conductivity were assessed. Results indicated that the increasing content of glass aggregates and ISSA would reduce the density of the blocks. Also, the effects of WGA on the compressive strength were almost negligible while slower strength was obtained when 20% of cement was replaced by (ISSA) due to its low pozzolanic activity. Furthermore, the thermal conductivity decreased by 57% for 100% replacement of WGA and it would further lower by 10% with the addition of 20% ISSA.

Al-Awsh et al. [33] examined the efficiency of concrete walls to reduce the heat transfer through buildings by using volcanic scoria (VS), expanded polystyrene (EPS), vermiculite (VL), and low density polyethylene (LDP) as insulation materials to replace fine and coarse aggregates. Also, perlite, crumb rubber and vermiculite were treated to make plasters and mortars. VS, LDP and VL replaced the coarse aggregates by 45%, 10% and 5% by weight, respectively, while EPS was used as replacement of coarse aggregate by volume of 12%. The results showed that all blocks satisfied the minimum required strength by ASTM C129 (3.45MPa) while the thermal conductivity for the VS, EPS, LDP and VL blocks was 0.34, 0.371, 0.382, and 0.383 W/m K, respectively.

Al-Tamimi et al. [34] aimed to develop a new concrete block to minimize the demand for air conditioning. New configuration of the cavities was proposed using FEM to reduce the heat flow through the building envelope. Thereafter, perlite, high density

polyethylene and crumb rubber were utilized by 30, 20, and 20% by weight as insulation materials to minimize the thermal conductivity once more. The results of the thermal resistance of the new block without the insulation materials was enhanced by 71% compared to other blocks used in the market. Furthermore, the thermal conductivity of perlite, rubber and polyethylene blocks was 0.309, 0.387 and 0.404 W/m K, respectively, which had significant reduction of 33, 16 and 12% compared to the control block without insulation materials. Although there was significant reduction on compressive strength, the newly developed concrete block had enough strength to satisfy the minimum ASTM C129 standard requirements and was considered as a lightweight masonry hollow block.

Sassine et al. [35] did a case study about the efficiency of expanded polystyrene (EPS) to enhance the thermal resistance of hollow concrete blocks. 0, 6, 12, and 18 g of EPS were used to prepare four different hollow concrete blocks ($10 \times 20 \times 40$ cm) and determine their thermal resistance experimentally. The results displayed that the thermal resistance for the blocks were 0.16, 0.2, 0.25 and 0.31 $\text{m}^2 \cdot \text{K} / \text{W}$, respectively. Thus, the addition of 18 g of EPS to the mixture will reduce the thermal conductivity by almost double.

2.2 Finite Element Modelling (FEM)

Al-Hazmy [36] examined the significance of cavities on the thermal resistance of masonry bricks using FLUENT CFD software. There were three kinds of masonry hollow blocks made for the experiment, each with a distinct configuration: solid polystyrene, air, and hollow polystyrene (which was the most common). His findings showed that solid polystyrene-filled cavities decreased the heat output by up to 36%,

whereas the average daily heat rate reduction was 25% during summer days in Jeddah, Saudi Arabia. Contradictorily, because of air exchange within the cavities, the heat rate of hollow polystyrene was lowered by 6% which attributed to the air inside the hollow polystyrene.

According to Del Coz Díaz et al. [37], the finite element model (FEM) may be utilized to accurately represent the heat equation in hollow concrete blocks of various shapes and configurations. The boundary radiation and convection in the brick cavities is responsible for the nonlinearity. There was also understanding of the other processes, such as conduction and convection. From the study, it was stated that the total thermal efficiency of the mass decreases as the coefficient of thermal conductivity of material and mortar increases.

J. J. de. Coz Díaz et al. [38] conducted both theoretical and numerical studies to determine the optimal block, with the latter being carried out using a finite element model (FEM). In this study, the thermal conductivities of four types of bricks with different thermal conductivity were investigated for the phenomena of conduction, convection, and radiation. The optimum block was taken based on the thermal analysis and then a wall was made. For fifteen configurations and temperature distribution, the simulation was performed using FEM. Their results showed that the possibility to improve the thermal performance of the bricks by increasing length, size, and distribution of the holes and both material and mortar thermal conductivities were related to the overall heat transfer coefficient.

Baig and Antar [39] studied numerically the heat loss through conduction and natural convection of hollow blocks. The thermal resistance for different recces configuration and various numbers of air-filled cavities was computed in this study. The heat loss

through the walls was measured more accurately by considering the interaction between conduction and convection at the boundaries. Results demonstrated that minimizing the heat flow could be achieved by increasing the number of holes without sacrificing the strength of the blocks. Furthermore, by adjusting the configuration of the cavities inside the blocks, reducing the thickness of the solid material and using cavities with high aspect ratio and less width, a significant improvement in thermal insulation can be obtained as it would decrease the thermal bridges, the conduction and convection heat transfer effects.

Arendt et al. [40] used semi-analytical method to test the effect of hollow brick cavity concentration on static and dynamic thermal behavior. To mitigate the impact of radiation and convection, a dynamic thermal analysis of the hollow block with the optimal cavity shape was carried out. The analysis showed that for low thermal conductivity, the cavity concentration ratio of the block should be in the range of 30 to 45% to obtain the optimal thermal parameters of hollow blocks while from 45 to 65% for higher thermal conductivity, but the last was difficult to render practically since the thickness of webs and block ribs would be quite small and, hence, would be very fragile and easily damaged.

The impact of holes on the heat conduction of conventional and interlocking blocks was studied using MATLAB by Oluwole et al. [41]. It has been established that using interlocking blocks with staggered cavities can help to minimize heat conductivity. Alternatively, there was little positive effect on the holes of more than four. Furthermore, the staggered cavities did not attain the thermal conductivity advantage for traditional blocks but the blocks with four cavities were found successful in thermal insulated blocks. The lowest thermal resistance was obtained by using more than four cavities in the traditional blocks.

J. J. Del Coz Díaz et al. [42] offered a new approach for improving the thermal efficiency of block walls with large cavities. 3D wall analysis was developed using FEM to obtain the optimal configuration of blocks with multi-recesses. Results indicated that the thermal conductivity of the material, the size and configurations layout of the recesses influence the heat transmission through the wall. Later, the same authors tried to refine the mechanism of heat transfer process using FEM and the response surface approach. It was observed that the heat transmittance was minimized by increasing the surface radiation emissivity of the recesses [43].

Zhou et al. [44] examined the thermal efficiency of inserting a gypsum layer within concrete wall panel system numerically (using ABAQUS) and experimentally. Data from their tests and modeling have demonstrated that gypsum improves building envelope thermal insulation by 1.1°C.

Fioretti and Principi [45] investigated numerically using FEM the influence of radiation within the cavities for hollow clay bricks. Many coating substances with varying emissivity coefficients have been painted on the internal faces of the cavities. The results revealed that with a surface of 0.1 emissivity, the thermal conductivity of the bricks could be reduced up to 45 percent by coating the inner faces of the cavities.

Al-Tamimi et al. [46] used finite element model in ABAQUS to evaluate the optimal configuration of cavities for concrete blocks which could reduce the thermal conductivity of the wall. 23 models of blocks with various hollow shapes, regular and staggered arrangements were examined and the conduction, convection and thermal radiation within the cavities were also considered in accordance with EN ISO 6946. The findings revealed that the 51 percent hollow ratio will decrease the concrete brick's

average inner surface temperature by 7.18 °C. Further, it was observed that the heat flow for blocks with the same hollow ratio could be affected by the shape, number, and layout of the holes. Moreover, it had been found that the thermal efficiency of rectangular shapes was better compared to circular forms.

The thermal efficiency of hollow building blocks packed with phase change materials (PCM) using COMSOL software was numerically analyzed by Kant et al. [47]. Three types of commercial PCM (Capric acid, Paraffin and RT-25) were utilized to fill the blocks cavities. The study found out that the performance of capric acid was more efficient compared to the other two forms of PCM. For Capric acid, Paraffin and RT-25, the heat flux was reduced by 8.31, 6.07 and 3.61%, respectively.

The reduction of heat flow across walls using the finite volume technique was studied by Li et al. [48]. Clay hollow blocks with five rows of holes were used to build the wall and each row had five cavities. To achieve the best filling effect of the EPS, expanded polystyrene board (EPS) was used to fill the cavities with varying quantities and positions. Results revealed that the average decrement rates of the low EPS filling ratio (20 percent) had a greater effect on inner surface heat flow by 21.19%. Also, the external filled cavities had approximately (5.3-10.9%) higher decrement rates of inner surface heat flow than internal block cavities for all ranges (20-80%).

Hongxia et al. [49] analyzed numerically the heat transfer efficiency of a sintered coal gangue self-insulation block (SCGSB) and correlated its output with ordinary clay block. ANSYS software was used to simulate the blocks with staggered small rectangular cavities and two distinct thicknesses. The analysis indicated that, relative to clay block, SCGSB with cement mortar and the same thickness may save 50% energy,

while SCGSB with special mortar and 240 mm thickness could save up to 65% energy, relative to clay block with cement mortar.

Martínez et al. [50] studied experimentally and numerically the thermal efficiency of concrete blocks using different scenarios such as different material properties (normal and medium density), six various geometric arrangements and the inclusion of several insulated materials (extruded cardboard, rigid EPS and injected foam) within CMU cells. The results showed that considering the air flow inside the cells was vital as it contributed to the heat flow. Also, the density had a major impact on the behavior of the CMUs as the thermal resistance of the normal weight was 42% less than the medium-weight unit. Furthermore, the polyurethane foam was the best filled material with R-value 323% and 403% for normal and medium concrete blocks, respectively, less than the control one.

Friaa et al. [51] conducted a three-dimensional model using ABAQUS software to predict the effective thermal properties of a concrete masonry wall. The wall consisted of hollow blocks with air-filled cavities, regularly connected by head and bed joints. The study found out that the equivalent thermal conductivity is highly dependent on the integrated influence of heat conduction, normal convection and cavity radiation. Also, the number and configuration of holes impacted the equivalent thermal conductivity.

CHAPTER 3

Journal Article 1

Development of Energy-Efficient Hollow Concrete Blocks in the Field Using Perlite, Vermiculite, Volcanic Scoria and Expanded Polystyrene.

3.1 Abstract

The vital keys of sustainable development program are solving the issue of conventional energy usage and identifying appropriate alternative supplies. Many new thermal insulation materials have been founded in recent years to improve energy efficiency and reduce environmental impact. Because of characteristics like as low density, strong heat resistance, and cost effectiveness, these goods have shown their value in structures. Thermal insulation's effectiveness is determined by its thermal conductivity and capacity to retain its thermal properties over time. In this regard, new configuration of hollow concrete block was fabricated in the field and four various kinds of hollow concrete blocks were produced to assess the effectiveness of such concrete blocks in market. In addition, based on the experimentally measured thermal resistance, the economic feasibility, fuel energy usage, and CO₂ emissions were calculated. The results proved that all the newly developed blocks (perlite, vermiculite, scoria, and polystyrene) fulfilled the standard requirement by ASTM C129 for non-load bearing blocks for both compressive strength and absorption. In addition, the perlite and scoria blocks are categorized as light-weight concrete blocks as they had the lightest weight of (15.19 kg) and (17.07 kg) which lower by 25% and 15%, respectively, contrasted with the block controls (without insulation materials). Therefore, they had the highest reduction of thermal conductivity of almost 60% occurred on the scoria and

perlite as compared to that of the commercially produced in the market. Furthermore, a cost analysis found that the scoria block is the most affordable. When compared to normal market blocks, the best scoria wall may enhance heat resistance by roughly 144%. In terms of net present value (NPV) for 40 years, this solution might cut energy consumption from 272 to 109 \$/m². The VS-wall may reduce CO₂ emissions by a factor of 2.4 when compared to a commercial concrete block and a factor of 1.15 when compared to a control wall. Using by-products to make greener concrete masonry units that meet industry standards has the potential to save natural resources and energy while also benefiting the environment. Additionally, savings in concrete manufacturing and landfill site expenditures would contribute to the economic benefits of the strategy.

Keywords: Perlite; Vermiculite; Volcanic Scoria and Expanded Polystyrene; Strength; Thermal conductivity; Economic evaluation; Oil fuel usage; Emissions of carbon dioxide.

3.2 Introduction

The use of air conditioning is irreplaceable in Saudi Arabia due to the hot and arid climate which could reach 45 °C during the summer months [1]. Therefore, the consumption of energy in terms of electricity increased rapidly as the building sector consumes around 74% of the total electricity produced in Saudi Arabi and air conditioning accounts for approximately 67% of the total building's electrical consumption in Dammam city [2]. Further, the air conditioning absorbs around 71% of the total electricity in the hot climate like Jeddah while it accounts about 40% for the milder climate like Abha [2]. Other major factors are known as minor factors to contribute for energy dissipation, such as growing income, population growth and energy efficiency [3]. Therefore, the consumption of electricity will be increased to

provide a convenient indoor environment. Saudi Arabia's population is rising rapidly, as in many other countries around the world, and the demand for energy is increasing. KSA recorded a dramatic rise in electricity consumption between 2000 and 2020 because of rapid economic development. The peak demand for electricity jumped from 50 GW to 60 GW during time from 2012 to 2017, and by 2020 it is forecast to reach 70 GW [4]. During 2009-2017, the Saudi Electric Company invested at least SR 380 billion to satisfy this need [5]. There is also a critical need to establish policies for the use of resources that would promote sustainable growth. The Saudi Energy Efficiency Center (known in Arabic as KAFAA) has been established with the main objective of controlling energy usage in response to the increased concern about excessive power consumption in KSA. More than \$1.5 billion might be saved over the next 20 years if strong energy efficiency regulations are enforced, which would reduce the estimated power consumption by 5 to 10% and result in an extra capacity of 3 to 6 GW. As a result of these estimations, it has been determined that the government might save up to \$0.25 billion a year by adopting energy saving techniques and lowering air conditioning demand. [6]. The economy of KSA is heavily reliant on fossil fuel supplies, namely oil reservoirs, the decline of which would adversely affect the country's future growth. The overall demand of energy is rising annually by about 5-8%, which will result in the production of oil and oil demand being equal in 2035. It is because of this that the necessity for better thermal insulation in building envelopes has been revealed to the public, and a large number of researchers have investigated the existence of such materials [52][53][54]. Since much of the thermal load is transmitted via building walls, the use of ideal building materials in building walls may greatly minimize the load of thermal transmission to use less energy for cool buildings. The hollow concrete blocks are the most common building material used in wall

construction in Saudi Arabia. Therefore, new blocks will be developed in the field to reduce the thermal conductivity so that the energy consumption for both domestic and industrial buildings will be less.

Many researchers have used perlite, vermiculite, volcanic scoria and expanded polystyrene in concrete masonry blocks to improve heat insulation [11]–[13], [55], [56]. For instance, Topcu and Iskdag [57] studied the effect of using perlite as a lightweight aggregate in clay bricks. It was concluded that 30% of perlite was found to be the most suitable ratio as it reduces the thermal conductivity to 0.215 W/m.K as contrasted to control bricks with 0.465 W/m.K. Al-Hadhrami and Ahmad [20] assessed a complete program on two types of concrete blocks and nine kinds of clay bricks in Saudi Arabia. The study was for thermal performance efficiency of the ability to add insulation materials like polystyrene and perlite inside the holes. The results proved that filling the insulation materials inside the cavities or mix it within the masonry brick decreased the thermal conductivity significantly. The thermal resistivity increased by around 50% by adding perlite into the holes of concrete blocks. Sengul et al. [23] provided more details about the influence of perlite on the lightweight concrete thermal conductivity and mechanical properties. Perlite with various dosage from 20% to 100% replaced natural aggregate and mixed with superplasticizer and air entraining admixture. The results proved that substitution of 60% of perlite decreased the thermal conductivity and strength by 42% and 84%. Al-Tamimi et al. [34] added a 30% of perlite to a new designed concrete block to minimize the demand for air conditioning. The result of the thermal conductivity of perlite block was 0.309 W/m K which had significant reduction of 33% contrasted to the control block without insulation. Al-Jabri et al.[10] suggested that vermiculite is not viable to produce concrete blocks due its low compressive

strength while polystyrene is an effective material for producing lightweight concrete block to be applied in non-load bearing walls. Al-Awsh et al.[33] examined the efficiency of concrete walls to reduce the heat transfer through buildings by using vermiculite (VL), volcanic scoria (VS) and expanded polystyrene (EPS) as insulation materials to replace coarse and fine aggregates. vermiculite, and volcanic scoria replaced the coarse aggregates by 5% and 45% by weight, respectively, while EPS was used as replacement of coarse aggregate by volume of 12%. The results showed that all blocks satisfied the minimum required strength by ASTM C129 (3.45MPa) while the thermal conductivity for the VL, VS and EPS blocks was 0.383, 0.34 and 0.371 and W/m K, respectively. Hossain [58] examined the use of volcanic scoria as coarse and fine aggregates on the potential industrial utilization. The results proved that scoria fulfilled the required strength and density by ASTM standards. Likewise, scoria could be used as heat-insulating material in building construction as it had a low thermal conductivity between 0.15 to 0.4 W/m.K.

Xu et al. [24] used expanded polystyrene beads (EPS) to produce lightweight hollow concrete blocks. Three dosages of 15, 20, and 25% by volume of EPS were prepared to examine its effects on density and compressive strength. The results showed that the most critical parameters for determination density and strength were EPS dosages and water to cement ratio and as the mentioned parameters increased, the density decreased as well as the compressive strength. Sassine et al.[59] did a case study about the efficiency of expanded polystyrene (EPS) to enhance the thermal resistance of hollow concrete blocks. 0, 6, 12, and 18 g of EPS were used to prepare four different hollow concrete blocks and determine their thermal resistance experimentally. The results displayed that the thermal resistance for the blocks were 0.16, 0.2, 0.25 and 0.31 m²·K/

W, respectively. Thus, the addition of 18 g of EPS to the mixture will reduce the thermal conductivity by almost double.

This study attempts to demonstrate the industrial viability of manufacturing hollow concrete blocks using Perlite, Vermiculite, Volcanic Scoria, and Expanded Polystyrene. The mix designs employed in this investigation were determined after a series of laboratory scale trials [33], [34]. Mechanical properties were evaluated at 7, 28 days to meet ASTM C-129 criteria for 4.14 MPa compressive strength (for non-load bearing walls). Density and water absorption experiments were performed to assess physical qualities. Moreover, the heat flow meter method was employed to evaluate the thermal resistance and conductivity after 28 days. The technical viability of the mixtures and the overall production costs of all blocks were also evaluated economically.

3.3 Experimental Work

3.3.1 Materials

The detailed information about the materials used were described below:

a. Cement

The cement employed in this study was ASTM C 150 Type I Portland cement, which is a type of cement that is extensively used in the construction industry in Saudi Arabia. With a specific gravity of 3.15, a thermal conductivity of 0.44 W/m.K, a melting point of 1450 °C, and all other properties that met the standards of ASTM C 150 [60][61].

b. Fine and Coarse Aggregate

Dune sand, which is plentiful in this area, was used as the fine material for this project. The fine aggregate utilized had a specific gravity of 2.56 and 0.6 percent water absorption. The coarse aggregate used was crushed limestone rock in two sizes: 3/8

inch (9.53 mm) and 3/16 inch (4.76 mm), all of which had a specific gravity of 2.60 and a 1.10 % water absorption rate.

c. Perlite

It's a natural material with good acoustic and thermal insulation capabilities that is porous, lightweight, fire resistant, and has excellent porosity [62]. Table 1 presents the chemical structure of perlite which depict the presence of silica, potassium, alumina, calcium, and magnesium[63]. Lightweight perlite had a dry loss density between 80-150 kg/m³ and a thermal conductivity coefficient of 0.04–0.06 W/mK [53]. Perlite's water absorption was exceptionally high, around 100% of its weight, due to its porous nature [34]. Figure 2-(a) shows the size of light-weight perlite aggregates with a maximum sieve size No.4.

Table 1: Chemical composition of expanded perlite [63]

Constituents	O	Ca	Na	Si	K	Al	Mg	Fe	Trace	Water
Weight %	47.5	0.6	3.40	33.8	3.5	7.2	0.2	0.6	0.48	3.0

d. Vermiculite

Vermiculite is a multi-layer micaceous mineral (Chemical hydrated magnesium aluminum silicate). Vermiculite expands 15 times in volume when heated up to 1600°F or subjected to chemical reactions. As a result of the expansion, the substance's moisture absorption (reaches up to 450%) and water retention capacities are enhanced, while also allowing for free air flow [64]. The Arabian Vermiculite Industries Company in Dammam, Saudi Arabia, provided the natural vermiculite. As shown in Figure 2-(b), the vermiculite aggregate utilized in this study had a size range from 0-3mm and a density of 100 kg/m³ and a thermal conductivity of 0.06 W/m.K [60]. The composition of Vermiculite used is reported in Table 2 [65].

