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Development of energy-efficient hollow concrete blocks using perlite, vermiculite, volcanic scoria, and expanded polystyrene

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ABSTRACT

Sustainable development programs focus on reducing traditional energy usage and finding alternative energy sources. Thermal insulation materials can improve energy efficiency and reduce negative environmental impact, and be cost-effective by using low density, strong heat resistance, good thermal conductivity, and durability. Consequently, a novel arrangement of hollow concrete blocks was manufactured on-site in this research. In order to assess the commercial viability of these hollow concrete blocks, four distinct variants (perlite, vermiculite, scoria, and polystyrene) were investigated. Economic viability, fuel energy use, and CO_2 emissions were also assessed using experimentally obtained thermal resistance. All the newly produced blocks have fulfilled the compressive strength and absorption criteria set by the standards for non-load-bearing blocks. The perlite and scoria blocks, with their respective lowest dry density of 1544 and 1673 kg/m^3, qualified as lightweight concrete blocks. As a result, their thermal conductivity was over 60% lower than that of the commercially made blocks. In addition, the scoria block proved to be the most cost-effective option. When compared to a normal market block, the best scoria wall may enhance the heat resistance by 144%. In terms of the net present value (NPV) for 40 years, this solution cut energy consumption from 272 to 109 \$/m^2 (about a 150 % reduction). As an additional benefit, constructing a wall out of scoria blocks resulted in a 2.4 and 1.15-fold decrease in CO_2 emissions compared to conventional and control blocks. Furthermore, this study emphasizes the potential environmental benefits, such as saving natural resources, energy, and money by using these by-products to make greener concrete masonry units.

1. 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 days of summer months [1]. Therefore, energy consumption in terms of electricity has increased rapidly as the building sector consumes around 74% of the total electricity produced in Saudi Arabia, and over 67 % of all building electricity used in Dammam city is devoted to powering the air conditioning units [2]. Air conditioning also absorbs 71 % of total electricity in hot cities like Jeddah and 40 % in milder climates like Abha [2]. Factors, such as population growth, economic development, and energy efficiency also contribute to energy dissipation [3].

Saudi Arabia's population and energy demand are rapidly increasing. The country recorded a significant rise in electricity consumption between 2000 and 2020 due to economic development. The peak demand for electricity rose from 50 GW to 60 GW between 2012 and 2017 and is forecast to reach 70 GW by 2020 [4]. To meet this demand, the Saudi Electric Company invested over \$100 billion between 2009 and 2017 [5]. The Saudi Energy Efficiency Center was established to regulate energy usage and to address concerns of excessive power consumption. Tight energy efficiency regulations could save over \$1.5 billion over the next 20 years, reducing power consumption by 5–10% and providing an extra capacity of 3–6 GW. The government could also save up to \$0.25 billion a year by adopting energy-saving techniques and reducing air conditioning demand [6].

Saudi Arabia's economy heavily relies on fossil fuel supplies,

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particularly oil. As the energy demand rises annually by 5–8%, it is projected that the oil supply and demand will be equal in 2035. Therefore, the necessity for better thermal insulation in building envelopes has been revealed to the public, and many researchers have investigated the existence of such materials and techniques that could lower thermal conductivity and reduce energy needs for buildings and factories [7–10].

Many researchers have been using perlite, vermiculite, volcanic scoria, and expanded polystyrene in concrete masonry blocks to improve their heat insulation [11–15]. For instance, Topcu and Iskdag [16] 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 dosage as it reduces the thermal conductivity to 0.215 W/m.K as compared to their controlling bricks with 0.465 W/m.K. Al-Hadhrami and Ahmad [17] conducted a detailed program on two types of concrete blocks and nine kinds of clay bricks in Saudi Arabia. The study was conducted to assess the thermal performance efficiency by adding insulation materials like polystyrene and perlite inside the holes. The results proved that the thermal conductivity was decreased significantly by filling the insulation materials inside the cavities or inserting them within the masonry bricks. The thermal resistivity was increased by around 50 % by adding perlite into the holes of the concrete blocks.

Sengul et al. [18] elaborated on the influence of perlite on lightweight concrete's thermal conductivity and mechanical properties. With various dosages from 20% to 100%, perlite replaced the natural aggregate and was mixed with superplasticizer and air-entraining admixtures. The outcomes showed that the substitution of 60% of perlite decreased the thermal conductivity and strength by 42% and 84%, respectively. Al-Tamimi et al. [19] added 30% of perlite to a newly designed concrete block to enhance its thermal efficiency. The thermal conductivity of the perlite block was 0.309 W/m K, representing a 33 % drop over the control block without insulating materials. Al-Jabri et al. [20] revealed that vermiculite is not viable for producing concrete blocks due to its low compressive strength, while polystyrene is an effective material for producing lightweight concrete blocks with low thermal conductivity. Al-Awsh et al. [21] investigated the effectiveness of concrete walls in minimizing heat exchange in buildings by replacing fine and coarse aggregates with vermiculite (VL), volcanic scoria (VS), and expanded polystyrene (EPS). Vermiculite and volcanic scoria replaced the coarse aggregates by 5% and 100% by weight, respectively, while EPS was substituted for the coarse particles by a volume of 12 %. The findings indicated that all three types of blocks were strong enough to pass the strength requirement, whereas the thermal conductivity for the VL, vS and EPS blocks was 0.383, 0.340, and 0.371 W/m K, respectively. Hossain [22] examined the use of volcanic scoria as coarse and fine aggregates as a potential industrial utilization. The results proved that scoria fulfilled the required strength and density by ASTM standards. Likewise, because scoria had a low thermal conductivity (0.15–0.40 W/m.K), it could be used as an insulator in the building industry.

Xu et al. [23] used expanded polystyrene beads (EPS) to produce lightweight hollow concrete blocks. Three dosages of 15, 20, and 25% by volume of EPS were used to examine their effects on density and compressive strength. The results showed that the most critical parameters for determining density and strength were EPS dosage and water-to-cement ratio. As these parameters increased, both the density and compressive strength decreased. Sassine et al. [24] performed a case study on the efficiency of expanded polystyrene (EPS) to enhance the thermal resistance of hollow concrete blocks. Experimentally, 0, 6, 12, and 18 g of EPS were used to prepare four different hollow concrete blocks and determine their thermal resistances. The results indicated that the thermal resistances of the blocks were 0.16, 0.2, 0.25, and 0.31 $m^2 \cdot K/W$, respectively. Thus, adding 18 g (31.3 % by volume) of EPS to the mixture tends to make it have almost twice the thermal resistance.

This field study attempted to demonstrate the industrial potential of manufacturing hollow concrete blocks using Perlite, Vermiculite, Volcanic Scoria, and Expanded Polystyrene. Following a series of laboratory-scale trials, the mix proportions employed in this investigation were identified [19,21]. The mechanical characteristics were evaluated at 7 days and 28 days to ensure compliance with ASTM C129. Physical properties were examined using density and water absorption tests. Thermal resistance and conductivity were recorded with a heat flow meter after 28 days. The technical applications and economic visibility of the mixes, as well as the total production cost, were also looked at.

This paper presents novel hollow concrete blocks that were manufactured on-site using four variants of materials of the blocks (perlite, vermiculite, scoria, and polystyrene) for commercial viability. The developed blocks were found to have required compressive strength and absorption and are considered as lightweight with low thermal conductivity. The scoria block was found to be the most cost-effective option in the study's cost analysis, cutting energy consumption by 60% and reducing CO_2 emissions by 2.4 times compared to the conventional blocks. The study also highlights the potential of using by-products to make greener concrete masonry units that meet the industry standards, which can save natural resources, and energy and reduce costs while benefiting the environment.

2. Materials and methods

In this section, the materials used in producing the blocks are addressed, and the mix design and detailed methodology for casting the blocks in the field are presented.

2.1. Materials

2.1.1. Cement

The cement employed in this study was ASTM C 150 Type I Portland cement, which 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 the other properties met the standards of ASTM C 150 [25,26].

2.1.2. Fine and coarse aggregate

Dune sand, which is plentiful in eastern and central Saudi Arabia, was used as the fine material for this project. The fine aggregate utilized had 0.6 percent and 2.56 water absorption and specific gravity, respectively. The coarse aggregate used was a crushed limestone rock of two sizes 3/8 in. (9.53 mm) and 3/16 in. (4.76 mm), all of which had a specific gravity of 2.60 with a water absorption rate of 1.10%.

2.1.3. Expanded perlite

Perlite is a volcanic rock excavated from mines. In order to make it expanded and porous perlite is heated to a high temperature. This expanded perlite is lightweight and has good insulation properties [27]. Lightweight perlite has a dry loss density of between 80 and 150 kg/m^3 and a thermal conductivity coefficient of 0.04–0.06 W/mK [8]. Due to its porous nature, perlite's water absorption was exceptionally high, reaching around 100% of its weight [19]. Table 1 and Fig. 1 show chemical composition and particle size distribution for the expanded perlite, respectively. The pertile and its chemical composition were provided from Arabian Vermiculite Industries [28]. Fig. 3-a shows the size of lightweight perlite aggregates with a maximum sieve size of No. 4 (4.75 mm), and its particle size distribution is shown in Fig. 1.

2.1.4. Expanded vermiculite

Vermiculite is a multi-layer micaceous mineral (i.e., hydrated magnesium aluminum silicate). Vermiculite expands 15 times to its original volume when heated up to 1600°F or when it is subjected to chemical reactions. As a result of this expansion, the substance's moisture absorption may reach up to 450 %, and its water retention capacities become enhanced [29]. The composition of the expanded vermiculite used is reported in Table 2, while Fig. 2 shows the particle distribution

Table 1
Chemical composition of expanded perlite [28].

Materials	Silicon (SiO_2)	Aluminum (Al_2O_3)	Potassium (K_2O)	Sodium (Na_2O)	Iron (Fe_2O_3)	Calcium (CaO)	Magnesium (MgO)	Trace	Oxygen (by difference)	Bound Water
Weight %	33.8	7.2	3.5	3.4	0.6	0.6	0.2	0.2	47.5	3

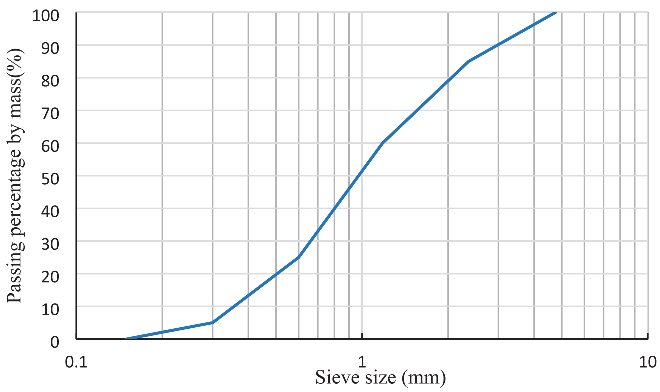


Fig. 1. Sieve analysis of expanded perlite.

size of the expanded vermiculite. The vermiculite and its chemical composition and particle distribution size was provide from Arabian Vermiculite Industries Company [30,31]. The expanded vermiculite aggregate utilized in this investigation had a size range of 0.2–3 mm (Fig. 2 and Fig. 3-b), with a bulk density of 100 kg/m^3 and thermal conductivity of 0.06 W/m.K [25].