Table 2: Composition of vermiculite [65]

Materials	SiO ₂	MgO	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	CaO	TiO ₂	Others	L.O. I
Weight %	46	16	16	13	4	3	2	0.6	0

e. Volcanic Scoria

Volcanic basaltic rocks are the primary source of the lightweight material known as scoria. A total of 180,000 square kilometers of these rocks may be found scattered throughout thirteen distinct lava fields known as Harrats[11]. As scoria contains trapped air, it reduces the weight of concrete and improves its insulating properties. Coarse scoria lightweight aggregates (4.76 and 9.53 mm) were utilized in place of the typical coarse aggregates, as illustrated in Figure 1. Its thermal conductivity is 0.27 W/mK, and its absorption rate is 11% while it has a density of 1500 kg/m³[66].



Figure 1: Volcanic Scoria Coarse aggregate (a) VS (# 3/8 in) (9.52mm); (b) VS (# 3/16 in) (4.76mm)

f. Expanded Polystyrene (EPS)

A common method of producing expanded polystyrene is to evaporate the pentane that has been mixed with the polystyrene grains before molding them. As a result of this technique, a white, rigid, closed-cell foam is produced, with thermal conductivity of

0.036 W/m, density ranging from 15 to 75 kg/m³, and water absorption of 1.5% [53]. The higher the density, however, the better insulation performance is achieved. EPS utilized in this project was procured from AL-Rashed Polystyrene factory in eastern Saudi Arabia with a size of beads ranged from 5 to 7 mm in diameter, Figure 2-(c).

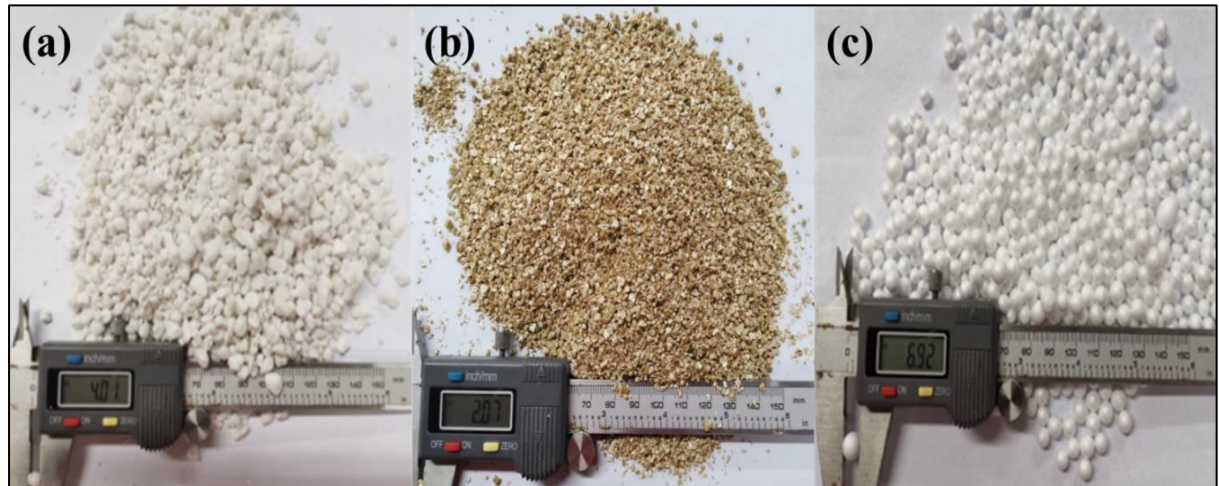


Figure 2: Shape and average sizes in mm of (a) Perlite; (b) Vermiculite; (c) Polystyrene

3.3.2 Mix Proportions

After a long period of experimentation in the laboratory, the mix proportions employed in the field this time were based on earlier investigations [33], [34]. The proportion of the three-replacement inclusion was selected as a balance between thermal and mechanical performance. In the first mix, which considered as a control mix with no inclusion of any insulated materials, but in the second mix, fine aggregate was replaced by 30% perlite whereas 5% vermiculite was added as a replacement of coarse aggregate by weight in the third mix. The fourth type of insulated blocks were made with a ratio of 0.45 scoria coarse aggregate to fine aggregate. Finally, as indicated in Table 3, 14 % expanded polystyrene was employed to replace coarse aggregate by volume. With no usage of superplasticizer, w/c ratios were fixed at 0.495 in all combinations.

Table 3: The mix design for 1 m³

Materials	Control	Perlite	Vermiculite	Scoria	Polystyrene
Cement content (kg)	195	250	250	195	195
Water content (kg)	115	154	208	173	115
w/c ratio	0.495	0.495	0.495	0.495	0.495
Coarse aggregate (# 3/8 in) (9.52mm) kg	1132	339	856	-	755
Coarse aggregate (# 3/16 in) (4.76 mm) kg	338	226	256	-	226
Fine aggregate (Sand) (kg)	451	264	359	792	576
Replacement materials (kg)	-	113	58	648	2.23
Percent of replacement (%)	0	30	5	100	14

3.3.3 Preparation the Innovative Block Steel Mold

Our team created a 400 × 200 × 200 mm new block steel mold for manufacturing usage [34]. The design was determined after extensive finite element analysis (FEM). The selected design was chosen for its low heat conductivity without affecting other mechanical properties. Several elements collaborated to control heat flow through hollow blocks. All these variables were determined by considering the hollow ratio (HR), aspect ratio (AR), cavity width, thermal bridges, and quantity and arrangement of cavities [46]. From a technical and practical point of view, a modest change in the specifications of the thickness of the thermal bridge was advised this time for field production of the mold. As a result of this, the weak point that connects the two portions of the block specimens was enlarged to 35 mm in thickness. Figure 3 shows the block mold dimensions as per ASTM C129 [67].

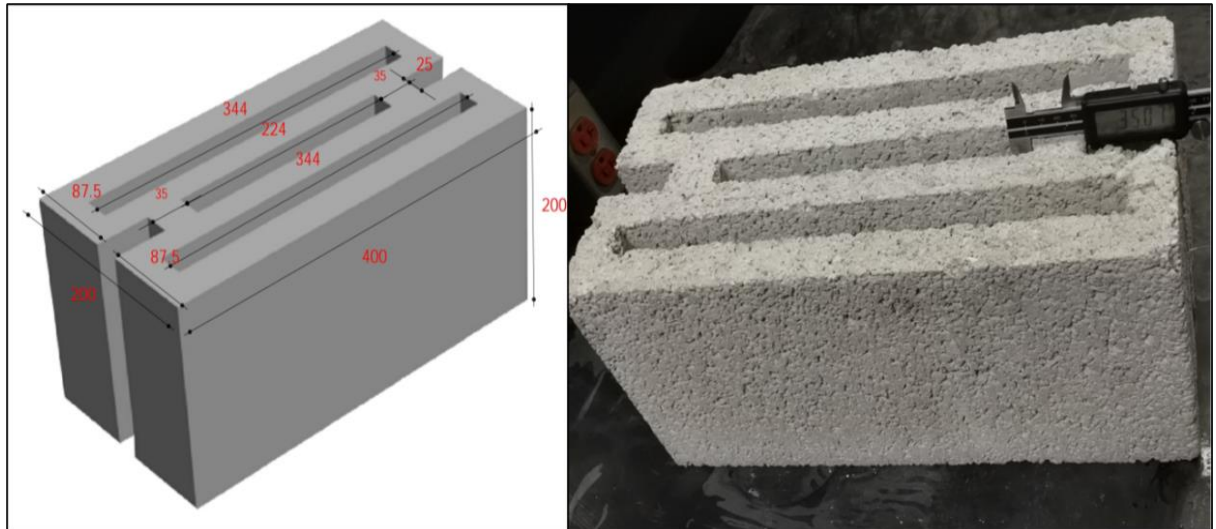


Figure 3: Geometry and dimensions of the fabricated blocks

3.3.4 Mixing, Casting and Curing Specimens in the Factory

The hollow concrete blocks were made commercially at Advance Concrete Products in Dammam's Second Industrial Area utilizing the specified mix proportions. The replacement materials were added after the aggregates were weighted and mixed for 3 minutes with cement and water in a concrete mixer with a maximum capacity of 1500 kg. After homogenizing the concrete mix, it was delivered by forklift with a hooper to the automatic concrete block production machine. After roughly 15 seconds of compaction and vibration with 70 kPa pressure, the mould was removed, and the hollow concert blocks were eventually formed as shown in Figure 4-a. After this, the blocks were covered with burlaps and polyethene plastic sheets to avoid water evaporation (Figure 4-(b)).



Figure 4: Manufacturing process (a) blocks making machine; (b) blocks covered with burlaps and polyethene sheets

3.3.5 Testing Specimens

A total of 63 samples were cast to assess the compressive strength, density, absorption, and the thermal conductivity as clarified in Table 4.

Table 4: Total number of specimens and the standards applied

Test type	Standard	Specimen number for each mix	Total number of specimens	Testing age
Compressive strength	ASTM C129	6	30	7, 28 days
Density and absorption	ASTM C140	3	15	28 days
Thermal conductivity	ASTM C518	3	18	28 days

a. Compressive Strength

Each kind of block was tested for compressive strength using three full size specimens at 7 and 28 days curing according to ASTM C140 [68]. All tests were performed using an ASTM C1716 universal testing machine (MATEST) with a 3000 kN loading capability[69]. In accordance with ASTM C1552 (Figure 5), the top and bottom of the blocks were sealed with a 1 cm thick cement/sand mortar (1:3) [70]. For a uniform distribution of weight over the block's cross-sectional area, a solid steel plate was put on top and bottom of the block. In this case, the force was delivered at 0.5 kN/s till failure. By dividing the maximum load by the average net area of three absorption specimens, the net area compressive strength is derived. The ASTM C129 specifies that non-load bearing blocks should have an average net area compressive strength of 4.14 MPa [67].

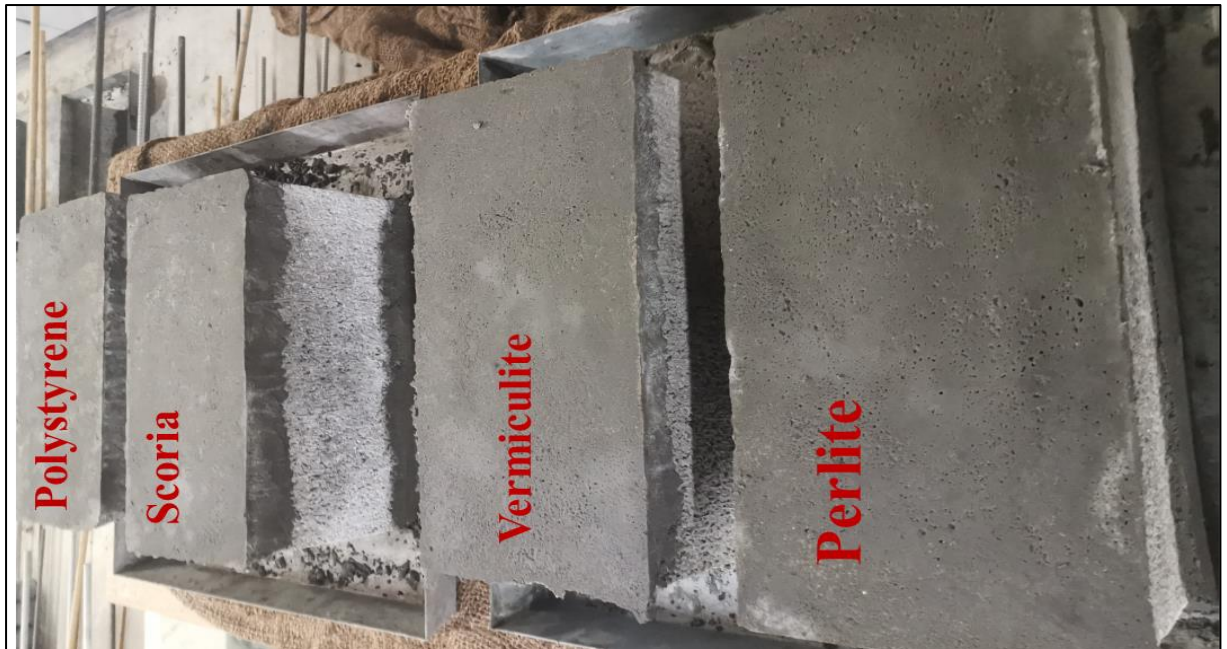


Figure 5: Capping specimens for compressing test

b. Density and Absorption

The ASTM C140 was used to evaluate the oven-dry density and absorption of three types of hollow concrete blocks [68]. Each sample was weighed after 24 hours in 25°C water (W_i). The samples were weighed while suspended on a metal wire and completely submerged (W_s) as shown in Figure 6. Then, they were taken from the water for 1 minute and wiped clean of any apparent surface water. At 110 °C for no less than 24 hours, the specimens were heated in an air ventilated oven until two consecutive weighings at two-hour intervals indicated an additional loss of no more than 0.2% of the previously computed specimen weight (W_d).

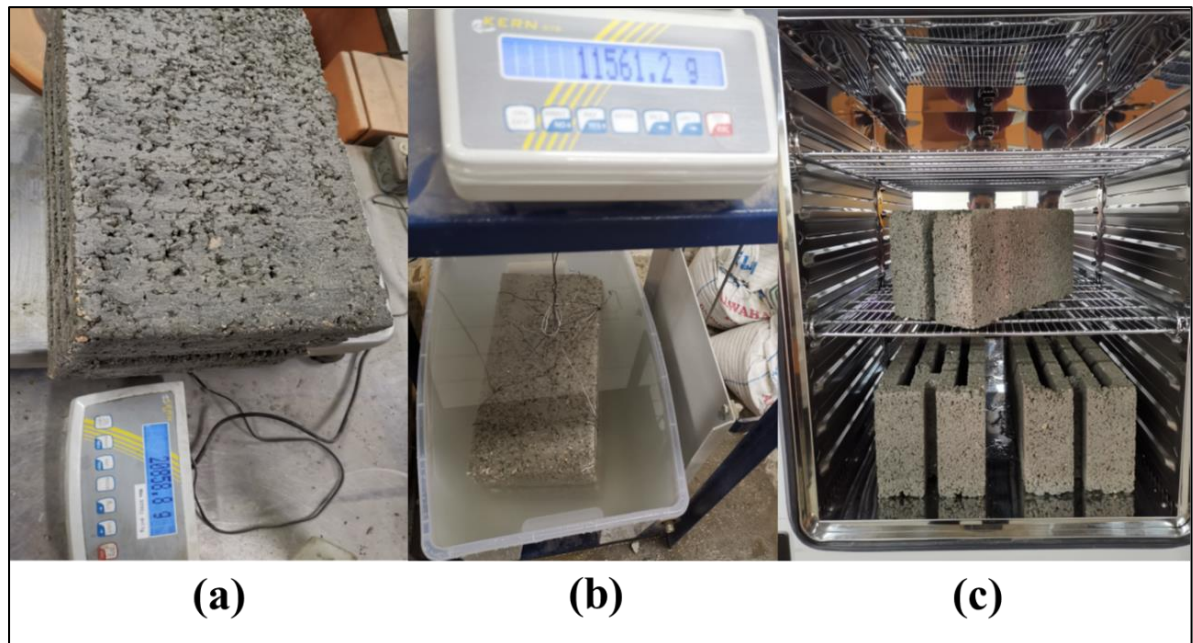


Figure 6: (a) Immersed weight (W_i); (b) Saturated weight (W_s); (c) Oven-dry weight (W_d)

c. Thermal Conductivity

In accordance with ASTM C 518, the thermal conductivity of hollow concrete blocks was evaluated with a FOX600 heat flow meter [71]. A serial RS-232 interface connects the FOX600 to an air pump, cooling unit, and computer, as shown in Figure 7-(a) [72].

During the test, a 610×610 mm specimen with a thickness of up to 203 mm is placed between two plates of varying temperatures [72]. The heat flow meter can test materials from 0.01 to 0.35 W/m.K, with external thermocouples up to 2.5 W/m.K [72]. As illustrated in Figure 7-(b), a full-size specimen was examined on its own from each type, then two blocks were connected using standard mortar to evaluate the effect of the thermal bridge produced between the blocks (double-blocks). Prior to evaluating the selected samples, a reference sample with known thermal conductivity values at different temperatures was used to calibrate the measurement instrument. The samples were then dried in an oven at 60°C for 48 hours to guarantee that moisture in the concrete did not alter the thermal conductivity measurement. Then the cavities had to be adequately sealed to prevent air leakage and heat loss. The remaining area of the guard heater was covered with a polystyrene board to prevent heat from being disbursed in transverse directions, as illustrated in Figure 7-(c). Also, on both sides of the specimen, rubber sheets were also applied so that the plates would not lose heat owing to friction. The test specimen's upper and lower faces were held at 45 and 20 °C, respectively, with an average temperature of 32.5 °C. In order to improve measurement precision, thermocouples are attached directly to the sample surfaces. A direct calculation of thermal conductivity was calculated by utilizing heat flux, temperature difference, and sample thickness.

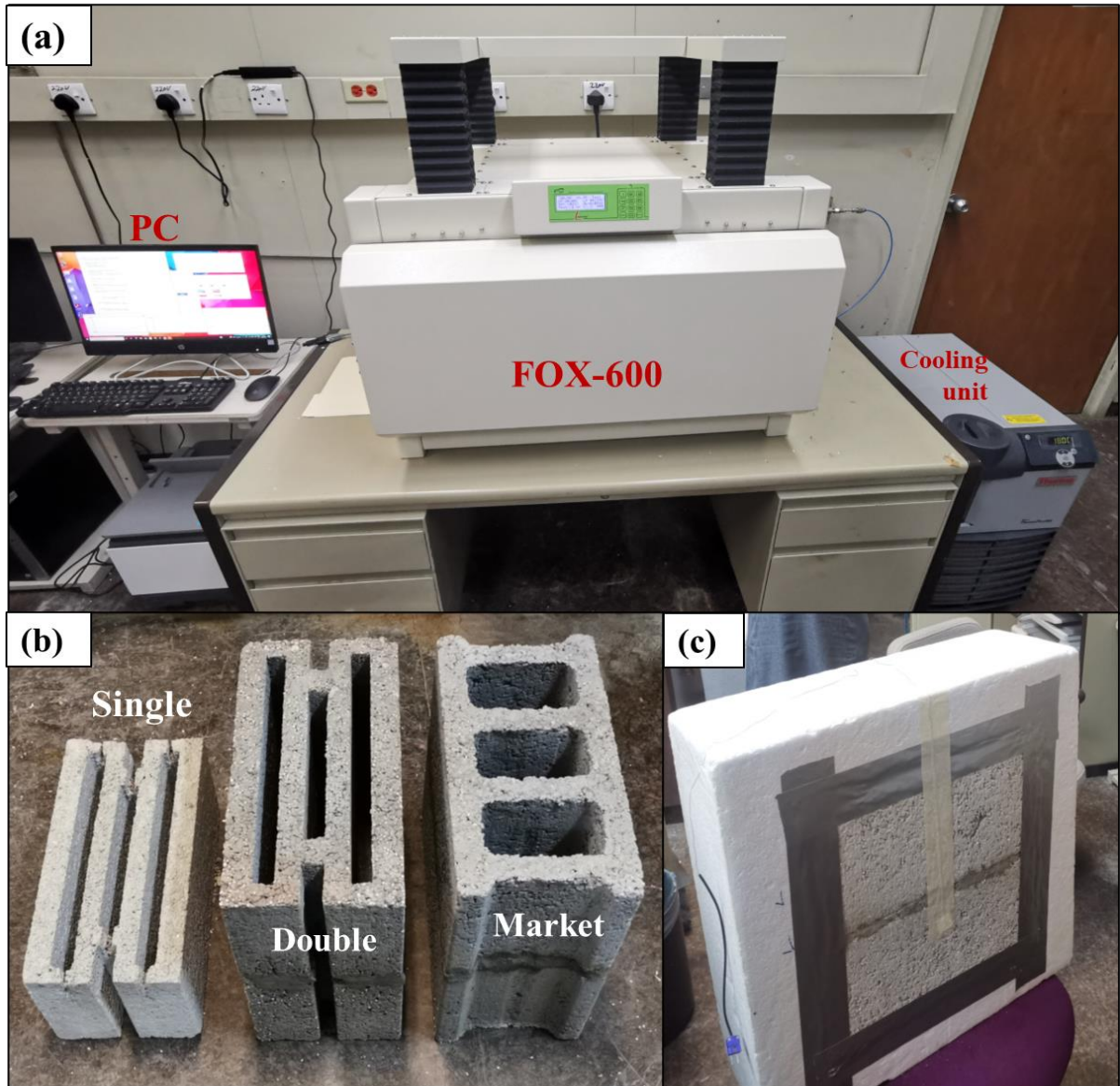


Figure 7: (a) FOX600 instrument setup; (c) Tested specimens; (b) Samples preparation

3.4 Results and Discussions

3.4.1 Compressive Strength

A compressive strength experiment was performed at 7 and 28 days after the production of the hollow concrete blocks to evaluate their commercial viability. Average Net-area compressive strength data were shown in Table 5 and Figure 8 for each of the four mixes. After seven days of curing, the control block's strength was 5.64 MPa, whereas

the perlite and vermiculite blocks' strengths were almost 30% lower than the control blocks. While the scoria and polystyrene blocks had only a drop of 10%. At 28 days of curing time, the control, scoria, and polystyrene blocks had almost the same strength of 6 MPa and the strength of perlite and vermiculite decreased by 20% compared to the control one. The compressive strength of the perlite and vermiculite particles was the lowest due to their water-absorbing characteristics as well as their nature because they are weak materials [25], [60]. Adding to this, perlite reduces hydration heat and requires a long curing period [73]. Also, Evaporation or dissipated moisture can produce a decrease in hydration in the capillary pores, which in turn can lead to a reduced strength [74]. For polystyrene block, it is possible that the smooth surface and rounded shape of polystyrene materials caused less of an adhesive bonding between the polystyrene particles and cement paste, causing a lower compressive strength [35], [75]. It is noteworthy that the strength increased by 20% between 7 and 28 days as an effect of curing. ASTM C 129 specifies a minimum 28-day standardized requirement of 4.14 MPa for non-loadbearing blocks. Consequently, all the manufactured blocks met these criteria, as highlighted in Figure 8.