2.1.5. *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 a thermal conductivity of 0.036 W/m, a density ranging from 15 to 75 kg/m^3, and a water absorption of 1.5% [8]. The higher the density, however, the better insulation performance is achieved. The EPS utilized in this research was procured from the Al-Rashed Polystyrene Factory in eastern Saudi Arabia with beads ranging from 5 to 7 mm in diameter, Fig. 3-c.

2.1.6. *Volcanic scoria (VS)*

Volcanic basaltic rocks are the primary source of the lightweight material known as scoria. A total of 180,000 square kilometers of these rocks are found scattered throughout thirteen distinct lava fields known as Harrats in western Saudi Arabia [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 "local carbonate" aggregates, as illustrated in Fig. 4. Its thermal conductivity is 0.27 W/mK, and its absorption rate is 11%, while it has a density of 1500 kg/m^3 [32].

2.2. *Mix proportions*

After detailed preparatory experimentation in the laboratory, the mix proportions employed in the field were selected [19,21]. The proportion of the four-replacement inclusions was designed with a goal of optimizing both mechanical and thermal performance. The fine, coarse, and both aggregate (fine and coarse) sizes were replaced by weight with perlite, vermiculite, and scoria, respectively, while the coarse aggregate replaced the expanded polystyrene by volume because it is a very lightweight material, and it isn't easy to be replaced by weight. In the perlite blocks, the fine aggregate was partially replaced by weight with 30% of perlite. This mix was the optimal mix after 18 trial mixes were conducted [33]. The replacement (5% vermiculite by weight) was achieved with a partial fine aggregate for the vermiculite blocks. For the scoria block, the coarse aggregate was replaced by scoria aggregate with a change in the coarse to a total aggregate ratio (from 0.765 in control to 0.45 in scoria concrete mix) to provide the necessary cement paste to bind the scoria aggregate. In the expanded polystyrene block, 14 % expanded polystyrene was employed to replace the coarse aggregate by volume. The mix design of the vermiculite, scoria and expanded polystyrene blocks is the optimal mixes after several trial mixes were conducted elsewhere [21]. It is noted that all trial mixes for selecting the optimal dosages for each mix were conducted and discussed in detail in [19,21]. The w/c ratio was maintained in all combinations at 0.495% without using a superplasticizer. (see Table 3).

2.3. *Design features of the fabricated block mold*

For this field study, an innovative block steel mold with a dimension of 400 × 200 × 200 mm was manufactured. Al-Tamimi et al. [19] designed several geometries using ABAQUS software. The design was aimed at finding out the optimum design that optimizes the thermal and mechanical properties. Several variables were determined by considering the hollow ratio, thermal bridges, aspect ratio, cavity width, and quantity and arrangement of cavities [34]. A steel mold was manufactured with a geometry similar to the optimum geometry presented elsewhere [19] with a little change in the width of the thermal bridge, as shown in Fig. 5 (i.e. the weak point that connects the two portions of the block specimens was enlarged from 28 to 35 mm in width). All the dimensions in the block mold were determined based on ASTM C129 [35].

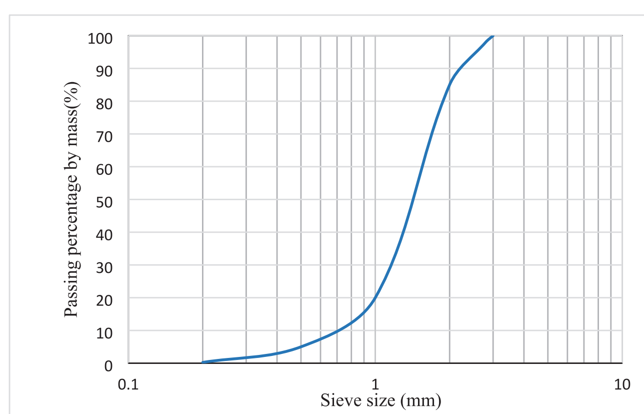


Fig. 2. Sieve analysis of expanded vermiculite.

Table 2
Chemical composition of expanded vermiculite [31].

Materials	Silicon (SiO_2)	Magnesium (MgO)	Aluminum (Al_2O_3)	Potassium (K_2O)	Iron (Fe_2O_3)	Calcium (CaO)	Titanium (TiO_2)	Fluorine (F)
Weight %	38.93	22.03	8.99	5.43	8.45	3.62	1.1	0.59