It should be emphasized that the strength for the blocks produced in the factory should not increase dramatically compared to once produced in the laboratory[27], [76]. Although the compaction and vibration method using automatic concrete block production machine could reach a pressure up to 70 kpa while in the laboratory scale it compacted manually. This could be ascribed to the effect of weather condition in the field and curing methods[22].

Table 5: Results of oven-dry density, unit weight, absorption, and compressive strength (at 7 and 28 days)

Block type	Oven-dry density (kg/m ³)	Weight/Block (Kg)	Water Absorption		Average Net-area compressive strength (MPa)	
			(kg/m ³)	(%)	7 days	28 days
Control	2091.15	20.17	178.94	8.56	5.64	6.33
Perlite (30%)	1544.37	15.19	198.77	12.87	3.84	5.05
Vermiculite (5%)	1981.57	18.93	213.53	10.78	3.68	5.14
Scoria (45%)	1672.52	17.06	147.11	8.80	5.09	6.54
Polystyrene (14%)	1926.44	19.50	123.23	6.40	4.77	6.26

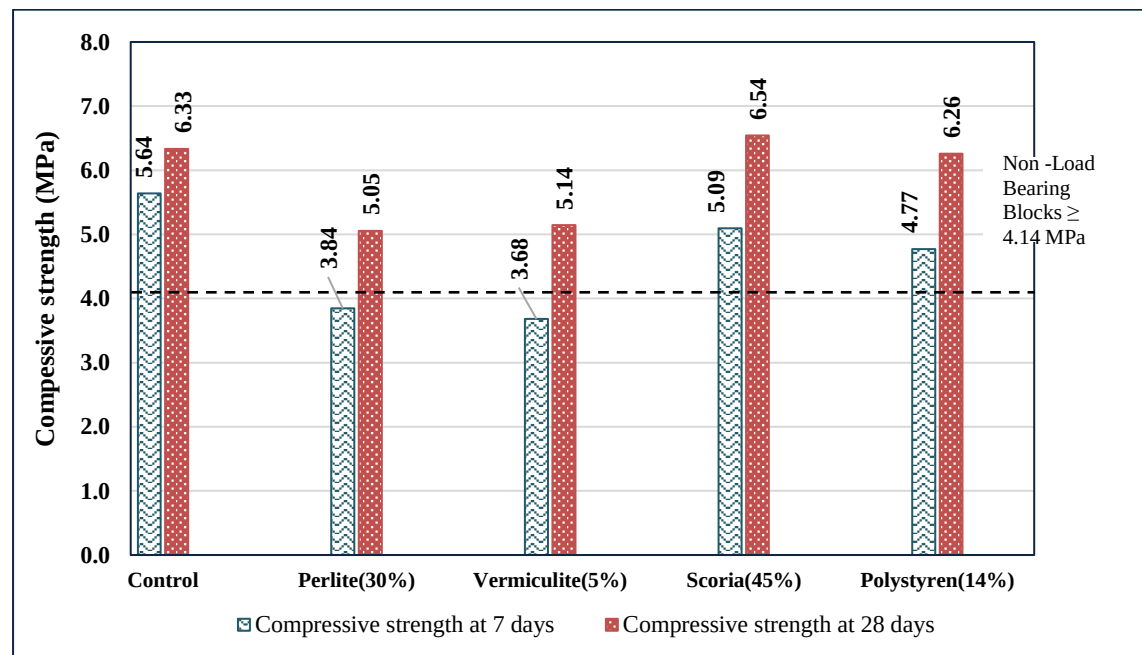


Figure 8: Compressive strength of the produced blocks at 7- and 28-days curing period

3.4.2 Oven-dry density, Unit weight and Absorption

Each of the five kinds of the produced concrete blocks (Control, Perlite, Vermiculite, Scoria and Polystyrene) manufactured had its oven dry densities, unit weight and absorption listed in Table 5. The control block had the highest oven dry density of 2091.15 kg/m³. When compared to control block without replacement, the perlite and

scoria blocks had the highest density loss of 26.15% and 20%, respectively. High inclusion ratio of perlite in the mix by 30 %, the drop in coarse to total aggregate ratio (from 0.765 to 0.6) and the light density of perlite particles itself which had a density of 150 kg/m^3 were both responsible for this high reduction. While replacing all limestone aggregate in Scoria block by volcanic scoria aggregate (light aggregate) was the main reason for the reduction in density compared to control block as illustrated in Figure 9. Although Vermiculite and polystyrene particles had the lowest density relative to the other materials, they had the lowest reduction on density by only 5% and 7% which attributed to low percentage of inclusion on the mixture. It should be noted that any block with an oven-dry density greater than 2000 kg/m^3 is considered a normal aggregate concrete block in ASTM C129, whereas blocks with densities between 1680 and 2000 kg/m^3 are considered medium weight and blocks with densities lower than 1680 kg/m^3 are designated lightweight blocks [67]. According to this standard, the perlite and scoria blocks are categorized as light-weight concrete blocks, whereas the all other types of blocks produced could be considered as medium-weight concrete blocks. Considering the density of masonry concrete blocks is essential for several reasons. First, a lighter building may carry more dead weight, which influences the dimensions of the structure's beams, columns, and foundations, as well as its ultimate construction cost [77], [78].

As illustrated in Figure 10, which shows that the control blocks' water absorption was 178.94 kg/m^3 , whereas the vermiculite and perlite blocks had the highest water absorption of 213.55 and 198.77 kg/m^3 which were higher by 20% and 11%, respectively compared to control block. This may be attributable to the reality that the vermiculite aggregate has a high absorption ability which could reach up to 450% while the absorption ability of perlite is 100% since they are porous in nature[65]. Scoria-

manufactured blocks' water absorption was 147.11 kg/m^3 which was lower than control block by 18%. It was found that polystyrene blocks had the lowest absorption with a value of 123.12 kg/m^3 , attributed to the lack of absorption ability of polystyrene [79]. 208, 240, and 288 kg/m^3 are the ASTM C90 maximum water absorption values for normal weight, medium weight, and lightweight blocks [80]. The absorption ratings for all types of blocks were acceptable and within the standard's range when compared to the criteria of this standard.

Figure 11 indicates that the control block weighed 20.17 kg more than any of the other hollow blocks created from the four different substituted products. In addition, the perlite hollow block was significantly lighter by 5 kg than the control block as it had a weight of 15.19 kg. Aside from that, with a weight of 17.06 kg, the Scoria blocks was 15% lighter than the control block, which is a significant advantage. The vermiculite blocks, on the other hand, weighed 18.93 kg each. Nonetheless, there was only a 3% difference in the weight of the polystyrene block (19.5 kg) to the weight of the control blocks.

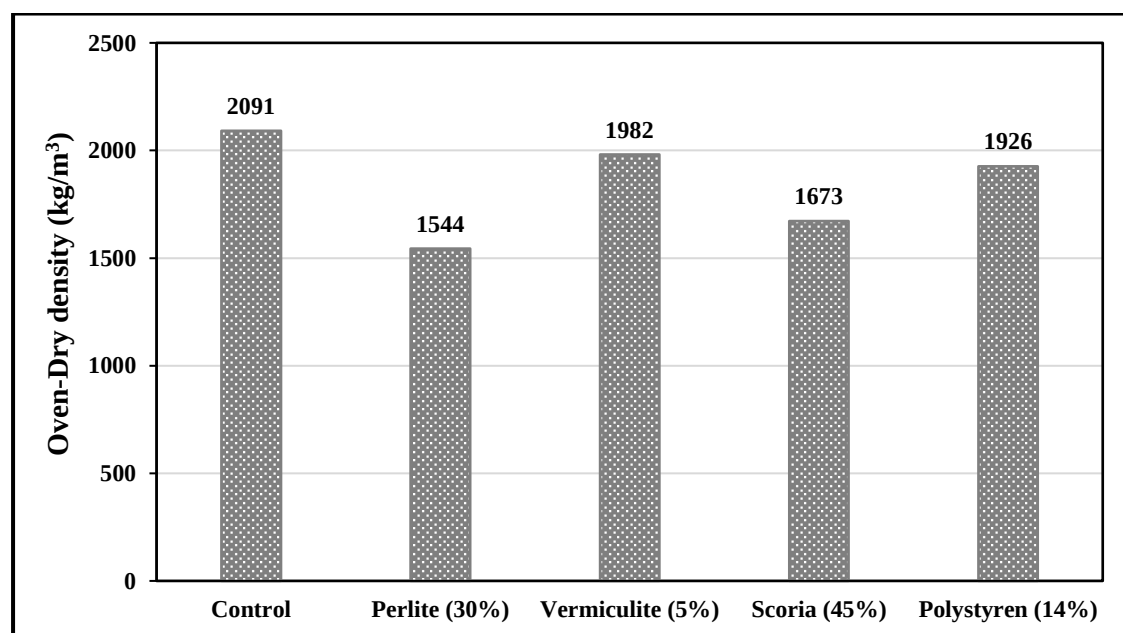


Figure 9: Oven-Dry densities for the blocks (kg/m^3)

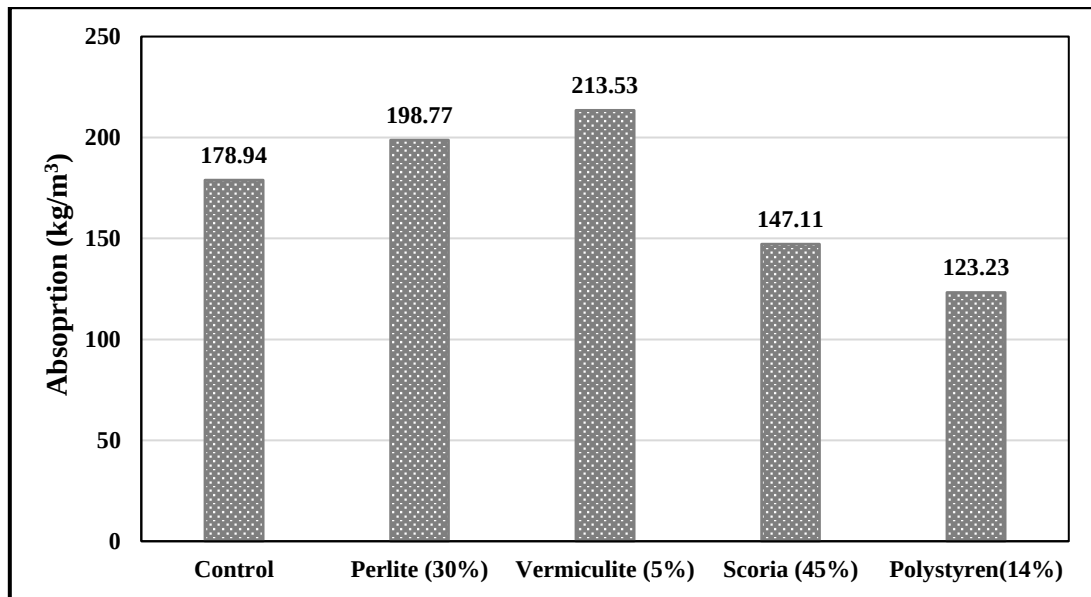


Figure 10: Absorption of the produced blocks per cubic meter

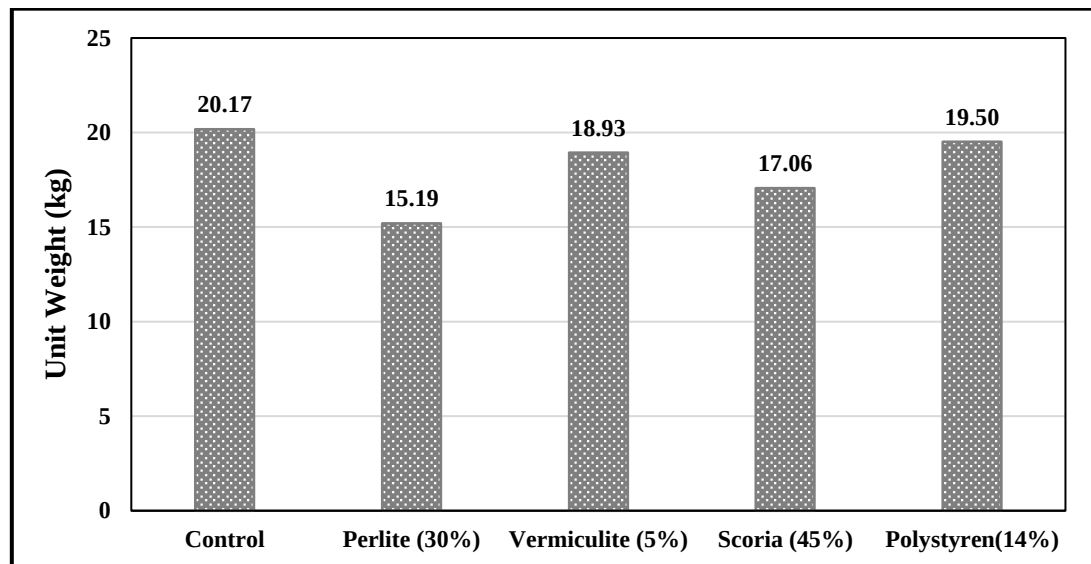


Figure 11: Weigh of the individual blocks

3.4.3 Thermal Conductivity

The density of concrete blocks has a direct impact on their thermal conductivity, as the existence of air spaces inside the concrete reduces its thermal conductivity, referring to the fact that concrete's thermal conductivity is larger than that of air [10]. Two samples of each block type were analyzed independently, and then joined together to determine the effect of the thermal bridge generated by joint mortar on this study. Additionally, it

was compared to a market block with three holes that is commonly used in the construction sector to assess how well it performed. For the single blocks, Table 6 displayed the average thermal conductivity and thermal resistance of each kind, with their improvement and decrease in percentage as compared to the market one, while Table 7 offered that for the double blocks (2-joined blocks). It was discovered that the market block has an average thermal conductivity (k-value) of 0.738 W/m.k. Meanwhile, the average thermal conductivity of control blocks (our design without insulating materials) was reduced by 53% (0.344 W/m.k) when contrasted to the market, which demonstrates that block shape has a significant influence on block performance [50], [81]. As a result of the addition of vermiculite and polystyrene, the thermal conductivity of the blocks remained nearly the same at 0.348 W/m.K and 0.340 W/m.K, respectively, as when compared to the control block, which accounts for a 1% reduction in thermal conductivity ascribed to the fact that the amounts of vermiculite particle and polystyrene used were only 5% and 14%, respectively. In addition, the scoria and perlite blocks showed the greatest reduction in conductivity of all the samples. Comparing thermal conductivity of scoria blocks and perlite to that of market blocks, it was found to be lowered by 59% (0.303 W/m.K) and 57% (0.314 W/m.K), respectively, while it was reduced by 12 % and 9%, respectively, when compared to the control block.

The data for the 2-blocks joined together with cement mortar show a similar trend to the single blocks in terms of a depletion in equivalent thermal conductivity for the produced hollow blocks (53% control, 60% perlite, 54% vermiculite, 61 scoria and 56% polystyrene) as contrasted with the market hollow block which had the highest thermal conductivity of 0.929W/m.K, Figure 12. Further, it could be observed that the effect of

the thermal bridge increased the thermal conductivity by around 20% compared to single block in the market block whereas it was between 5% and 9% on the other types.

In addition, various stringent laws have been imposed to ensure that thermal insulation is installed in all buildings in Saudi Arabia. Specifically, the Saudi building code stipulated that the maximum U-values for exterior walls should not be less than 0.342 W/m².K and the maximum R-values could not be less than 2.92 m².K/W [82]. For individual blocks produced in this study, the R-values range between 0.580 and 0.661 m².K/W, indicating a significant improvement in resistance that might reach up to 144% on scoria blocks when compared to market blocks, which have a resistance of 0.271 m².K/W, as seen in Figure 13. Despite the significant increase in the thermal characteristics of these blocks, the findings of the R-value calculations will fail to perform of the requirements of the Saudi building code regulations. Therefore, additional insulation layers such as polystyrene board will be used to meet the thermal requirements of the building design. The wall thickness may be reduced because of the improved thermal qualities, allowing for more floor space to be made accessible.

Table 6: The average thermal conductivity and resistance of single blocks

Test type	Thermal conductivity (W/m.K)	Reduction in k value (%)	Thermal resistance R (m ² .K/W)	Improvement in R (%)
Market	0.738	-	0.271	-
Control	0.344	53.39	0.580	114.02
Perlite (30%)	0.314	57.45	0.643	137.27
Vermiculite (5%)	0.348	52.84	0.576	112.54
Scoria (45%)	0.303	58.94	0.661	143.91
Polystyrene (14%)	0.340	53.93	0.589	117.34

**Table 7: The average thermal conductivity and resistance of the double blocks
(2-joint blocks)**

Test type	Thermal conductivity (W/m.K)	Reduction in k value (%)	Thermal resistance R (m ² .K/W)	Improvement in R (%)
Market	0.929	-	0.216	-
Control	0.438	52.85	0.457	111.57
Perlite (30%)	0.365	60.71	0.551	155.09
Vermiculite (5%)	0.427	54.04	0.496	129.63
Scoria (45%)	0.362	61.03	0.557	157.87
Polystyrene (14%)	0.405	56.40	0.498	130.55

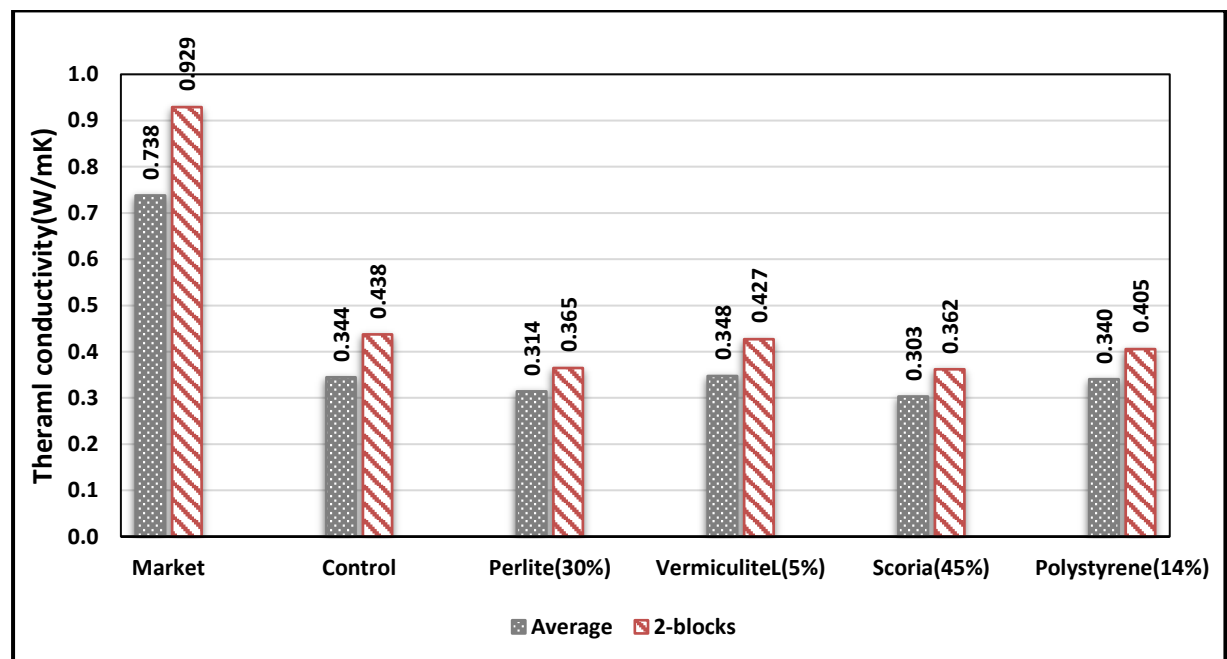


Figure 12: Thermal conductivity of the single and double blocks

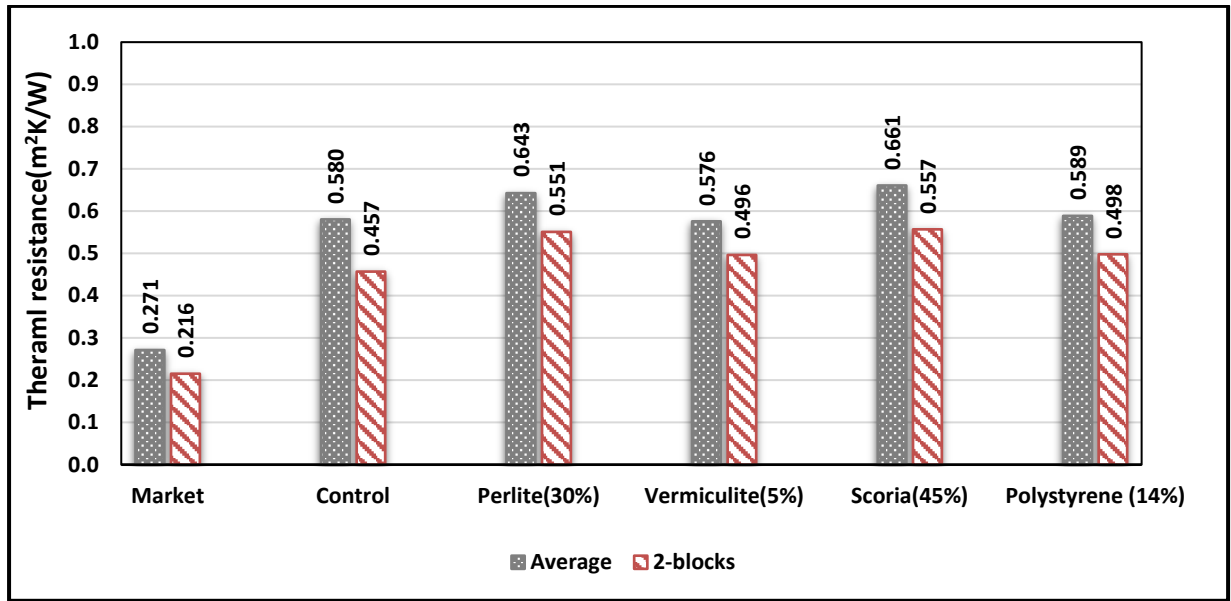


Figure 13: Thermal resistance of the single and double blocks

3.4.4 Cost Analysis

In accordance with the current masonry block market pricing in eastern Saudi Arabia, the overall cost per square meter of each wall, the price of each item in the mix proportions, the operational cost, and the profit rate were all calculated. The costs of the masonry hollow block walls are shown in Table 8, which includes the costs of all the materials. Market concrete blocks currently cost \$0.42 each, while the control blocks in this study cost \$0.41 each. Due to the 0.01 \$/Block disparity between the estimated and market pricing values, all prices and computations have been verified is valid. Newly created blocks are cheapest in scoria by roughly 0.46 \$/block and polystyrene by 0.5 \$/block, respectively. Perlite's high price is mirrored in its block pricing, which is the most expensive at \$1.11 per block.

Table 8: Cost analysis of a masonry wall for 1 m²

Materials	Material cost per unit for the manufactured block walls										
	Materials	Control		Perlite		Vermiculite		Scoria		Polystyrene	
	kg/\$	kg	\$	kg	\$	kg	\$	kg	\$	kg	\$
Cement content	0.060	195	11.70	250	15	250	15	195	12	195	11.70
Water content	0.002	115	0.20	154	0	208	0	173	0	115	0.20
Coarse aggregate (3/8) in	0.006	1132	7.15	339	2	856	5	---	---	755	4.77
Coarse aggregate (3/16) in	0.006	338	2.06	226	1	256	2	---	---	226	1.38
Fine aggregate (Sand)	0.002	451	0.76	264	0	359	1	792	1	576	0.98
Replacement materials (kg)	---	---	---	113	60	58	62	648	13	2	8.92
Σ	0.08	2231	21.88	1346	79.12	1987	85.00	1808	26.30	1869	27.94
Weight/ Brick (kg)		20.17		15.19		18.93		17.06		19.5	
No. of bricks		111		89		105		106		96	
cost/brick (\$)		0.20		0.89		0.81		0.25		0.29	
Operating cost/brick (\$)		0.08		0.08		0.08		0.08		0.08	
Profit (\$)		0.13		0.13		0.13		0.13		0.13	
Total cost/brick (\$)		0.41		1.11		1.02		0.46		0.50	
mortar cost (\$/m²)		0.04		0.04		0.04		0.04		0.04	
wall cost (\$/m²)		5.18		13.87		12.83		5.81		6.35	
Note: the price of Perlite, Vermiculite, Scoria and Polystyrene is 0.53, 1.07, 0.02 and 4 \$/kg											

All the blocks utilized in this study have been subjected to a cost evaluation. If the payback period is to be calculated, the cost of electricity for all types of masonry walls must be taken into consideration. You can figure out how much energy your air conditioner uses by using Eq. (1) which is based on thermal resistance ($m^2 \text{ } ^\circ\text{C} / \text{W}$) of the wall, D equals 2185 K days relying on a temperature of $24.5 \text{ } ^\circ\text{C}$ on Dhahran, Saudi Arabia, and the air conditioner's thermal performance coefficient ($C= 2.16$) [20], [83]:

$$E = \frac{0.024 \times D}{R \times C} \text{ kWh/m}^2 \quad (1)$$

The yearly air conditioning system energy consumption E (kWh/m^2) and the Saudi Power Company's electricity rate (6.67 cents/kWh) were both utilized in Eq. (2) to calculate the annual energy cost for each wall in the current study.

$$EC = ET \times E \quad (2)$$

While the net present value (NPV) of a wall could be estimated utilizing the annual energy cost (EC) , the cost of wall per meter square (BC) and the present worth factor (PWF) as shown in Eq. 3 [20]:

$$NPV = PWF \times EC + BC \quad (3)$$

The PWF may be calculated using the formulae below, where ($i = 2.5 \%$) ,(e = 2%) and (n assumed to be 40 years) represents the discount rate, inflation rate, and the block's lifetime in Saudi Arabia[20], [84], [85]:

$$PWF = \frac{1}{i - e} \left(1 - \left(\frac{1 + e}{1 + i} \right)^n \right) \text{ for } e \neq i \quad (4)$$

$$PWF = n \cdot (i + e) \text{ for } e = i \quad (5)$$

Table 9: Evaluation of the economics of various concrete walls

Wall type	Description	Annual energy (kWh/m ²)	Annual energy cost (\$/m ²)	Annual energy saving (\$/m ²)	Brick cost (\$/m ²)	Increase in brick cost (\$/m ²)	Payback period	NPV (\$/m ²)
Market	Normal	112.40	7.50	0	5.38	0	0	272
Control	Developed	53.12	3.54	3.95	5.18	-0.2	-0.05	131
Perlite (30%)	Developed	44.06	2.94	4.56	13.87	8.49	1.86	118
Vermiculite (5%)	Developed	48.95	3.26	4.23	12.83	7.45	1.76	129
Scoria (45%)	Developed	43.59	2.91	4.59	5.81	0.43	0.09	109
Polystyrene (14%)	Developed	48.75	3.25	4.25	6.35	0.97	0.23	122

The results for yearly air conditioning system energy consumption and the annual energy cost for each type of the produced blocks were addressed in Table 9 and Figure 14. The energy consumption for the market block wall was 112.40 kWh/m² and had a dramatic drop of almost 53% by developing the new design. The consumption would decrease up to 60% when the insulation blocks were used. Based on the Saudi Electricity Company's energy pricing (6.67 cents/kWh), the estimated cost will be 7.5 \$/m² when the market blocks are utilized. This cost will drop to 3.54 \$/m², which means it will save about 3.95 \$/m² by using the control block. The findings confirmed that scoria is the best type of block, saving up to 68.81 kWh/m² and 4.6 \$/m² per year, about 2.6 times less than the market wall, followed by perlite block wall.

To determine the payback period for different types of walls, a payback period analysis is performed. Divide the increase in block costs by yearly energy savings to get it. For each square meter of wall surface, this yearly cost savings is equal to the difference in annual energy costs between walls constructed of developed blocks and those of markets. The annual cost growth for walls is equal to that difference in cost per square meter. The payback period for the scoria was only 0.09 years since it had the lowest material cost. Due to the higher cost of the raw materials (vermiculite and perlite), the payback period for these materials was 1.86 and 1.76 years, respectively. When selecting thermal insulation block types, payback durations and energy savings rates are among the most significant considerations. The net present value (NPV) is the most critical consideration when determining which insulating block to utilize, as stated in Equation (3), since it considers both the annual energy usage and the block costs.

A comparison of the net present value (NPV) of the produced walls shows that the scoria block wall had the least NPV of all the ones considered. It was 60% less than the market block. In addition, the market concrete block's NPV is 272 \$/m². The NPV might be decreased to \$131 per square metre by altering the shape of market concrete blocks (i.e., the NPV was reduced by around 52%). As a result, the best wall (scoria block) enhances heat resistance by 158% when compared to commercial concrete blocks. Improvements like these might lower net present value from 272 to 109 \$/m² which nearly 2.5 times, as illustrated in Figure 15. Traditional block walls should be replaced with the VS wall in Saudi residential and commercial construction.

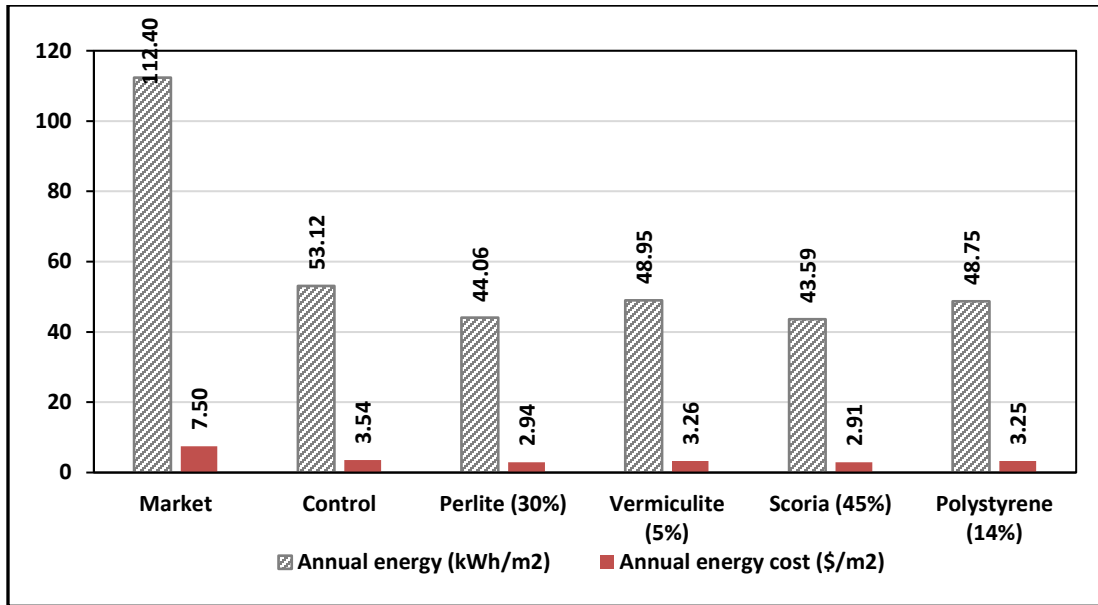


Figure 14: Annual energy consumption and cost for the developed masonry walls

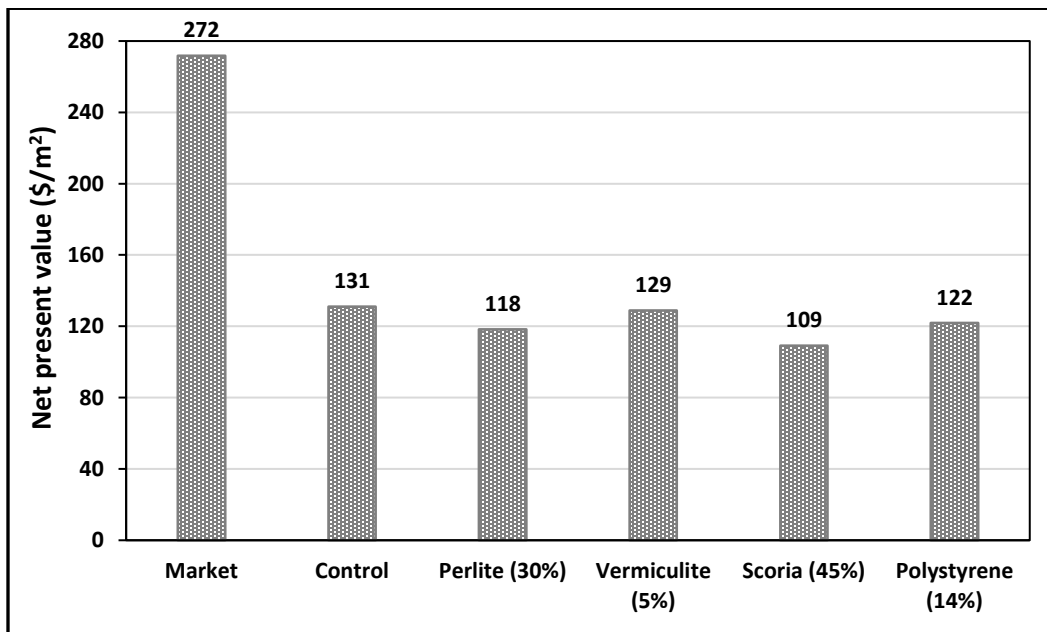
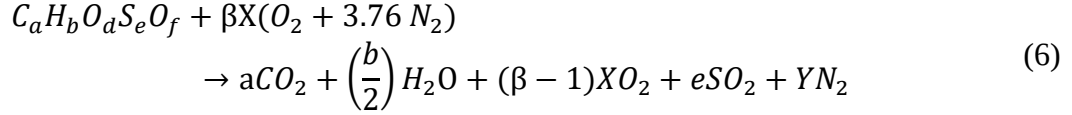


Figure 15: Net present value using different masonry wall

3.4.5 Emissions of Carbon Dioxide (CO₂) and Fuel Consumption

Increased exterior wall thermal resistance minimizes heat transmission in the construction industry. Fuel use and air pollution should also be reduced. Fuel combustion may be modelled using the following generic equation [86]:



Oxygen equilibrium principles are used to determine X and Y parameters, which are represented by this equation. [86]:

$$X = \left(a + \frac{b}{4} + e - \frac{d}{2}\right) \quad (7)$$

$$Y = 3.76\epsilon X + \left(\frac{f}{2}\right) \quad (8)$$

By neglecting the emissions of CO, SO₂, and NO_x, it is feasible to calculate the rate of combustion products emitted from a kilogram of fuel using Equation 9 [87]:

$$M_{CO_2} = \frac{a CO_2}{M} \equiv kg \frac{CO_2}{kg} / kg \text{ fuel} \quad (9)$$

Fuel's weight in kilograms per kilomole (kg/kmol) may be calculated using the following equation: [87]:

$$M = 12 a + b + 16 d + 32 e + 14 f \text{ (kg/kmol)} \quad (10)$$

Using the equation below, we can figure out the emission of CO₂ [87]:

$$M_{CO_2} = \frac{44 a}{M} m_{FA} \quad (11)$$

According to this equation, m_{FA} is the total amount of fuel consumed each year which calculate by using the thermal resistance of a wall (R_{wall}), the space heating system's fuel efficiency (η_s), daily temperature at the location of the study (D), and the lower heating value of the fuel(LHV)[86]:

$$m_{FA} = \frac{86400 D}{R_{wall} \times LHV \times \eta_s} \quad (12)$$

Table 10 summarizes the results of the emission computation, including all the parameters that were considered.

Table 10: Variables used to calculate CO₂ emission levels

Fuel	LHV	η_s (%)	Chemical formula
Fuel-oil	40.604×10^6 J/kg	82	$C_{7.3125}H_{10.407}O_{0.04}S_{0.026}N_{0.02}$
Natural gas	34.534×10^6 J/m ³	90	$C_{1.05}H_4O_{0.034}N_{0.022}$
Coal (Soma)	23.023×10^6 J/kg	70	$C_{7.078}H_{5.149}O_{0.517}S_{0.01}N_{0.086}$
LPG	46.046×10^6 J/kg	90	$C_{3.7}H_{4.1}$

Six different types of blocks with four different types of fuels were used to assess the environmental consequences of thermal insulation walls. Table 10 lists the chemical formulas for many types of fossil fuels, including oil, natural gas, coal, and LPG. Based on the yearly heating demand calculated using dynamic techniques, the fuel consumption and CO₂ emissions are predicted. Fuel usage and CO₂ emissions are reduced when the thermal resistance improves. Therefore, the control and Scoria-blocks may cut fuel consumption by around 53% and 60%, respectively, when used in place of the market concrete blocks on the wall with the greatest consumption of 43.2 kg/m².year. The use of perlite blocks would also lower usage by 58%. Oil may be replaced with any fossil fuel, including coal,

and the resulting percentages are relatively static. Therefore, the kind of wall, not the type of gasoline, is the most important factor in determining fuel consumption.

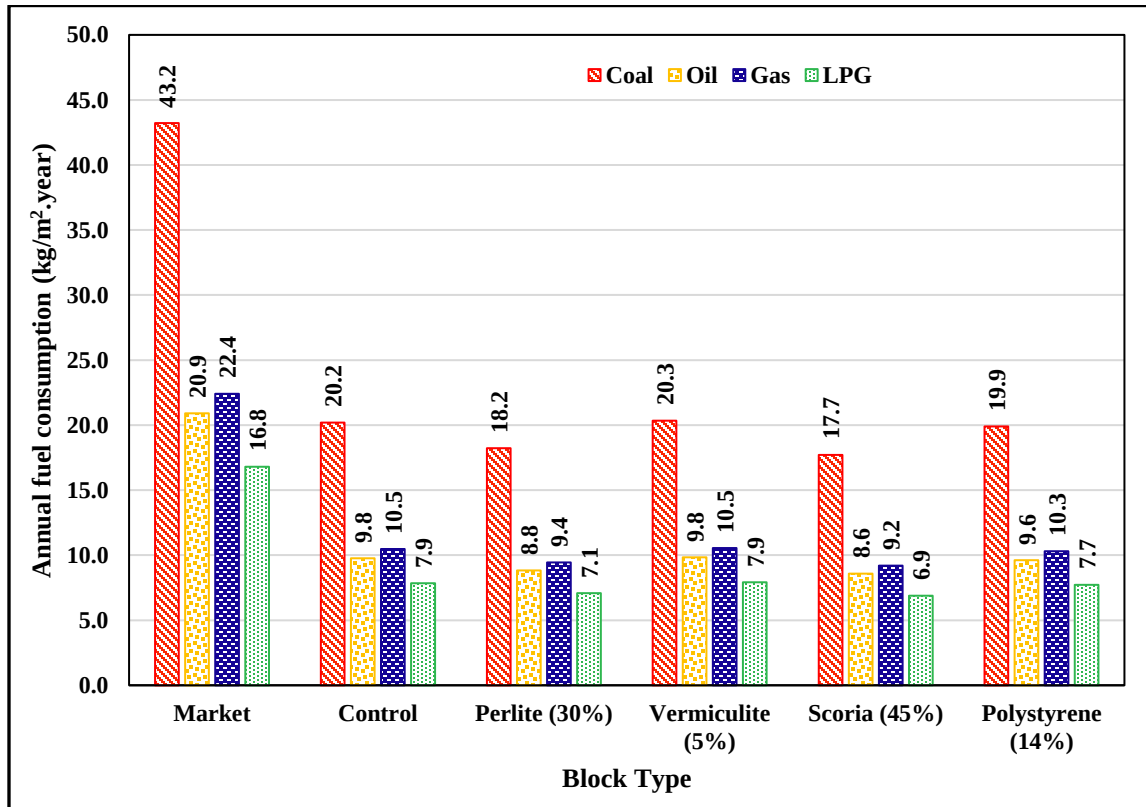


Figure 16: Annual fuel consumption with various wall types

The market concrete wall's CO₂ emissions were 59, 67 and 153 (kg/m².year) for LPG, oil and coal, respectively, and 56 m³/ m².year for natural gas (see Figure 17). By using a control concrete block, this might be reduced to 26, 31and 63 (kg/m².year) for LPG, oil and coal, respectively, and 28 m³/ m².year for natural gas. Notably, coal has the worst environmental impact, whereas LPG has the least negative effect on the environment. When compared to coal, LPG fuel may reduce CO₂ emissions by 2.4 times. Furthermore, for all types of walls, oil fuel consumption is lower than gas use. However, as can be shown in Figure 16 and Figure 17, it produces more CO₂ than gas does. Figure 17 shows that the

CO₂ emissions of all fuel types were reduced by 2.1 times compared to the market wall. The volcanic scoria block can reduce CO₂ emissions by 2.4 times compared to the market and 1.15 times compared to the wall of control while Perlite-block wall is second best in terms of reducing CO₂ emissions. These new walls are envisioned as environmentally sustainable and cost-effective alternatives to classic masonry walls.