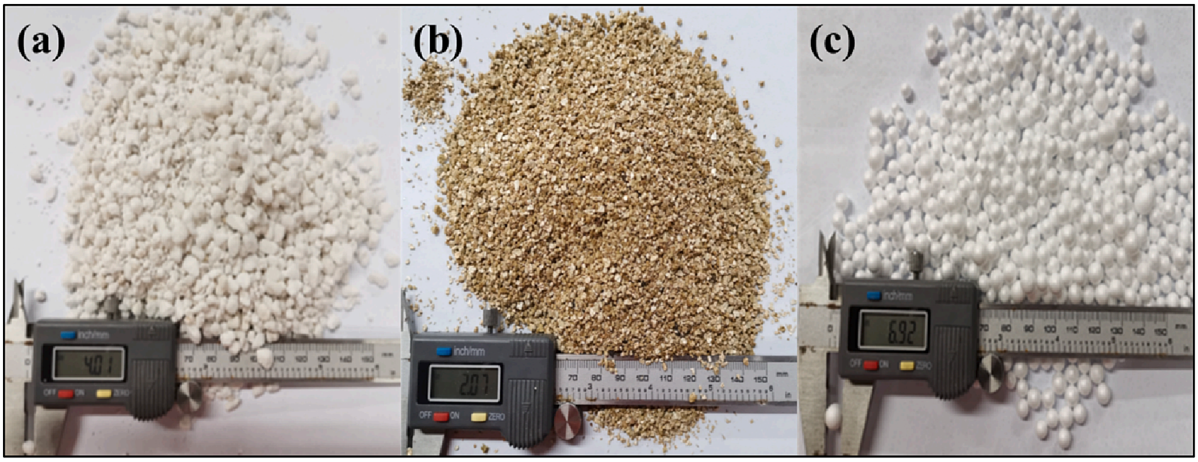


Fig. 3. Sizes (in millimeters) and typical appearance of (a) Perlite; (b) Vermiculite; (c) Polystyrene.

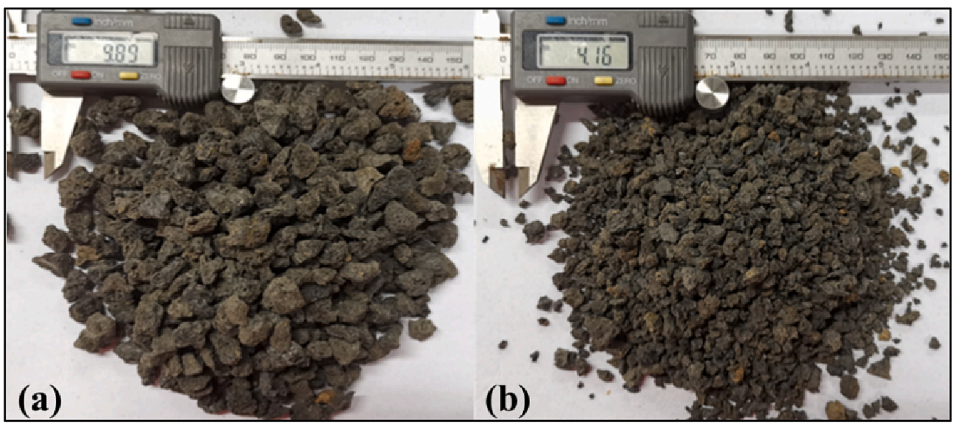


Fig. 4. Volcanic Scoria coarse aggregate (a) vS (# 3/8 in) (9.52 mm); (b) vS (# 3/16 in) (4.76 mm).

Table 3
Mix design for 1 m^3.

Materials	Control	Perlite	Vermiculite	Scoria	Polystyrene
Cement (kg)	195	250	250	195	195
Water (kg)	115	154	208	173	115
w/c ratio	0.495	0.495	0.495	0.495	0.495
Coarse aggregate (# 3/8 in) (9.52 mm) 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

2.4. Specimen preparation in the field: mixing, casting, and curing

The blocks were cast at a block factory in Dammam's Second Industrial Area, eastern Saudi Arabia. The cement, fine and coarse aggregates were mixed together until homogeneity was confirmed. After that, the light-weight materials were added to the mix, keeping the mixer rotating for 3 extra minutes until the mix became homogeneous. After homogenizing the concrete mix, the forklift delivered it to the block production machine with a hooper. After roughly 15 s of compaction with 70 kPa pressure, the mold was removed, and the hollow concrete blocks were eventually formed, as shown in Fig. 6-a. The blocks were then wrapped in wet burlap and sheets to keep the water in place for hydration (Fig. 6-b).

3. Experimental campaign

In this section, the produced concrete blocks were transported from the factory to the King Fahd University laboratory to assess their mechanical, physical, and thermal characteristics, as stated in Table 4.

3.1. Compressive strength

Each kind of block was tested for compressive strength using three full-size specimens after 7 and 28 days of curing according to ASTM C140 [36]. All tests were performed using an ASTM C1716 testing machine with a 3000 kN loading capability [37]. In accordance with ASTM C1552, the top and bottom of the samples were sealed with a 1 cm thick cement/sand mortar (1:3) Fig. 7 [38]. Solid steel plates were attached to the block's top and bottom for consistent weight distribution over the block's cross-sectional area. In this instance, the force was applied at a rate of 0.5 kN/s until the specimen failed. The failure load and average net area are used to calculate the net area compressive strength. The average net area is calculated by dividing the net volume obtained from the absorption test by the average height of the specimens. ASTM C129 specifies that non-load-bearing blocks should have an average net area compressive strength of 4.14 MPa [35].

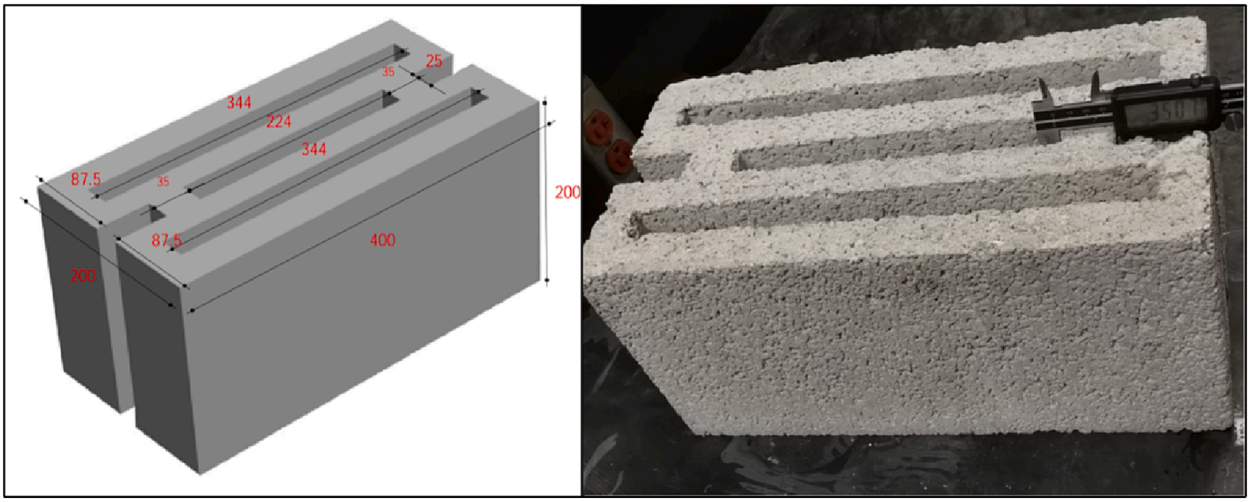


Fig. 5. Geometry of the manufactured blocks (all dimensions in mm).

Fig. 6. Manufacturing process: (a) Blocks casting machine; (b) blocks covered with wet burlaps and polyethylene sheets.

Table 4
The different test types, standards, and testing age.

Test type	Standard	Test specimens required	Overall tested specimens	Age of testing
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

3.2. Density and absorption

ASTM C140 was used to assess the density and absorption of the three types of hollow concrete blocks [36]. Each sample was weighed after immersion for 24 h in water (Wi) at 25 °C. The blocks were totally immersed in water and weighed while hanging using a steel wire (Ws), as shown in Fig. 8. Then, they were taken from the water for 1 min and wiped clean of any apparent surface moisture. The samples were heated at 110 °C for no less than 24 h in a well-ventilated oven until repeated weightings at two-hour intervals showed a weight loss of 0.2 % or less (W_d).

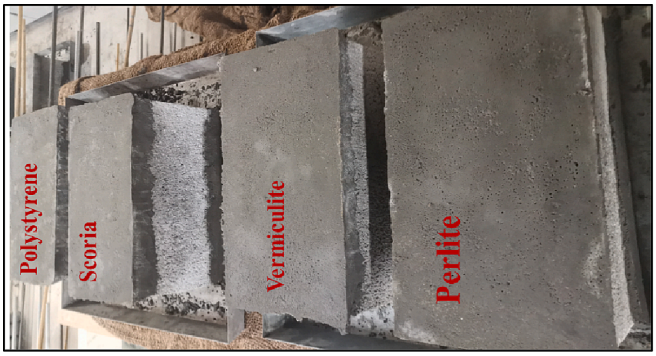


Fig. 7. Capping specimens for compression test.

3.3. Thermal conductivity

The thermal conductivity of the blocks was assessed using a FOX600 heat flow meter, as depicted in Fig. 9-a and 9-b as per ASTM C518 [39]. The test was conducted by simply placing a 610 × 610 mm specimen (with a maximum thickness of 203 mm) across two plates of varying temperatures [40]. The heat flow meter can test materials from 0.01 to 0.35 W/m.K and is compatible with external thermocouples with a maximum output of 2.5 W/m.K [40]. As illustrated in Fig. 9-b, a full-size specimen was examined on its own from each type of blocks. For the purpose of evaluating the impact of the thermal bridge created between the blocks, two blocks were bonded with regular mortar (double blocks). A reference sample with confirmed thermal conductivities over a wide temperature range was used to calibrate the testing machine before the selected samples were analyzed. Heating the samples in an oven for 48 h at 60 °C is a common practice to ensure that the moisture contents of the samples are eliminated and the samples are fully dried out before measuring their thermal conductivity. This is done to prevent any errors or inaccuracies in the thermal conductivity values that might be caused by the presence of moisture [33]. The cavities were adequately sealed to prevent air leakage and heat loss. To prevent heat from being distributed in transverse directions, the remaining area of the guard heater was covered with a polystyrene board, as demonstrated in Fig. 9-c. Also, rubber sheets were applied on both sides of the specimen so that the plates do not lose heat owing to friction. The upper and lower plates were held at 45 and 20 °C, respectively, with an average temperature of 32.5 °C. In order to improve the measurement precision, thermocouples were attached directly to the sample surfaces. The thermal conductivity was calculated using the sample thickness, temperature difference, and heat flux.