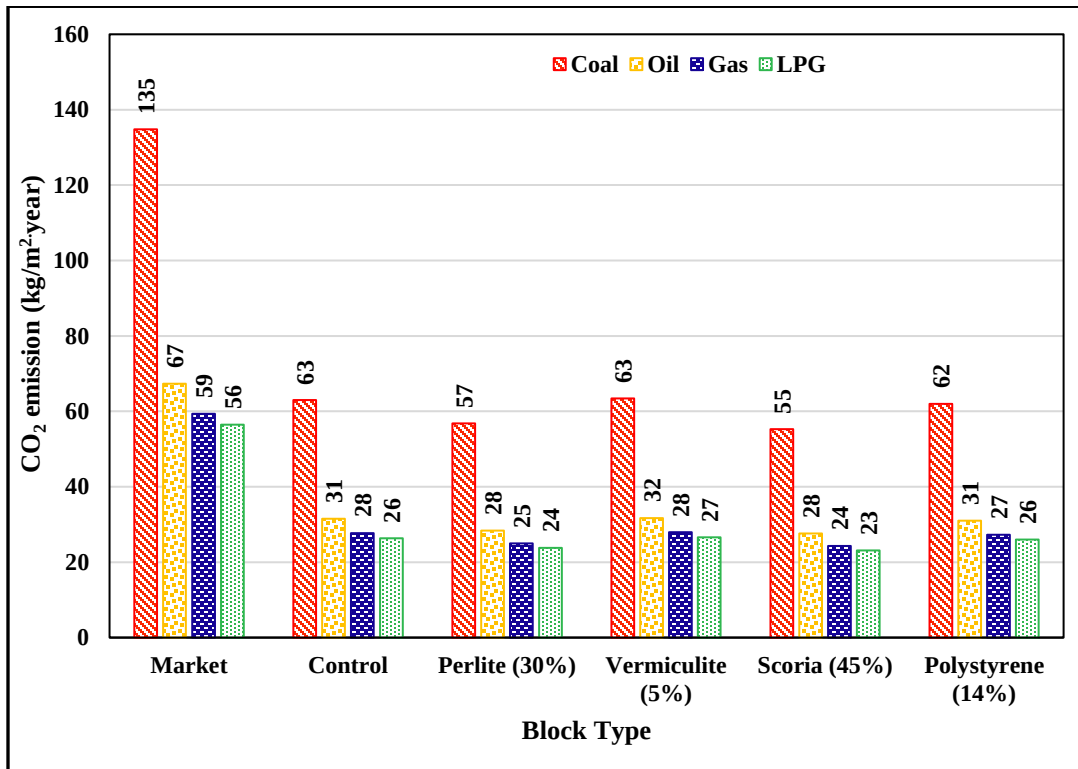


Figure 17: CO₂ emissions with different thermal insulation walls

3.5 Conclusion

For industrial and residential structures, new masonry blocks built in fully automated industrial processes were mechanically, thermally, and economically evaluated for application as exterior wall options. Many of the coarse aggregate was replaced with vermiculite, scoria, and polystyrene components, while perlite was utilized to replace the

fine aggregates. To further enhance thermal performance, the block's cavities were reorganized in a way that differed from those currently on the market in Saudi Arabia. For ASTM C-129, a compressive strength of 4.14 MP, mechanical characteristics were tested at 7, 28 days to ensure conformity (for non-load bearing walls). The physical properties of water were evaluated by conducting water absorption tests. Using a heat flow meter, the suggested blocks were tested for thermal conductivity and resistance after 28 days. It was also based on Dhahran, Saudi Arabia's climate data for the initial cost and energy usage costs for air-conditioning systems. The treated walls' overall cost was compared to the Saudi market's current wall. At the conclusion of this investigation, the quantity of oil utilized, and CO₂ emissions were evaluated to assess the ecological effect and long-term viability of these possible blocks. The following outcomes may be taken from the findings of the experimental program:

1. The newly developed blocks (perlite, vermiculite, scoria, and polystyrene) fulfilled the standard requirement by ASTM C129 for non-load bearing compressive strength. However, the highest reduction on the strength after 28 days with almost 20% was occurred on perlite and vermiculite blocks due to their water-absorbing characteristics as well as their nature because they are weak materials.
2. Perlite and scoria blocks had the highest density loss of 26.15% and 20%, respectively, when compared to control block. Thus, the perlite and scoria blocks are categorized as light-weight concrete blocks, whereas the all-other types of blocks produced could be considered as medium-weight concrete blocks.
3. Vermiculite and perlite blocks had the highest water absorption of 213.55 and 198.77 kg/m³ which were higher by 20% and 11%, respectively compared to

control block. However, upon comparison with the requirements of the ASTM C129 Standard, it was revealed that the absorption levels for all the types of blocks were acceptable and within the standard's range of permissible values.

4. With a 5 kg weight difference from the control block (20.17 kg), perlite hollow block was the lightest while Scoria block weighed 17.06 kg, which is 15% lighter than the control.
5. In comparison to hollow market blocks, the control block produced in this study had a 53.4% lower equivalent thermal conductivity. Whereas comparing thermal conductivity of scoria blocks and perlite to that of market blocks, it was found to be lowered by 59% (0.303 W/m.K) and 57% (0.314 W/m.K), respectively, while it was reduced by 12 %and 9%, respectively, when compared to the control block.
6. The new design of control blocks reduced the energy consumption of the market block wall by roughly 53% which saves annually around 3.95 \$/m². Whereas using scoria blocks save 68.81 kWh/m² and \$4.6/m² annually, almost 2.6 times less than the market wall.
7. Thermal resistance is increased by 158% in the best wall (scoria block) as compared to commercial concrete blocks, which reduces the net present value from 272 to 109 \$/m² approximately 2.5 times.
8. In the case of market blocks, annual oil consumption is 43.2 kg/m² and CO₂ emissions are 135 kg/m². Scoria blocks might reduce these quantities by as much as 17.7 and 55 kg/m².year.

3.6 Acknowledgments

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CHAPTER 4

Journal Article 2

Development of Eco-Friendly Hollow Concrete Blocks in the Field Using Wasted High-Density Polyethylene, Low-Density Polyethylene, and Crumb Tire Rubber

4.1 Abstract

The necessity for eco-friendly green buildings will continue to raise answering the climatic change challenges, while the need for energy saving is vital to protect the natural environment. Masonry concrete blocks are classified as one of the most affordable ways to solve this issue. In this regard, the new configuration of hollow concrete blocks was fabricated in the field. Three distinct kinds of hollow concrete blocks were produced to assess the effectiveness of such concrete blocks in the market. In addition, the experimentally determined thermal resistance was used to calculate the expenses, oil consumption, and CO₂ emissions. Blocks made with crumb rubber failed in the ASTM C129 tests for non-load bearing compressive strength, whereas those made with control and high-density polyethylene (HDPE) met the standard requirements. It was shown that the inclusion of rubber particles reduced the strength by 56%. The control block used in this investigation has a thermal conductivity of 53.4% lower than the commercial hollow blocks. While the inclusion material had a smaller impact than the arrangement of holes, HDPE thermal conductivity decreased by 6.4% compared to the control block. Likewise,

the control-block wall's layout can reduce the power consumption by 53%. Moreover, HDPE and LDPE-blocks lower the consumption by 54 and 57%, respectively, saving roughly 4.26 (\$/m². year). Furthermore, oil consumption and CO₂ emissions decreased by 56% when HDPE with 20% replacement was utilized. Reducing our reliance on oil as an energy source implies cleaner air and a lighter carbon footprint. It is possible to reduce the world's pollution by buildings using these materials.

Keywords: High-density Polyethylene; Low-density polyethylene; Rubber; Insulated concrete blocks; Strength; Thermal conductivity; Economic evaluation; Oil fuel usage; Emissions of carbon dioxide

4.2 Introduction

Non-biodegradable materials like crumb rubber and plastic wastes present a hazard to our world's ecology. Burying and landfilling are the traditional methods for disposing of those harmful materials that cause ecological risks. Therefore, the developed countries are now studying several alternatives [88] The European Tire and Rubber Manufacturers Association (ETRMA) estimated the annual production of waste plastic and tyre rubber of about 300 and 5.1 million metric tons, respectively, in 2018 all over the world [89], [90]. There is also the fact that only 7% is recycled each year, with the remaining 8% being burned and the remainder disposed of in landfills [91]. Waste disposal has become extremely expensive owing to the large amounts of funds and effort needed, leading to contamination of waterways. It is difficult to recycle and dispose of in the environment because of its low biodegradability and the strict regulations [92]. Because of this, it is possible to protect the environment and natural resources such as aggregates by utilizing these materials in building, as well as reduce the amount of energy used, and the amount

of carbon dioxide emitted [90]. Conversely, this contribution remains extremely restricted in terms of scale, thereby requiring the creation of innovative markets in order to diversify into novel products [27].

Hollow concrete blocks are the most prevalent material frequently utilized as building envelope components, particularly in developing countries. Attributed to its low thermal conductivity and material usage, hollow concrete block is a preferable choice from economic and environmental perspectives for making concrete walls in a predominantly hot and arid climate. Additionally, the building of masonry walls may serve various functions such as structural, fire protection, and acoustic insulation [93]. Developing techniques to partially substitute some of its components, such as cement or aggregates, with alternative materials such as plastic or rubber, is becoming increasingly popular [34]. Various research [27], [33], [34], [52] have been performed on this issue, developing ecologically friendly hollow concrete masonry blocks while retaining an appropriate degree of compressive strength. All the preceding studies confirm that the inclusion of by-products into the mix tend to lower the production costs while minimizing the environmental effect of raw material extraction.

In this regard, the thermal, acoustic, and electrical characteristics of masonry units are highly dependent on the design of the casting moulds. Many moulds have substantial cavities and pronounce wall slenderness. Produced plastic and rubberized blocks should be manufactured under the same rigorous manufacturing conditions as normal blocks to minimize the failure of the new masonry blocks during de-molding or delivery. This is indeed necessary to acquire low-cost construction products that can be used successfully and efficiently in manufacturing facilities. The high cost of producing crumb rubber from

scrap tires and recycling waste plastic, on the other hand, has an adverse impact on the profitability of those building materials [94]. Despite the fact that there are several researches on the characteristics of those materials, studies on cost-benefit are still limited [95], [96]. To assure the long-term viability and profitability of these products, further and more extensive studies are needed.

To improve thermal insulation in concrete masonry blocks, several studies have been performed using polymers and rubber as alternative materials. Cairns [15] examined the usage of tire rubber in concrete masonry bricks. A water-to-cement ratio of 0.87 was used to incorporate rubber in three different proportions (10%, 25%, and 50%). Results indicated that the compressive strength was decreased by 22, 23, and 41% after 28 days of curing when the quantity of rubber content increased by 10, 25, and 50%, respectively. They also found a little increase in strength when the rubber chips were coated in a cement paste, which strengthened the link between the rubber and cement matrix. For pedestrian blocks, Sukontasukkul & Chaikaew [16] substituted crumb rubber for fine and coarse aggregates. Two dosages (10 and 20% by weight) of rubber were used in two different sizes (No. 6 and No. 20). Content and the size of rubber were the most effective factors of strength. In comparison to the control mix, the compressive strength of the 10% and 20% mixtures was reduced by about 45 and 85 %, respectively. A study by Ling [21] looked at the effect of replacing fine aggregate with 5 to 50% crumb rubber and a 0.45-0.5 water/cement ratio while maintaining a 5.6 fixed ratio of aggregate/cement in all mixtures. For non-structural purposes, the rubber content should not exceed 40%, and for structural purposes, no more than 10% of the total weight of the product should contain rubber. The masonry blocks created by substituting aggregates with crumb tire rubber were invented by Al-Aqeeli [26].

Coarse and fine particles of crumb rubber were utilized to cast three kinds of blocks with the incorporation of fine, coarse, and both types of rubber. Fine and coarse rubber blocks met the ASTM C129 criterion for a compressive strength of 3.5 MPa, although the coarse rubber particles had roughly 50% more strength than the fine rubber particles. Because of this, the thermal conductivity of the coarse rubber blocks was approximately 21% greater compared to that of the fine and both rubber sizes. Crumb rubber was also tested in the field by Sodupe-Ortega et al. [27] to produce bricks and long hollow blocks by automated machine. The content of rubber was on the range of 10 to 40% by weight with w/c ratios ranging from 0.7 to 0.9 in masonry blocks. The outcomes proved that using rubber with percentages greater than 20% became unrecommended and affected the compressive strength severely. Further, the higher is the water to cement ratios, the lower would be the compressive strength. Safinia & Alkalban [28] studied the ability to use plastic bottles inside the masonry unit blocks. 500-ml plastic bottles were placed inside the blocks (8 bottles per block) to be tested for compressive strength. 57% higher strength of the plastic bottles compared to Oman's market hollow concrete blocks was shown by the results. Similarly, Wonderlich et al. [29] demonstrated that recycled plastic bottles increased the compressive strength. Harder plastic bottles pushed the face shells outward, lowering the amount of area available for compression. Mathew et al. [30] applied the use of low-density polyethylene in solid concrete blocks. 5 to 30% by volume of waste plastic (LDPE) was used to replace the coarse aggregates with the same sizes. The results revealed that 15% was the optimum percentage of replacement which would give the maximum compressive strength of the plastic blocks. Al-Awsh et al. [33] have recently examined the efficiency of concrete walls to reduce the heat transfer through buildings by using low-density

polyethylene (LDP) as insulation materials to substitute fine and coarse aggregates. LDP replaced the coarse aggregate by 10% by weight. The results showed that all blocks satisfied the minimum required strength by ASTM C129 (3.45MPa), while the thermal conductivity for the LDP blocks was 0.382W/m K. Al-Tamimi et al. [34] aimed to develop a new concrete block to minimize the demand for air conditioning. A new configuration of the cavities was proposed using FEM to minimize the heat flow through the building envelope. Thereafter, to further reduce heat conductivity, 20% of the weight of high-density polyethylene and crumb rubber were used as insulating materials. The new block's (without the insulation materials) thermal resistance was 71% higher than those currently on the market. Furthermore, rubber and polyethylene blocks exhibited a thermal conductivity of 0.387 and 0.404 W/m K that was much lower than the control block. Although there was a significant reduction in compressive strength, the newly developed concrete block had enough strength to satisfy the minimum ASTM C129 requirements and was considered as lightweight masonry hollow block.

This study aims to present the viability of producing hollow concrete blocks using high-density polyethylene (HDPE), low-density polyethylene (LDPE), and crumb rubber (CR) as fully automated industrial processes. The mix designs used in this study were selected after a series of preliminary experiments conducted on laboratory scale under these studies [33], [34]. Coarse aggregate was replaced by 20% of HDPE and CR and 10% of (LDPE) by weight. Compressive strength tests were used to evaluate the mechanical characteristics at 7 and 28 days to fulfil the requirements of the ASTM C-129 for compressive strength of 4.14 MPa (for non-load bearing walls). Also, water absorption and density experiments were conducted to assess the physical properties. The thermal resistance and conductivity

were measured after 28 days using the heat flow meter method (ASTM C518). Moreover, an economic evaluation was conducted to establish the technical viability of the mixes and the overall production costs of all blocks. At the end of the study, CO₂ emissions and oil consumption were analyzed to determine the environmental advantages and long-term feasibility of this prospective block.

4.3 Experimental Research

This section shows the details about the materials used for casting the blocks, preparation of the steel mold, mixing, casting, and the specification of the three tests which were used to assess the specimens.

4.3.1 Materials

The details of the waste plastics and rubber, cement and fine and coarse aggregate used were described in this section:

a. Cement

To conduct this research, an ASTM C 150 Type I Portland cement that is regularly used in the Saudi Arabian building sector, was utilized. With a thermal conductivity of 0.44 W/m.K and a specific gravity of 3.15, all other characteristics satisfied ASTM C 150 requirements [60][61]. Cement provided by Saudi Cement Company has the following chemical components, which are shown in Table 11:

Table 11: Chemical composition of Cement (mass%)

Components	CaO	SiO ₂	Al ₂ O ₃	MgO	Fe ₂ O ₃	SO ₃	L.I.
Percentage (%)	64.35	20.52	5.64	2.11	3.8	2.1	0.7

b. Fine and Coarse Aggregate

Fine aggregate with a specific gravity and water absorption of 2.56 and 0.6% was used in this research. While the coarse aggregate utilized was the crushed limestone rock in two sizes, 3/8 inch (9.53 mm) and 3/16 inch (4.76 mm) and with water absorption of 1.10% and a specific gravity of 2.60.

c. High-density Polyethylene (HDPE)

Alizdihar Plastic Recycling Factory in Dammam provided the high-density polyethylene (HDPE) particles used in this experiment. As shown in Figure 18-(a), only one size of HDPE particles was utilized to replace coarse aggregate, which is similar in shape to lentils with a maximum diameter of 7 mm. Using raw materials that had not been processed or filtered in any manner was performed to imitate production conditions. HDPE had a density of 0.92 g/cm³ and a water absorption of 0%, and it had a thermal conductivity of 0.502 W/m.k [97], [98]. Table 12 summarizes the chemical composition.

Table 12: Chemical composition of high-density polyethylene (HDPE) [99]

Materials	PE	PP	PA	Water	Inorganic fillers	Alkyd/ acrylic	PVC
Weight %	81.30	9.50	1.32	0.14	3.22	4.03	0.48

d. Low-density Polyethylene (LDPE)

Low-density polyethylene (LDPE) is formed during the manufacturing process from the monomer ethylene. This project utilized recycled LDPE, which resulted from plastic packs

after an uncomplicated process in the plastics industry [100]. The plastic was collected, segregated, rinsed, and heated to about 60 °C before being crushed into granules at the recycling factory [101]. In this work, chipped particles in a circular form with a diameter ranging between 6 to 7 mm were used, as shown in Figure 18-(b). The LDPE utilized had a density of 860 kg/m³, and its thermal conductivity was 0.3 W/m.K, while its water absorption was 7.4% [102].

e. Waste Crumb Rubber

Mechanical shredding of used automobile tires is employed to make the crumb rubber for this study by the Saudi Rubber Products Company in Dammam, Saudi Arabia[103]. It was then subjected to a series of filtration processes in order to remove the steel from textile fibers [104]. Untreated crumb rubber with irregular shape and particle sizes ranging between 3 to 4 mm was applied as a coarse aggregate replacement, as illustrated in Figure 18-(c). Rubber particles had a thermal conductivity value of 0.243 W/m.k, a specific gravity of 1.12, and an absorption of 0% [105]. Table 13 summarizes the chemical constitution of crumb rubber [106].

Table 13: Tires chemical composition [106]

Materials	Sulfur (SO ₃)	Rubber	Carbon black	Metal	Textile	Zinc oxide	Additives
Average %	1	48	22	15	5	1	8

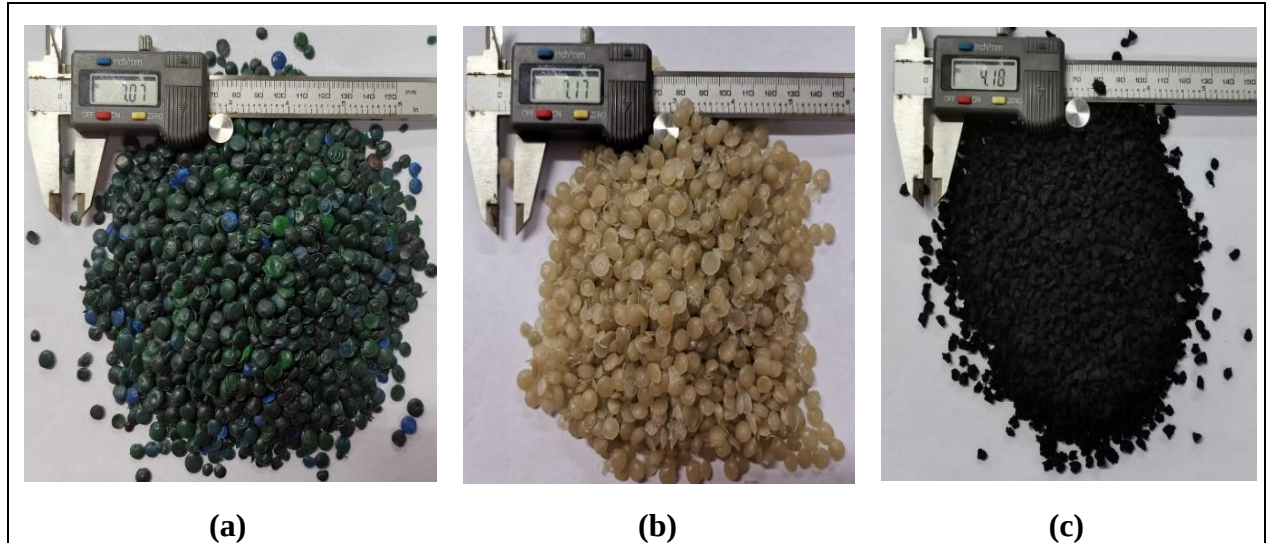


Figure 18: Shape and average sizes in mm of (a) HDPE; (b) LDPE; (c) CR

4.3.2 Preparation of the Innovative Steel Mold

A $400 \times 200 \times 200$ mm new block steel mold was fabricated to be used in the factory (i.e. field) based on a previous design invented by our team [34]. After a comprehensive investigation, the optimum design was chosen using the finite element method (FEM). The main target of the selected configuration was to achieve the lowest thermal conductivity without affecting the other mechanical properties. A wide range of variables influenced the rate at which heat moved through the hollow blocks. The aspect ratio (cavity length over height), hollow ratio, cavity width, thermal bridges, and the number and layout of cavities were all considered as factors impacting heat transmission mechanisms (conduction, convection, and radiation) across the block [46]. Therefore, all these factors were properly considered in the design, whereas a minor revision in the dimensions of the thickness of the thermal bridge was proposed this time for fabrication of the mold in the field from a technical and practical standpoint. To allow the block specimens to withstand the pressure

of the hydraulic forklift block clamps without damage, the thickness of the weak point that joined the two parts together was increased from 28 to 35 mm. The detailed dimensions of the block mold are illustrated in Figure 19, and the block was designed according to the ASTM C129 requirements [67].

Figure 19: Geometry and detailed dimensions of the fabricated blocks

The hollow concrete blocks were cast implementing the designed mix proportions at a commercial scale at the Advanced Concrete Products block factory (ACP) in the Second Industrial Area, Dammam, Saudi Arabia's eastern province. The aggregates were initially weighted and mixed with cement and water for 3 minutes in a concrete mixer with the highest ability of 1500 kg, and then the replacement materials were added to the mixer. After a homogenous concrete mix was achieved, the mixture was poured along a conveyor belt to be transported by a forklift equipped with a hooper to the automatic concrete blocks making machine, as displayed in Figure 20-(a) and (b). After the compaction and vibration were applied with 70 kPa of pressure for almost 15 seconds, the mold was removed, and the hollow concert blocks were finally produced (Figure 20-(c)). Following this step, the

curing process was established by spraying water three times a day for 28 days after covering the blocks with burlaps and polyethylene plastic sheets to prevent evaporating of water, as depicted in Figure 20-(d).

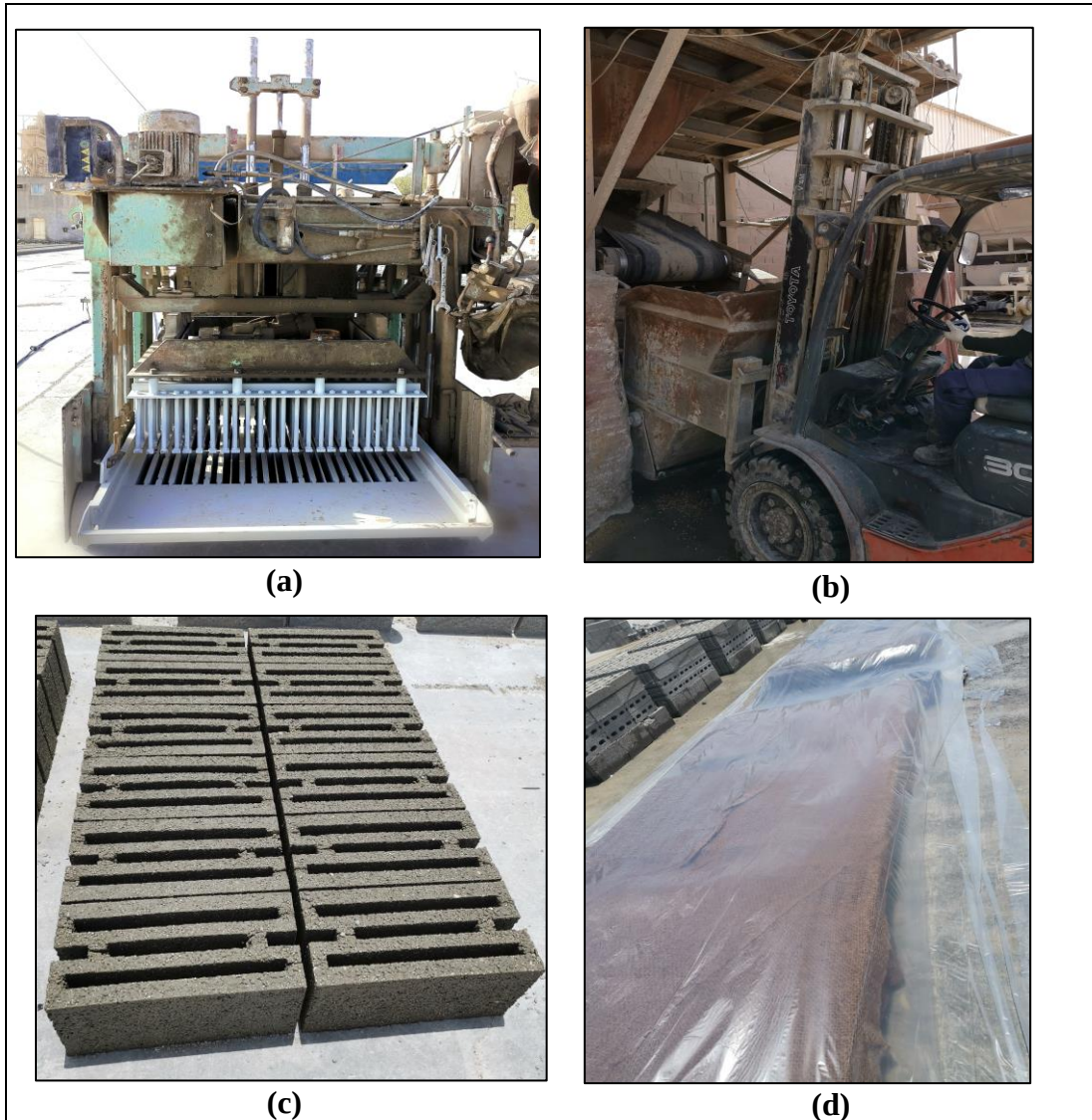


Figure 20: Manufacturing process at the factory: (a) blocks making machine; (b) forklift equipped with a hooper; (c) tray of hollow concrete blocks; (d) curing process

4.3.4 Testing Specimens

As shown in Table 14, a total of 51 specimens were cast to measure the compressive strength, density, absorption, and thermal conductivity.

Table 14: Total number of specimens and the standards applied

Test type	Standard	Specimen number for each mix	Total number of specimens	Testing age
Compressive strength	ASTM C129	6	24	7 and 28 days
Density and absorption	ASTM C140	3	12	28 days
Thermal conductivity	ASTM C518	3	15	28 days

a. Compressive Strength

After 7 and 28 days of curing, three full-size specimens for each type of mix were utilized to measure the strength of the blocks conforming to ASTM C140 [68]. A universal testing machine (MATEST) with a loading capacity of 3000 kN was utilized in all the tests in accordance with ASTM C1716 [69]. Conventional cement/sand mortar (1:3) with a thickness of 1 cm was used to coat the top and bottom of the blocks to spread the applied load eventually, as stated by ASTM C1552 (Figure 21-b) [70]. In order to distribute the weight evenly over the block's cross-sectional area, stiff steel plates were installed at the top and bottom of the block's regions, as shown in Figure 21-(a). The load was exerted at a continuous rate of 0.5 kN/s until the specimen failed. The net area subjected to compressive strength was evaluated by dividing the maximum force by the calculated average net area determined for each 3 absorption specimens. Individual unit blocks must have a minimum net area compressive strength of 3.45 MPa, while the mean of 3 units

should be higher than 4.14 MPa for non-load bearing blocks, as reported by ASTM C129 [67].

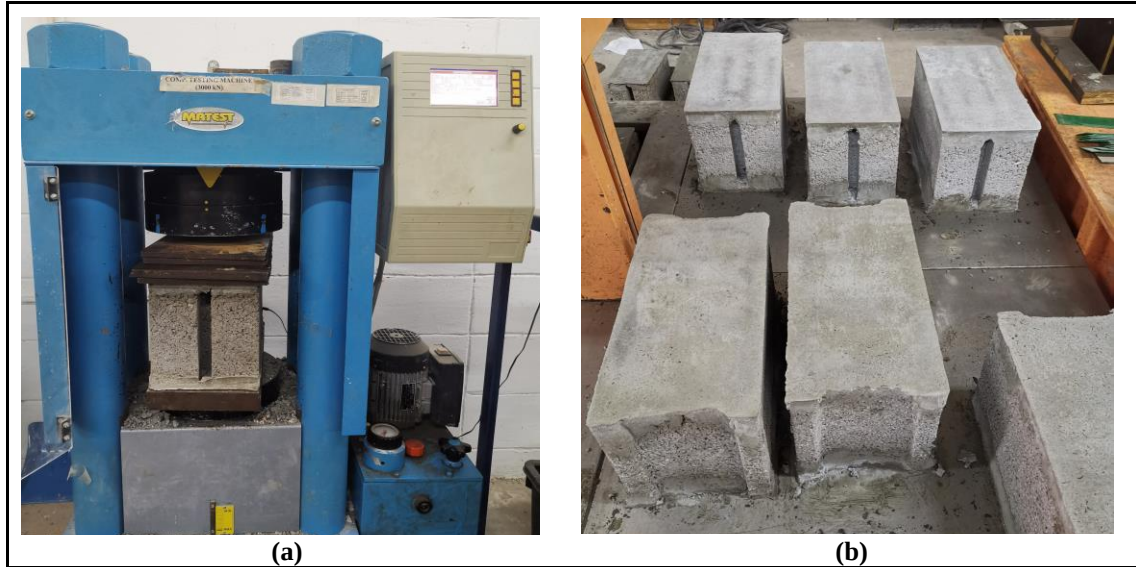


Figure 21: (a) Matest compression test machine; (b) capping specimens before testing

b. Density and Absorption

According to ASTM C140 [68], three typical hollow concrete blocks were oven-dried and evaluated for density and absorption. For each sample, the mass was estimated following a 24-hour immersion in 25°C water (W_i). The samples were weighed while suspended on a metal wire and completely submerged in water (W_s). The specimens were then taken from the water and drained for one minute through a coarse wire mesh, with all visible surface water removed using a damp cloth before being weighed. After that, they were heated in a ventilated oven at 110 °C over a period of 24 hours unless two sequential weighings at two h increments revealed an additional loss of no more than 0.2 percent of

the formerly calculated weight of the specimen (W_d). Equations (13–15) were used to compute the density and absorption of the specimens.

$$\text{Absorption (kg/m}^3\text{)} = \frac{(W_s - W_d)}{(W_s - W_i)} \times 1000 \quad (13)$$

$$\text{Absorption (\%)} = \frac{(W_s - W_d)}{W_d} \times 100 \quad (14)$$

$$\text{Oven dry density (kg/m}^3\text{)} = \frac{W_d}{W_s - W_i} \times 1000 \quad (15)$$

c. Thermal Conductivity

In this study, a heat flow meter device (FOX600) was utilized to evaluate the thermal conductivity of the hollow concrete blocks in accordance with ASTM C 518. The FOX600 equipment communicates with an air pump, cooling unit, and a personal computer via a direct RS-232 interface controlled by the “WinTherm32 v3” software package, as shown in Figure 22-(a) [72]. The WinTherm software package provides an easy-to-use tool for configuring experimental settings, displaying real-time test results, and saving and analyzing the data. In the test section, a 610×610 mm sample with a thickness of up to 203 mm was placed between two plates that were kept at various temperatures during the assessment (Figure 22-(c)) [72]. The heat flow meter enables assess materials with thermal conductivities of 0.01 to 0.35 W/m.K, with external thermocouples allowing for up to 2.5 W/m.K. [72]. The precision and reproducibility of this automated system are its most essential attributes. Accuracy refers to the degree of variance in measurement, taking into

consideration the instrument's reproducibility as well as the physical characteristics of the test [12]. The equipment' accuracy is ± 1.0 percent to 0.5 percent, and its repeatability is about ± 0.5 percent [72]. A full-size specimen was tested separately. Two blocks were joined together using conventional mortar to study the effect of a thermal bridge developed by mortar between the blocks, as shown in Figure 22-(b). Prior to evaluating the selected samples, a reference sample with known thermal conductivity values at various temperatures was used to calibrate the instrument. In order to ensure that the samples had completely dried out, they were heated in an oven at 60°C for 48 hours to ensure that the thermal conductivity values were accurate. It, therefore, became necessary to thoroughly seal all of the cavities, preventing any heat loss from escaping laterally. Because the specimen's dimensions were only slightly smaller than the guard heater's thickness to cover the (610 $\times$ 610 mm), a polystyrene board was employed to fill the remaining space of the guard heater, ensuring that the heat was not spread in the transverse sides, as illustrated in Figure 22-(b). Additionally used on both sides of the specimen were rubber sheets that were positioned between the plates and the rough surface of the specimen to decrease the friction and heat loss between the surfaces. The test specimen's cold and hot surfaces were kept at 20 and 45 °C for the upper and the bottom surfaces, respectively, with a mean temperature of 32.5 °C. Thermocouples were immediately connected to the surfaces of the specimens, removing the influence of contact roughness, and enhancing the measurement precision. The thermal conductivity was obtained directly from the program using heat flux, temperatures difference, and sample thickness according to the following relation:

$$\text{Thermal conductivity}(\gamma)\left(\frac{W}{m \cdot K}\right) = \frac{\dot{Q} \times L}{\Delta T} \quad (16)$$

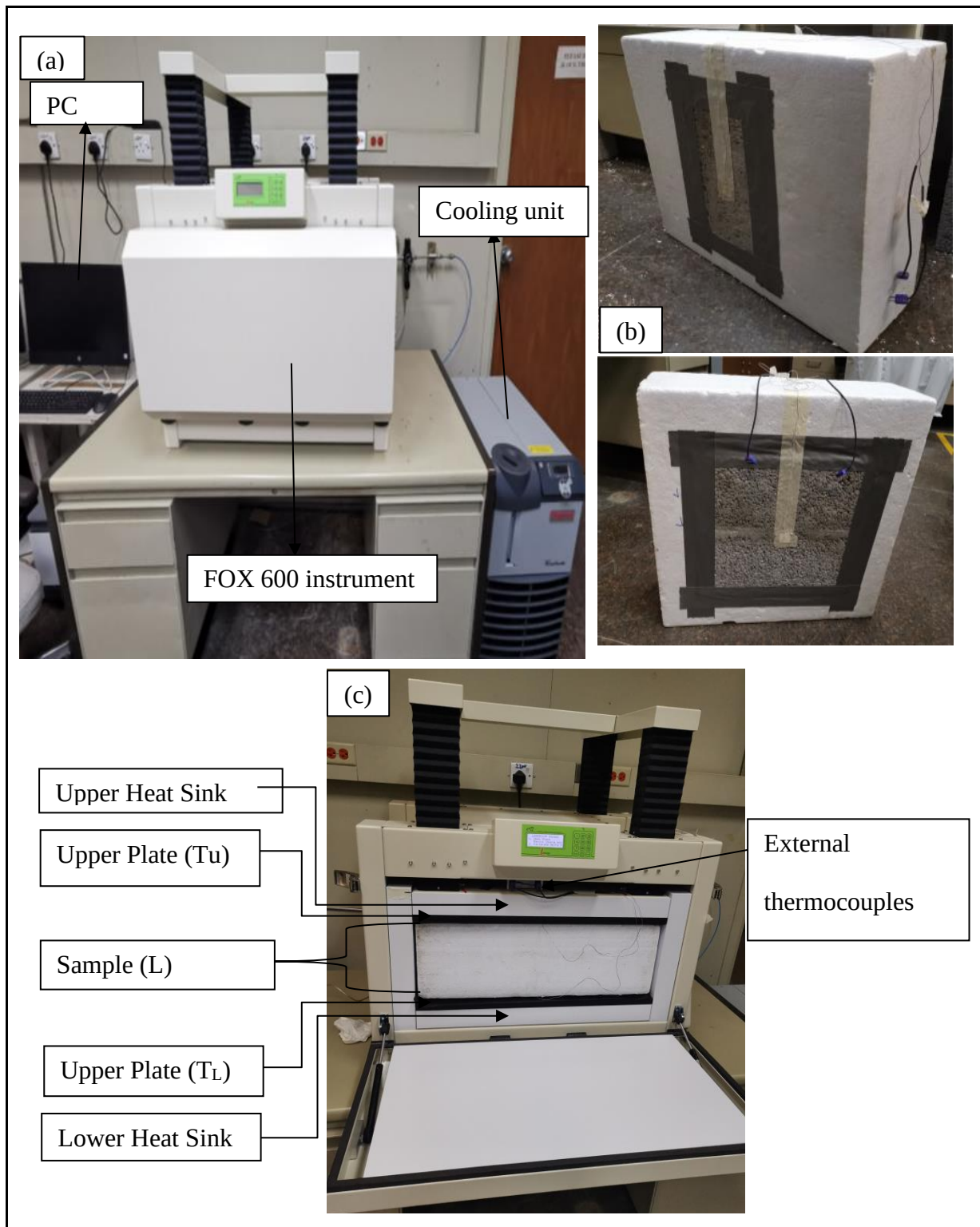


Figure 22: (a) Configuration of the FOX600 heat flow meter device; (b) Samples preparation; (c) Design of HFM apparatus

4.4 Results and Discussions

The results for three experiments which were used to assess the produced concrete blocks were shown below:

4.4.1 Compressive Strength

To assess the ability of the produced hollow concrete blocks to be commercialized effectively, a compressive strength test was performed at 7 and 28 days. Table 15 and Figure 23 present the average net-area compressive strength results for the four mixes. The control block had the largest strength with 5.64 MPa at seven days of curing time, whereas the strength for HDPE and LDPE blocks were decreased by 15.6% and 30.1% relative to the control one, respectively. Unfortunately, the acute strength reduction on the crumb rubber block was extremely noticeable by almost 67%. Following the same tendency, there was a marginal increase in the strength of HDPE blocks with 3.35 % compared to control one after 28 days of curing, which boosted the evidence of the consequence of cement content on the compressive strength. On the contrary, the strength of LDPE and RU blocks decreased by a total of 21.16 and 56 % as compared to the control block. The lowest 28-day standardized requirement is 4.41 MPa for non-loadbearing blocks according to ASTM C 129. Therefore, only the control, HDPE, and LDPE blocks have satisfied this requirement, whereas the crumb rubber failed to pass.

The sharp loss in strength of the rubber blocks might be provoked by several reasons that are not always easy to recognize, as argued by several authors [107]. The first reason could be ascribed to the softness of the surface of the rubber particles, which thus reduces the rubber-cement paste interaction [108]. Secondly, the rubber particle size and stiffness appear to be important variables in the loss of compressive strength [109]. The production

of bubbles surrounding the rubber particles during the mixing process is another likely explanation [17], [110]. Another reason is that the formation of air bubbles trapped on the surfaces of rubber particles could not be eliminated by the vibration and compaction process [111]. Furthermore, due to the fact that rubber is a hydrophobic substance, it prevented water from passing through the concrete structure during the curing time, which was necessary for cement hydration [112].

Finally, there are various types of pre-treatment like water-soaking, sodium hydroxide treatment, oxidation and sulphonation, plasma polymerization of ethanol on the surface of CR, and chemical coating of the rubber particles could be used to overcome the deficiencies and improve the compressive strength [113], [114],[115]. However, implementing these options in the factory to produce a rubber block in a large quantity appears to be not an attractive choice from a practical and commercial perspectives unless the treatment of rubber particles take place by their manufacturers without a major increase in the prices.