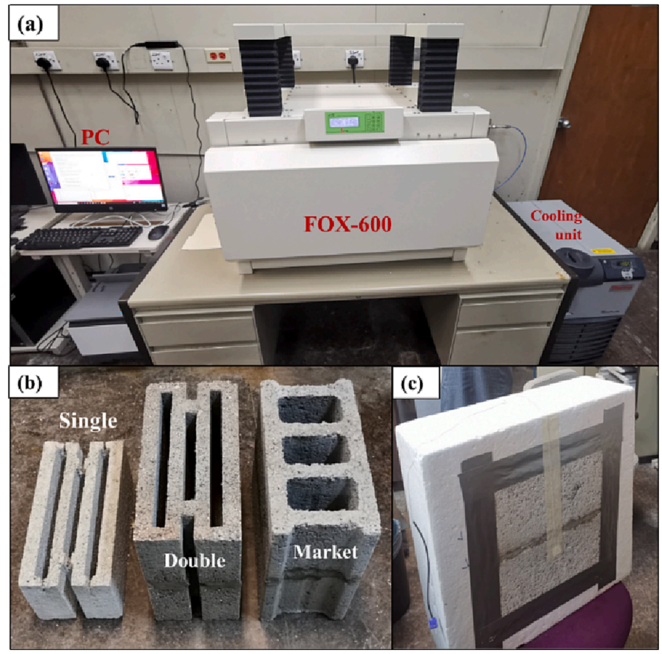


Fig. 9. (a) Setup of FOX600 instrument; (b) tested specimens; (c) specimens' preparation.

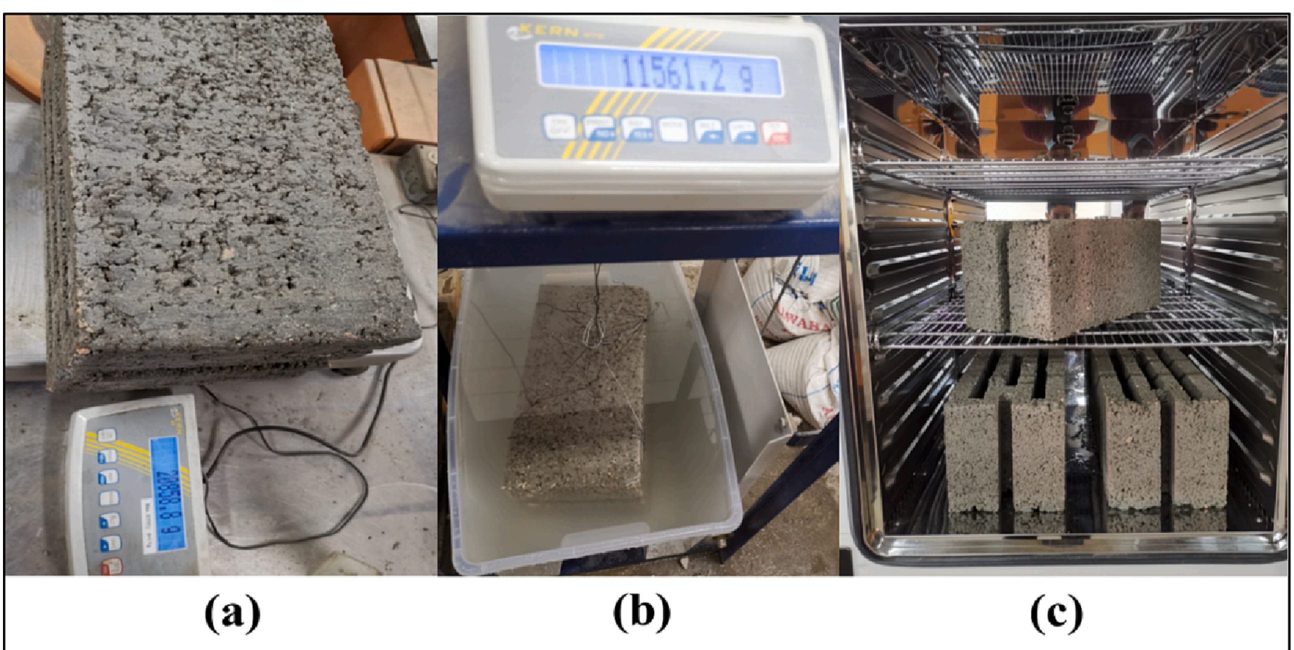


Fig. 8. (a) Immersed weight (Wi); (b) saturated weight (Ws); (c) oven-dry weight (W_d).

4. Results and discussion

4.1. Compressive strength

A compressive strength assessment was conducted after 7 and 28 days after producing the hollow concrete blocks to evaluate their commercial viability. The average net cross-sectioned area was used to assess the compressive strength data shown in Table 5 and Fig. 10 for each of the five mixes. After seven days of curing, the control block's strength was found to be 5.64 MPa, whereas the perlite and vermiculite blocks' strengths were almost 30 % lower than the control block. The strength of the scoria and polystyrene blocks had a drop of only 10 %. After 28 days of curing, the control, scoria and polystyrene blocks had almost the same strength of 6.0 MPa, and the strength of perlite and vermiculite decreased by 20 % compared to the control one. This reduction was ascribed to the weak structure of these materials, which caused the failure of the insulation particles rather than the hydrated cement or on the interfacial transition zone between cement paste and aggregate [25,41]. However, the variance reduction in the strength with time (7 and 28 days) in both perlite and vermiculite blocks compared to the control were reduced by 10 %. The reason behind decreasing the variance is due to either the moisture inside these particles, which can decrease the hydration with time [42], or due to the pozzolanic reaction of the vermiculite and perlite as they have a high content of silica, as shown in Tables 1 and 2. Similar behavior was observed when perlite and vermiculite were added to the concrete [43–45]. For the polystyrene blocks, it is possible that the smooth surface and rounded shape of polystyrene materials caused less adhesive bonding between the cement and the polystyrene particles, resulted a lower compressive strength [46,47]. It is noteworthy to report that the strength increased by 20 % between 7 and 28 days as a result of curing. Non-load bearing blocks must conform to the ASTM C129 standard, which sets the minimum standard requirement of 4.14 MPa for a 28-day test. Consequently, all the manufactured blocks met these criteria, as highlighted in Fig. 10.

It is worth mentioning here that the strength of the blocks produced in the factory should not increase dramatically compared to those produced in the laboratory [48,49]. However, the compaction and vibration method using an automatic concrete block production machine could reach a pressure of up to 70 kPa, while on the laboratory scale, the compaction was done manually. This could be ascribed to the effect of weather conditions in the field and curing methods [50].

Table 5
Density, unit weight, absorption, and compressive strength.

Block type	Oven dry density (kg/m^3)	Weight/Block (Kg)	Water Absorption		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 (100 %)	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

4.2. Density, unit weight and absorption

Each of the five types of manufactured hollow concrete blocks (Control, Perlite, Vermiculite, Scoria, and Polystyrene) had their oven-dry densities, unit weight, and absorption as listed in Table 5. The control block had the highest oven-dry density of 2091.15 kg/m^3. When compared to the control block without replacement, the perlite and scoria blocks had the highest density losses of 26 % and 20 %, respectively. A similar observation was noted in other researches [51,52]. The high dosage 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 responsible for the high reduction in density. The replacement of all limestone aggregate in the Scoria block with volcanic scoria aggregate (light-weight aggregate) was the main reason for the reduction in density as compared to the control block, as illustrated in Fig. 11. Although vermiculite and polystyrene particles had the lowest density compared to the other materials, they had the lowest reduction in density by only 5 % and 7 %, which could be attributed to the low dosage of inclusion in the mixture [21].

It must be noted that any block with an oven-dry density greater than 2000 kg/m^3 is considered a normal aggregate concrete block (ASTM C129), whereas blocks with densities between 1680 and 2000 kg/m^3 are considered medium weight, and those with densities less than 1680 kg/

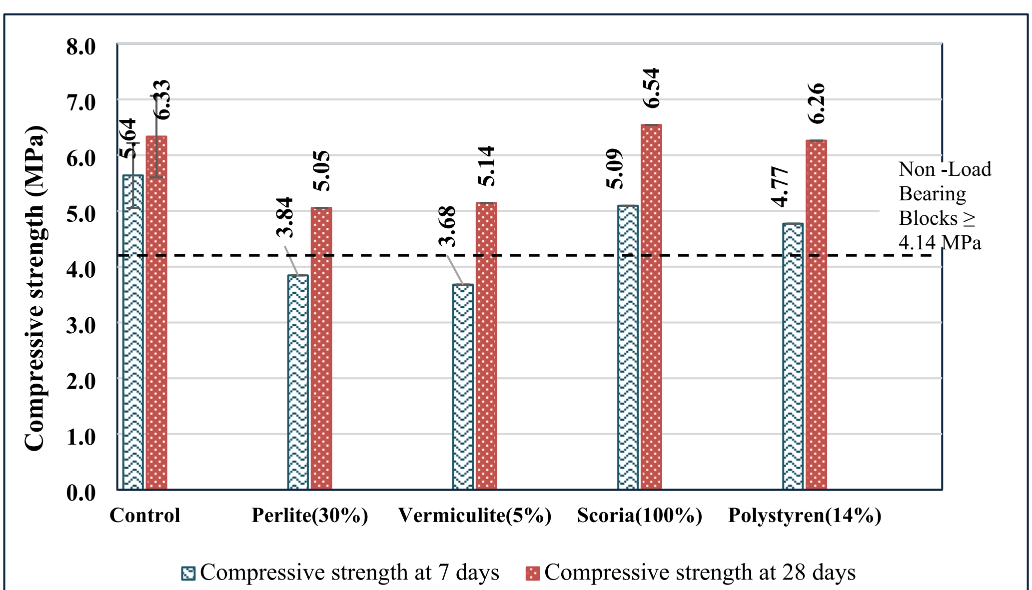


Fig. 10. 28-day compressive strength.

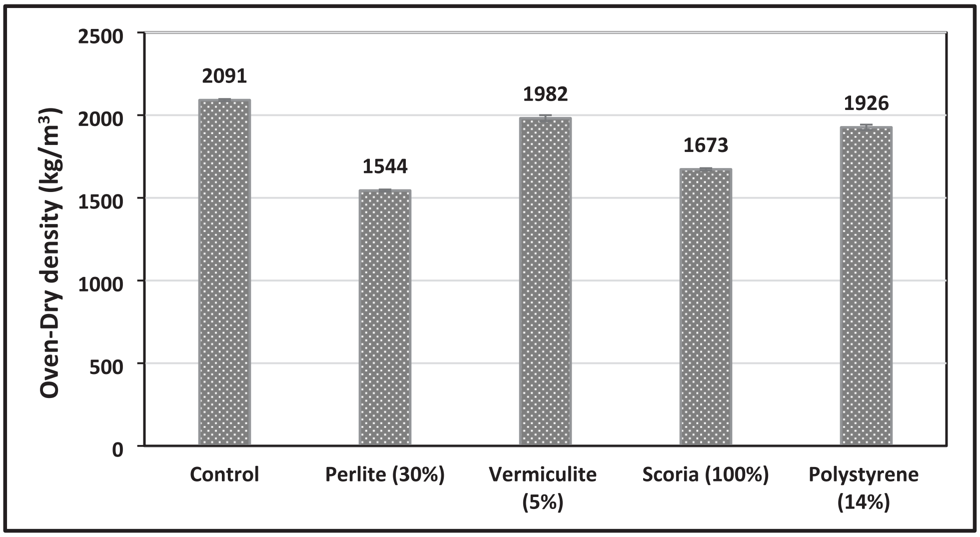


Fig. 11. Oven-Dry densities for the blocks.