Table 15: Results of oven dry density, absorption, and compressive strength (at 7 and 28 days)

Block type	Oven-dry density (kg/m ³)	Absorption (kg/m ³)	Absorption (%)	Average Net-area compressive strength (MPa)	
				7 days	28 days
Control	2091.15	178.94	8.56	5.64	6.33
HDPE	1755.63	135.65	7.73	4.76	6.55
LDPE	1912.18	128.85	6.75	3.94	4.99
Crumb Rubber	1824.76	148.08	8.12	1.87	2.79

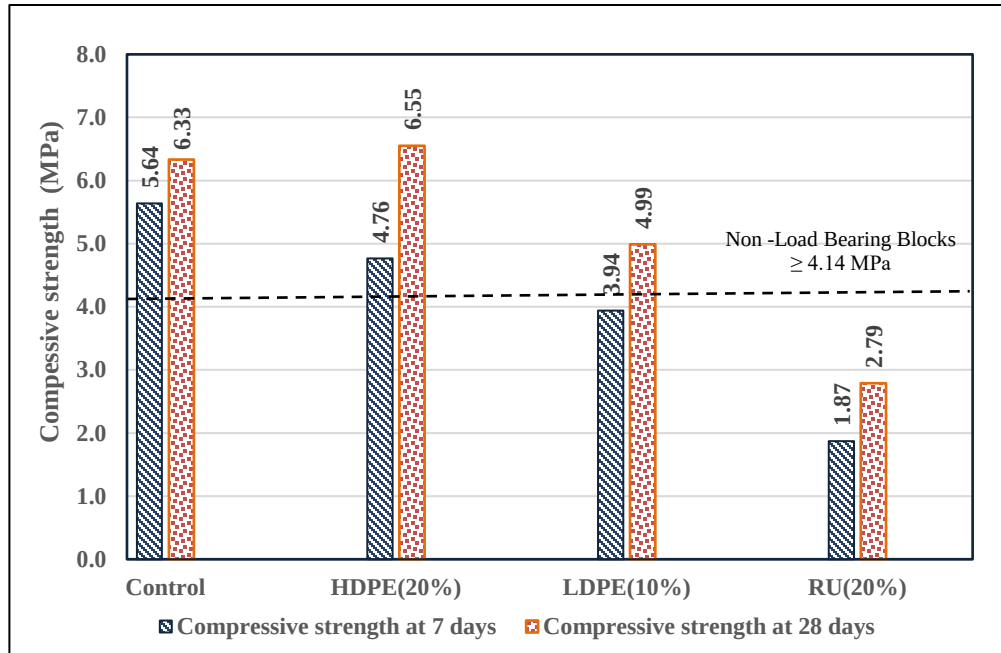


Figure 23: Compressive strength of the produced blocks at 7-and 28-days curing period

4.4.2 Oven-dry density and Absorption

Table 5 shows the average oven-dry densities of each type of the hollow concrete blocks (HDPE, LDPE, CR) produced. It was found that the lowest reduction in density of LDPE block was 8.6% as compared to the control block without substitution. This minor reduction is attributed to the lower percent of replacement of LDPE by only 10% and to a decrease in the coarse to total aggregate proportion in the mix design from 0.765 to 0.6. In contrast, the highest loss in density with 16% was observed when the HDPE was incorporated into the mix, which ascribed to a high percent of HDPE inclusion that tends to increase the porosity. While the density of the crumb rubber concrete block was slightly higher than HDPE by 3.8%, they had the same percentage of replacement of 20% and almost the same ratio of coarse to total aggregate. This is ascribed to the smaller density of HDPE particles of 920 kg/m^3 comparable to the density of crumb rubber of 1120 kg/m^3 . In contrast to the density of the conventional blocks, there was a 12.7% decrease in the density

of rubber blocks, as shown in Figure 24. In ASTM C129, a normal aggregate concrete block is defined as any block with an oven-dry density higher than 2000 kg/m^3 , while the medium weight concrete blocks should be in the range of 1680 to 2000 kg/m^3 and blocks with densities lower than 1680 are considered as lightweight concrete blocks [67]. Thus, according to this standard, the three types of blocks are classified as medium-weight concrete blocks, whereas the control block is as a normal weight. An important consideration in determining the density of masonry concrete blocks is that a decrease in weight will improve the working conditions, be more comfortable to handle, have a direct impact on how much dead load can be carried, and thus affect the final construction cost [77], [78].

As shown in Figure 25, the control blocks absorbed 178.94 kg/m^3 (8.56 %) of water, whereas the produced blocks made of rubber and HDPE absorbed somewhat less, approximately 8.12 and 7.73%, respectively. The LDPE blocks, on the contrary, had the lowest absorption, with a value of 6.75%, which is attributed to the low CA/TA ratio in the mix, means that the fine aggregate will be higher, thereby the voids inside the blocks will increase and leading to decrease the absorption in the LDPE block [33]. It's worth noting that the three types of blocks were all in the same range. This might be attributed to the fact that plastic and rubber have no absorption capacity. Maximum water absorption values of 208, 240, and 288 kg/m^3 are defined by ASTM C90 for blocks of various weights: normal, medium, and light [80]. When using the requirements of this standard as a reference, it could be noted that the absorption levels for all types of blocks were acceptable and within the standard's allowable limit.

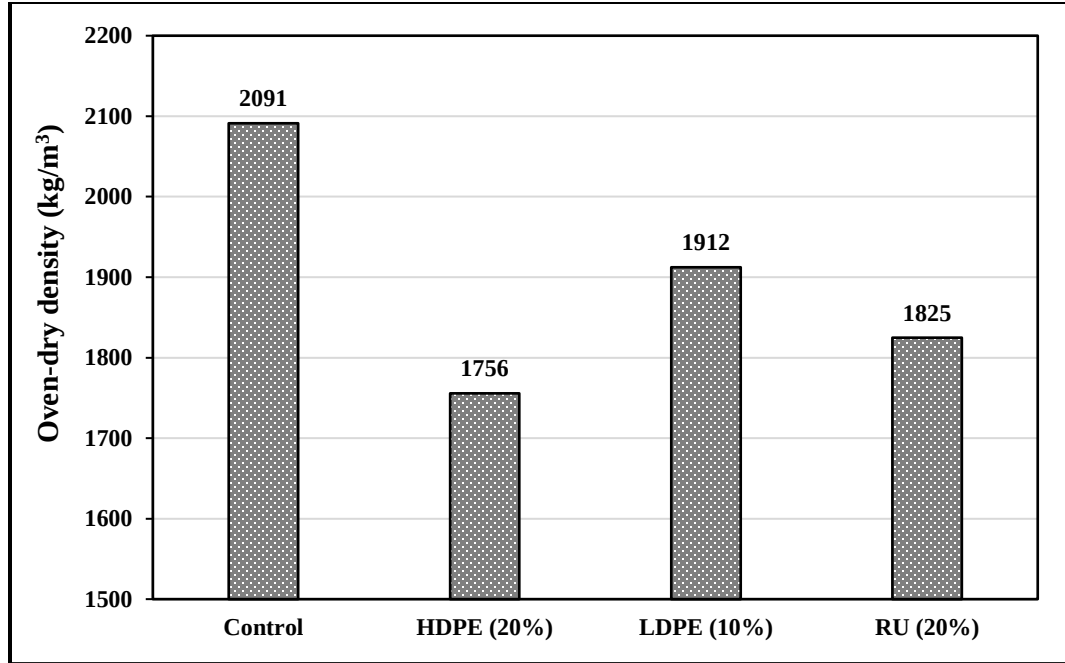


Figure 24: Oven-Dry densities for the blocks

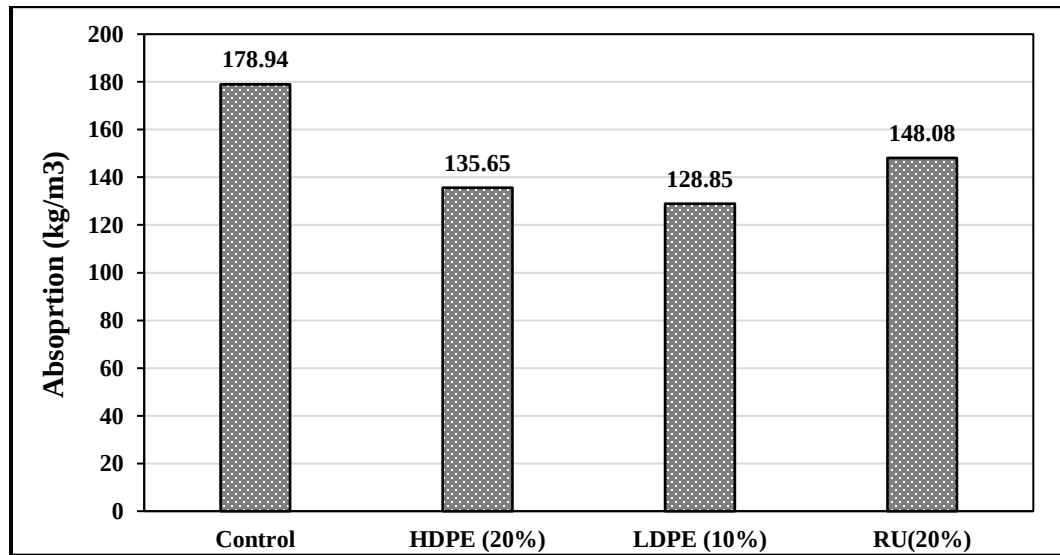


Figure 25: Absorption of the produced blocks

4.4.3 Thermal Conductivity

The thermal behavior of concrete blocks has a direct correlation to the density as the existence of air voids within the concrete will reduce the thermal conductivity, which is ascribed to the fact that the thermal conductivity of concrete is more than that of air [10].

In this regard, two samples were tested for each type of block and then joined together to study the thermal bridge effect due to joint mortar. Also, a market block with three holes that is commonly used in the construction was tested to compare it with our design. Table 16 exhibits the average thermal conductivity and resistance of the single block of each type with their improvement and the reduction in percentage as compared to the control one, while Table 17 presents the same results for the double blocks (2-joined blocks). As Figure 26 shows the equivalent thermal conductivity of each sample and the equivalent thermal conductivity of the 2-joined blocks. The findings reveal that the average thermal conductivity of the market block was 0.738 W/m.K and the average thermal conductivity (λ -value) of the control block was 0.344 W/m.K. Therefore, the effect of geometry enhanced the thermal conductivity up to 53.4%. While the effect of the inclusion material was slightly low compared to the effect of configuration, the average thermal conductivity of HDPE was decreased by 6.4% compared to the control block. Also, as the inclusion of LDPE particles was only 10%, the effect of this replacement was almost negligible of the equivalent thermal conductivity compared to the control block as they had almost the same value of 0.344 W/m.K and 0.343 W/m.K. Further, the highest conductivity reduction has occurred with HDPE blocks which had a 56.37% reduction compared to the market blocks.

For the 2-blocks joined together with cement mortar, it could be observed that the effect of the thermal bridge increased the thermal conductivity by around 20% compared to the single block in all mixes. Furthermore, the enhancement of the thermal resistance of produced blocks with the new configuration contrasted to the blocks available in the market was more than 100%, which again boosts the significant effect of geometry. Further, it could be worth mentioning that several strict regulations were issued to implement thermal

insulation in all buildings in Saudi Arabia. According to the Saudi Building Code, the regulations require maximum U-values for external walls to be $0.342 \text{ W/m}^2\text{.K}$ and the R-values not less than $2.92 \text{ m}^2\text{.K/W}$ [82]. The results for R-values of the produced blocks are between 0.457 and $0.5 \text{ m}^2\text{.K/W}$, as shown in Figure 27. Despite improving the thermal properties of these blocks, the results of the R-values will not satisfy the legislation for the Saudi building code. Therefore, extra insulation layers like polystyrenes board will be added to fulfill the stringent thermal requirements. However, because of the improved thermal qualities, insulation thickness might be reduced, allowing more floor space to be accessible.

Table 16: A single block's average thermal conductivity and resistance

Block type	Thermal conductivity (W/m.K)	Reduction in k value (%)	Thermal resistance R ($\text{m}^2\text{.K/W}$)	Improvement in R (%)
Market	0.738	-	0.271	-
Control	0.344	53.39	0.580	114.02
HDPE (20%)	0.322	56.37	0.620	128.78
LDPE (10%)	0.343	53.52	0.581	114.39

Table 17: The average thermal conductivity and resistance of the double blocks (2-joint blocks)

Test type	Thermal conductivity (W/m.K)	Reduction in k value (%)	Thermal resistance R (m ² .K/W)	Improvement in R (%)
Market	0.929	-	0.216	-
Control	0.438	52.85	0.457	111.57
HDPE (20%)	0.403	56.62	0.500	131.48
LDPE (10%)	0.423	54.47	0.473	118.98

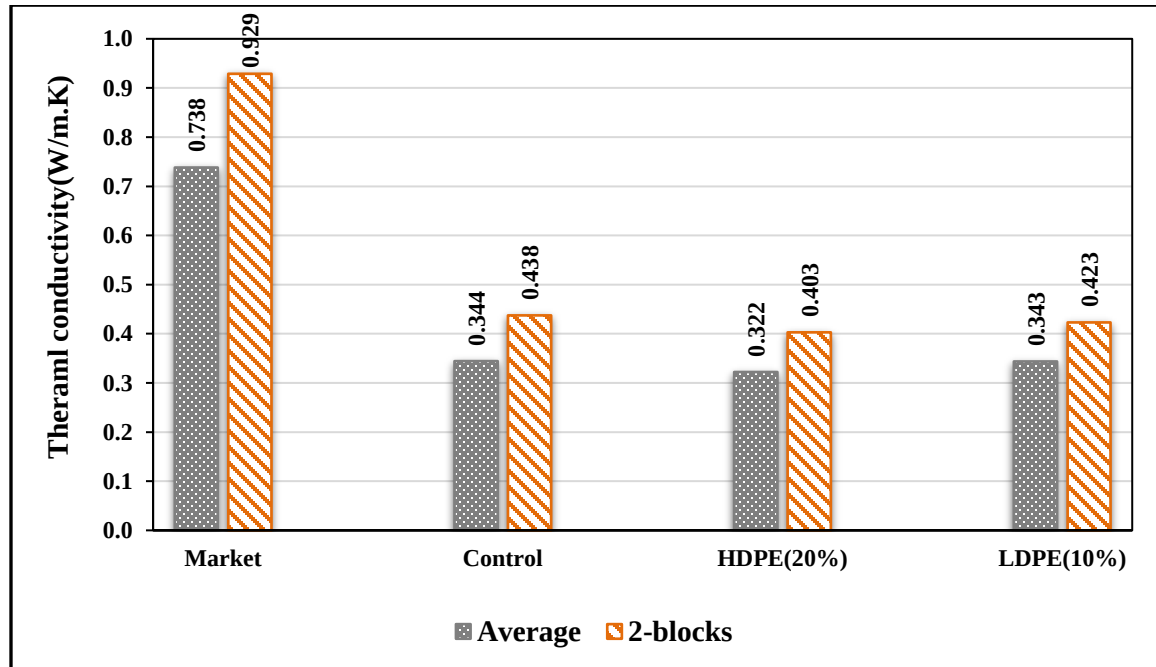


Figure 26: Thermal conductivity of the single and double blocks

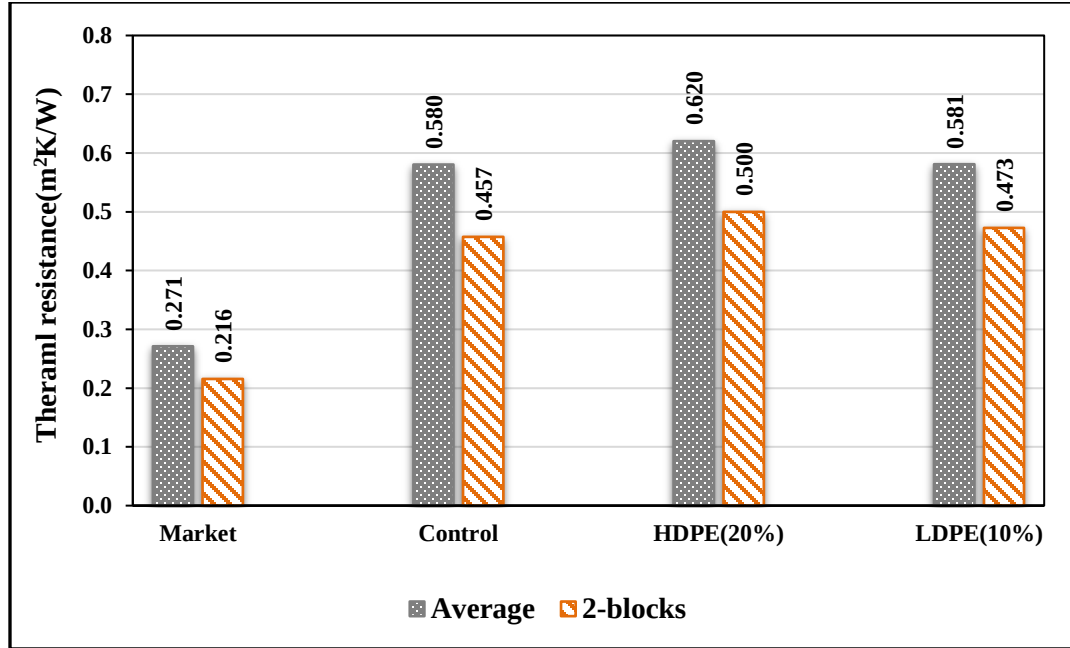


Figure 27: Thermal resistance of the single and double blocks

4.4.4 Cost Analysis

To estimate the initial cost of the developed blocks, the components' price of each mix was calculated. Then the operating cost, profit, and the mortar were added to evaluate the total cost of the masonry wall per meter square. The price of each component was reported according to the market in eastern Saudi Arabia where the blocks were manufactured while the price of HDPE and LDPE was obtained from Al-Izdihar Al- Awwal Plastic Recycling Factory. The initial cost of one meter square of HDPE and LDPE is more expensive than the control and market block masonry wall due to the high cost of the HDPE and LDPE. The HDPE and LDPE were fabricated using a high-quality process, starting by segregating the type of waste, then cleaning or washing them, and finally exposing them to a high temperature to remove the remaining impurities. For that reason, the price was very high. If these materials are used in the future, the plastic will not need to go through this process,

thus becoming cheaper. Moreover, the developed blocks are good from the environmental point of view. According to BUSINESS WIRE, the global concrete blocks and the brick market were reported at 1.9 trillion units in 2020 [116]. If the plastic is used in these blocks and bricks, about 1.92 and 4.06 million tons of LDPE and HDPE will dispose of in blocks (since 1.01 and 2.14 kg was utilized in each LDPE and HDPE block, respectively, see Table 18). Also, the same amount of natural aggregate will be saved for the new generation.

Table 18: Cost estimation for a meter square of a masonry wall system

Materials	Mix proportions by weight (kg/m ³)						
	Materials	Control		HDPE (20%)		LDPE (10%)	
	kg/\$	kg	\$	kg	\$	kg	\$
Cement content	0.060	195	11.70	250	15.00	195	11.70
Water content	0.002	115	0.20	135	0.23	111	0.19
Coarse aggregate (3/8) in	0.006	1132	7.15	638	4.03	708	4.47
Coarse aggregate (3/16) in	0.006	338	2.06	190	1.16	211	1.29
Fine aggregate (Sand)	0.002	451	0.76	393	0.67	681	1.15
Replacement materials (kg)	---	---	---	207	132.48	102	68.34
Σ	0.08	2231	22.64	1813	154.24	2008	88.30
Weight/ Brick (kg)		20.17		18.70		19.88	
No. of bricks		111		97		101	
cost/brick (\$)		0.20		1.59		0.87	
Operating cost/brick (\$)		0.08		0.08		0.08	
Profit (\$)		0.13		0.13		0.13	
Total cost/brick (\$)		0.42		1.80		1.09	
mortar cost (\$/m ²)		0.04		0.04		0.04	
wall cost (\$/m ²)		5.27		22.60		13.64	

Note: the price of HDPE and LDPE is 0.64 and 0.67 kg/\$

All types of masonry walls should be evaluated regarding their electrical energy costs. The energy required by the air-conditioning is determined using the equation below [20]:

$$E = \frac{0.024 \times D}{R \times C} \text{ kWh/m}^2 \quad (16)$$

The current economic research is being conducted in Dhahran, Saudi Arabia, where D equals 2185 K-days relying on a temperature of 24.5 °C [83]. Specifically, R is the thermal resistance of the wall ($\text{m}^2 \text{ }^\circ\text{C} / \text{W}$), and C denotes the thermal performance coefficient of the air conditioning system ($C=2.16$) [20]. It is vital to notice that Eq. (16) incorporates the energy usage of the exterior walls into the equation.

According to the Saudi Electricity Company's 6.67 cents/kWh tariff in 2020, the annual energy cost for each wall could be evaluated as follows:

$$EC = ET \times E \quad (17)$$

Energy tariff for electricity is marked by the letter ET (in cents per kilowatt-hour), whereas yearly air conditioning consumption is denoted by the letter E (in kWh/m^2).

The energy consumption ranged from 48.56 kWh/m^2 for a wall built using HDPE blocks to 112.40 kWh/m^2 for the normal market block wall. Figure 28 indicates that the control-block wall can minimize the electricity consumption by up to 53% just by the new design. The consumption would decrease by up to 54 and 57%, respectively when the LDPE-blocks or HDPE-blocks are to be used. Based on the Saudi Electricity Company's energy

pricing (6.67 cents/kWh), the annual estimated cost will be 7.5 \$/m² when the market blocks are utilized. This cost will drop to 3.24, 3.42, and 3.54 \$/m², which means the users will save about 4.26, 4.09, 3.95 \$/m² when the HDPE, LDPE, and control blocks are to be used, as can be seen in Figure 29.

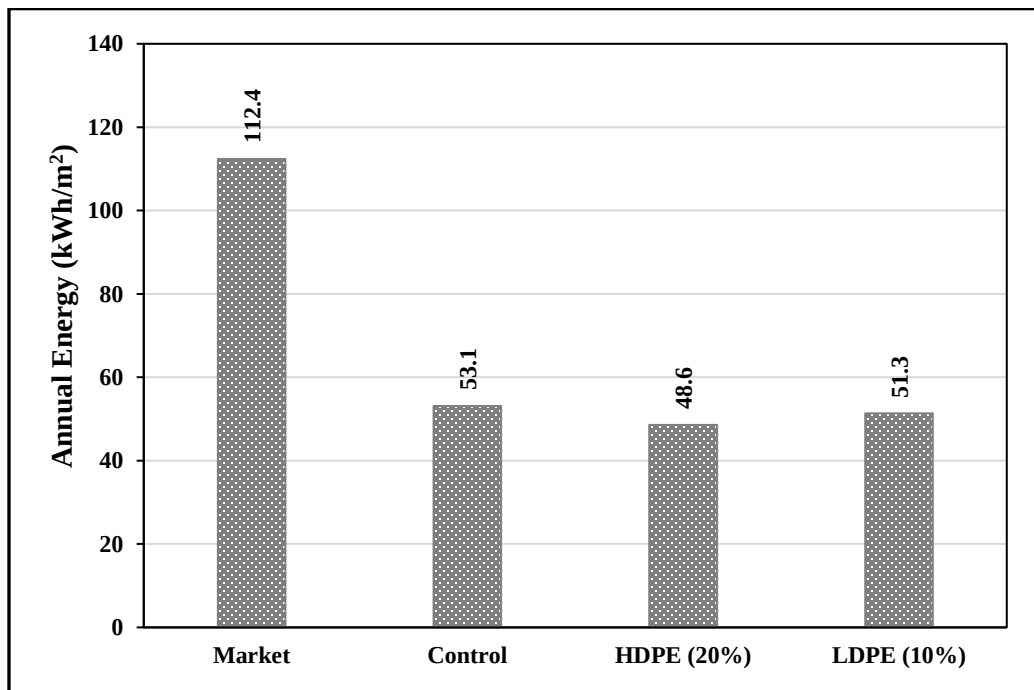


Figure 28: Annual energy consumption for cooling system when using different masonry walls

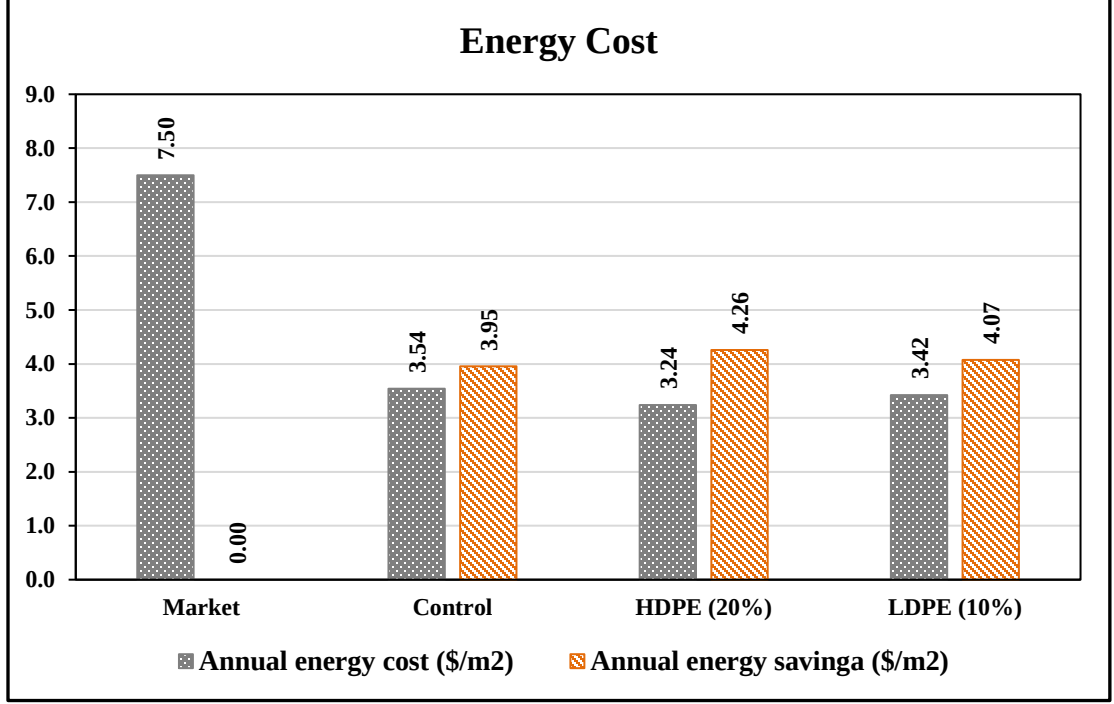
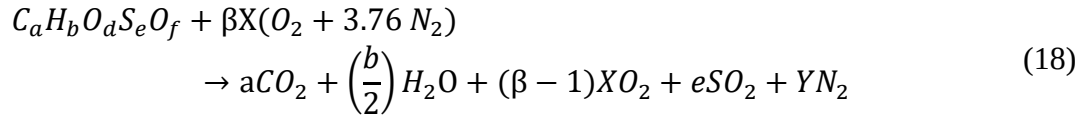


Figure 29: Annual energy cost and saving

4.4.5 Estimated the Fuel Consumption and CO₂ Emissions

As a result of the increased thermal resistance, the building will lose less heat and air pollution. Moreover, lower fuel combustion would reduce the fuel consumption and air pollution in the following ways [86]:



The parameters X and Y are determined using the following equations based on the oxygen equilibrium principles [86]:

$$X = \left(a + \frac{b}{4} + e - \frac{d}{2}\right) \quad (19)$$

$$Y = 3.76 \epsilon X + \left(\frac{f}{2}\right) \quad (20)$$

By ignoring the CO, SO₂, and NO_x emissions in Equation 7, it is possible to compute the rate of combustion products emitted from one kilogram of fuel [87]:

$$M_{CO_2} = \frac{a CO_2}{M} \equiv kg CO_2/kg fuel \quad (21)$$

where “M” (in kg/kmol) represents the kilomole weight of the fuel, which could be determined using the following equation [87]:

$$M = 12a + b + 16d + 32e + 14f \quad (22)$$

CO₂ emissions are calculated by using the following equation [87]:

$$M_{CO_2} = \frac{44 a}{M} m_{FA} \quad (23)$$

Where m_{FA} is the annual consumption of the fuel, which can be found by the following equation [86]:

$$m_{FA} = \frac{86400 D}{R_{wall} \times LHV \times \eta_s} \quad (24)$$

Based on the previous equation, the thermal resistance of a wall is represented by its R_{wall} (W/m².K), LHV (J/m³ or J/kg based on the fuel source) represents the lower heating value of the fuel, D (in degree-days) represents the location of the study and η_s (in percentage) is the space heating system's fuel efficiency, as reported in Table 19.

Table 19: The parameters used in CO₂ emission calculation [86], [87]

Fuel	LHV	η_s (%)	Chemical formula
Coal (Soma)	23.023×10 ⁶ J/kg	70	C _{7.078} H _{5.149} O _{0.517} S _{0.01} N _{0.086}
Fuel-oil	40.604×10 ⁶ J/kg	82	C _{7.3125} H _{10.407} O _{0.04} S _{0.026} N _{0.02}
Natural gas	34.534×10 ⁶ J/m ³	90	C _{1.05} H ₄ O _{0.034} N _{0.022}
LPG	46.046×10 ⁶ J/kg	90	C _{3.7} H _{4.1}

Chemical formulas for coal, oil, natural gas, and liquid petroleum gas (LPG) are listed in Table 19. Fuel consumption and CO₂ emissions for four different types of walls were estimated using four different kinds of energy sources. Figure 30 shows how the fuel consumption and CO₂ emissions of different wall types vary based on the yearly heating load predicted by dynamic techniques. Fuel consumption and carbon dioxide emission are reduced as a result of an improvement in the thermal resistance. Maximum fuel consumption and CO₂ emissions values were found in the market concrete block, which has the lowest thermal resistance (0.270 m²K/W), while low values were found in the highest thermal resistance block (block with HDPE 20%). It is estimated that the oil fuel consumption might be dropped by 53% when the control or LDPE-10% block is used in place of market block, while the reduction will be 56% if the HDPE-20% block is utilized. Coal or other fossil fuels have almost the same parentage when compared to oil fuel, so the type of block is the primary factor affecting the fuel consumption, and not the type of fuel.

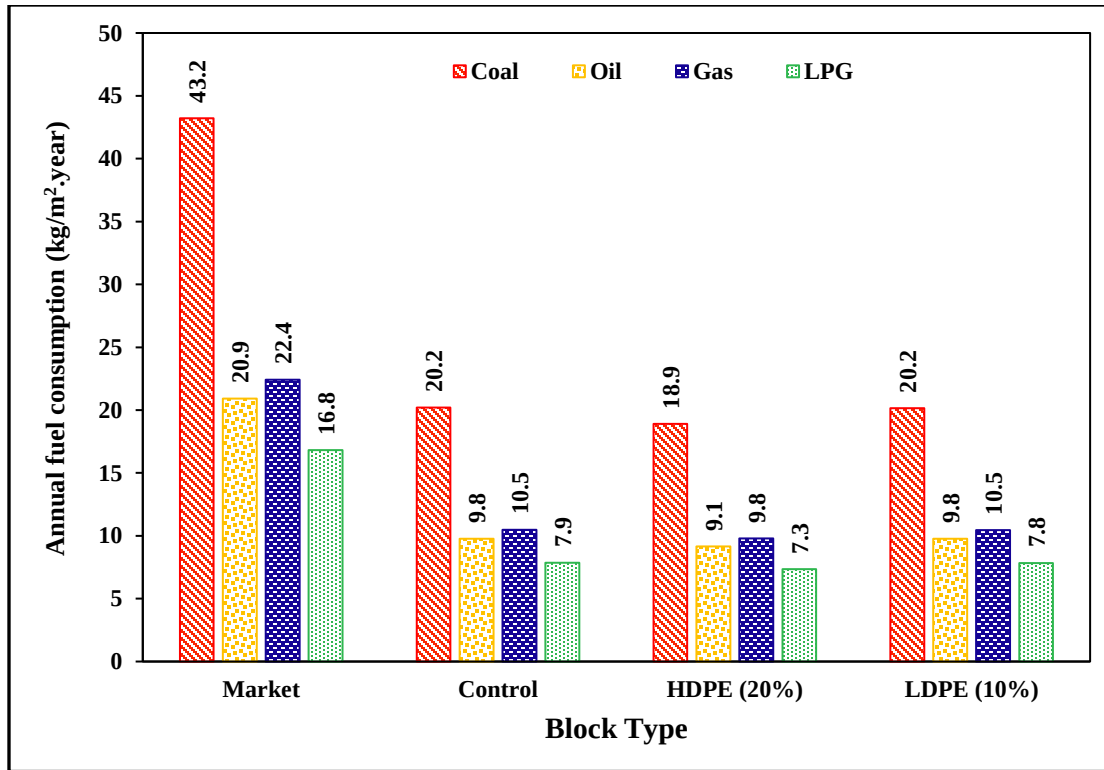


Figure 30: Annual fuel usage as a result of various wall types

Figure 30 shows that the CO₂ emission levels of the market block were 59, 67, and 135 (kg/m².year) for LPG, oil, and coal, respectively, and 56 m³/m².year for natural gas. The use of the control or LDPE-10 % block might reduce this amount to 28, 31, and 63 (kg/m².year) for LPG, oil, and coal, respectively, and to 26 m³/m².year for natural gas. When it comes to the impact of fuel on the ecosystem, coal fuel has the worst impact compared to LPG fuel, which has the least negative impact. LPG has the potential to reduce CO₂ emissions by around 2.4 times when compared to coal. For all types of blocks, the use of oil fuel is lower than the consumption of gas fuel, which is another advantage. However, as seen in Figure 30 and Figure 31, it produces significantly more CO₂ than gas.

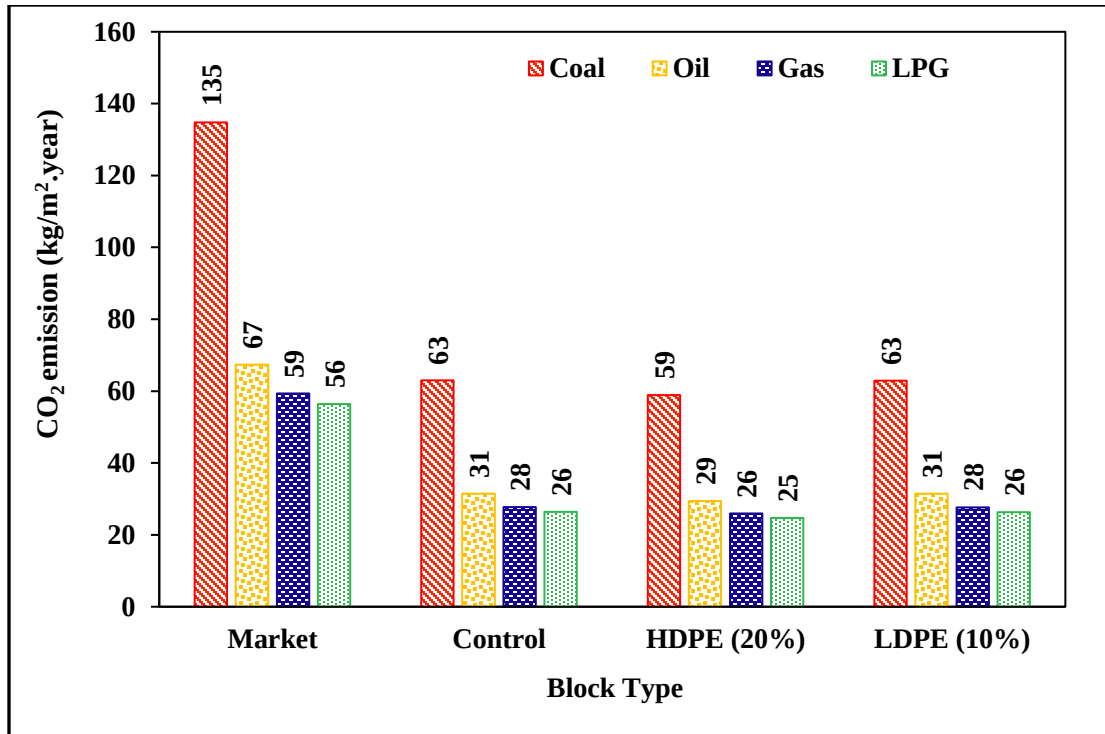


Figure 31: CO₂ emissions linked to varied thermal insulating walls

4.5 Conclusions

This research looked at the feasibility of casting hollow concrete blocks utilizing HDPE, LDPE, and crumb rubber in a fully automated industrial process. The mechanical properties of the blocks were assessed at 7, 28 days to meet ASTM C-129 criteria for a compressive strength of 4.14 MPa (for non-load bearing walls). Water absorption experiments were conducted to assess their physical qualities. After 28 days, the heat flow meter assessed the thermal resistance and thermal conductivity. Also, the technical viability of the mixtures and the overall manufacturing costs of all blocks were economically evaluated. The amount of oil used, and CO₂ emissions were assessed at the end of the research to assess these potential blocks' environmental impact and long-term feasibility. This study indicates that adding inclusion materials tends to reduce the compressive strength and density compared to using the control mixture. This is because of their low

strength (relative to concrete) and poor adherence to the cement paste on rubber and plastic particles. Conversely, adding HDPE polyethylene improves the heat conductivity. The following summarizes the highlights of the compressive, density, absorption, and thermal conductivity, as well as other properties:

1. The newly developed blocks (control, HDPE, and LDPE blocks) fulfilled the standard requirement by ASTM C129 for non-load bearing compressive strength, while the blocks produced with crumb rubber failed to pass. The maximum reduction in the strength of 56% was achieved when the Ru particles were utilized. The sharp loss in strength of the rubber blocks could be attributed to the softness of rubber particles' surface, which reduces the interaction and bonding between rubber and cement paste.
2. The highest loss in density with 16% was attained when 20% of HDPE particles were used. Thus, all three types were classified as medium-weight concrete blocks, whereas the control block (without insulation) had a normal weight.
3. Upon comparison with the requirements of the ASTM C129 Standard, it was revealed that the absorption levels for all the types of blocks were acceptable and within the standard's range of permissible values.
4. The control block developed in this study has the lowest equivalent thermal conductivity compared to hollow market blocks by 53.4 %. Further the inclusion of material's influence was somewhat lower than the configuration's, HDPE average thermal conductivity fell by 6.4% compared to the control block.
5. According to the results, compared to a single block of concrete, the effect of the thermal bridge increased thermal conductivity by around 20% in all mixtures.

6. The influence of geometry on the thermal conductivity of hollow concrete blocks was remarkable. The aspect ratio, hollow ratio, thermal bridges, and cavity width been responsible for decreasing the blocks' heat transfer.
7. Because of the high price of HDPE and LDPE, the initial cost of one meter square of HDPE and LDPE is more expensive than the control and market block masonry wall.
8. The annual energy consumption could be minimized by 53% by using the new design of the control block while the HDPE and LDPE-blocks would reduce the consumption by up to 54 and 57%, respectively, which saves around 4.26 annually (\$/m². year).
9. When market blocks are utilized, the oil consumption and CO₂ emissions are 43.2 and 135 kg/m²/year. When HDPE with 20% replacement is utilized, these values might fall by 20 and 59 (kg/m².year). Reduced reliance on oil for energy means less pollution for the environment and less reliance on oil. Such materials can mitigate the globe from air and land pollution by being used in buildings.

4.6 Acknowledgement

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CHAPTER 5

Conclusions and Recommendations

5.1 Conclusions

New masonry blocks built-in fully automated industrial processes were mechanically, thermally, and economically evaluated for application as exterior wall options for industrial and residential structures. Many coarse aggregates were replaced with vermiculite, scoria, polystyrene, high-density polyethylene, low-density polyethylene, and crumb rubber components, while perlite was utilized to replace the fine aggregates. To further enhance thermal performance, the block's cavities were reorganized to differ from those currently on the market in Saudi Arabia. For ASTM C-129, compressive strength of 4.14 MPa, mechanical characteristics were tested at 7, 28 days to ensure conformity (for non-load bearing walls). The physical properties of water were evaluated by conducting water absorption tests. The suggested blocks were tested for thermal conductivity and resistance employing a heat flow meter after 28 days. It was also based on Dhahran, Saudi Arabia's climate data for air-conditioning systems' initial cost and energy usage costs. The treated walls' overall cost is compared to the Saudi market's current wall. After this investigation, the quantity of oil utilized, and CO₂ emissions were evaluated to assess these possible blocks' ecological effect and long-term viability.

The results proved that all the newly developed blocks (perlite, vermiculite, scoria, and polystyrene, high density polyethylene, low density polyethylene) fulfilled the standard

requirement by ASTM C129 for non-load bearing blocks for both compressive strength of 4.14 MPa whereas blocks made with crumb rubber failed to meet the requirement. In addition, the perlite and scoria blocks are categorized as light-weight concrete blocks as they had the lightest weight of (15.19 kg) and (17.07kg), which were lower by 25% and 15%, respectively, contrasted with the block controls (without insulation materials). Also, Vermiculite and perlite blocks had the highest water absorption of 213.55 and 198.77 kg/m³ which were higher by 20% and 11%, respectively compared to control block. Further, the new design of the control blocks had the largest influence on the thermal conductivity as it reduced by 54% while scoria and perlite had the highest reduction of thermal conductivity of almost 60% compared to that of the commercially produced in the market. However, upon comparison with the requirements of the ASTM C129 Standard, it was revealed that the absorption levels for all the types of blocks were acceptable and within the standard's range of permissible values. Furthermore, a cost analysis found that the scoria block is the most affordable as it had the lowest unit price. In terms of energy consumption, the new design of control blocks reduced the energy consumption of the market block wall by roughly 53%, which saves annually around 3.95 \$/m². Whereas using scoria blocks save 68.81 kWh/m² and \$4.6/m² annually. The Scoria-wall may reduce CO₂ emissions by a factor of 2.4 when compared to a commercial concrete block.

5.2 Recommendations

As a result of the experimental study procedures, the following suggestions for further research are possible:

- Extending the work to study the durability of the developed blocks.
- Developing a numerical model to forecast the failure load and validate the experimental work and find the heat transmission coefficient in order to compare it with the values required by Saudi Building code.
- A new method of capping with silver could be used to avoid errors in compressive strength and time savings as a result of unequally distributed load caused by the cement mortar capping problem.
- Make a combination between the mixed materials like perlite as a replacement of cement and scoria instead of aggregate and filling the holes with polystyrene board to enhance the thermal properties.
- Using different curing method like carbon dioxide in order to increase rate of hydration and strength early.
- Building a complete wall with plaster and test its thermal resistance in the real life.

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