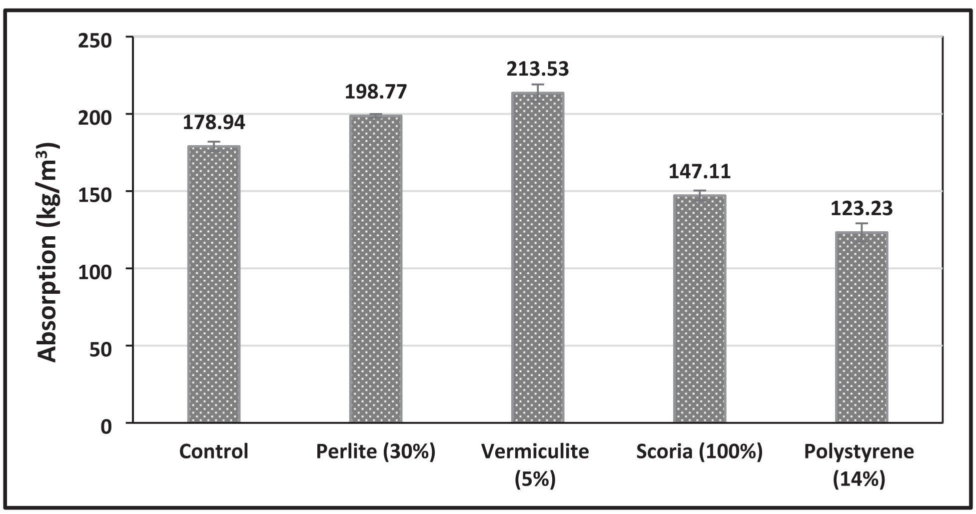


Fig. 12. Absorption of the produced blocks.

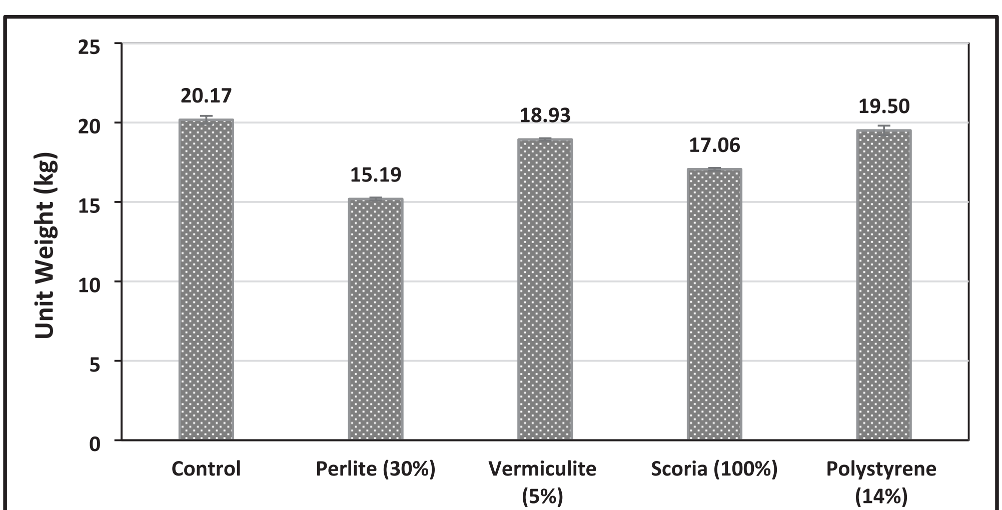


Fig. 13. Weigh of the individual blocks.

Table 6
Average thermal properties of single blocks.

Type of Blocks	Thermal conductivity (W/m.K)	Improvement in k value (%)	Thermal resistance R (m^2.K/W)	Increase 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 (100 %)	0.303	58.94	0.661	143.91
Polystyrene (14 %)	0.340	53.93	0.589	117.34

m^3 are designated as lightweight blocks [35]. According to this classification, perlite and scoria blocks are considered lightweight concrete blocks, whereas all the other types could be considered as medium-weight concrete blocks. The concrete blocks density is important as a lighter building material may carry less dead weight, which will lead to reduce the dimensions of the beams, columns, and foundations. Reduction in dimensions means a decrease in ultimate construction cost [53,54].

Fig. 12 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. These were higher by 20 % and 11 %, respectively, compared to the control blocks. 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 almost 100 % since both of these materials are porous in nature [55]. Scoria-manufactured blocks' water absorption was 147.11 kg/m^3, ranking beneath the control block by 18 %. It was found that polystyrene blocks exhibited the least amount of absorption by having a level of 123.23 kg/m^3, which could be attributed to the low of absorption ability of polystyrene [56]. It is noted that 208, 240, and 288 kg/m^3 are the ASTM C90 maximum water absorption values for normal, medium, and lightweight blocks [57]. The absorption ratings for all investigated block types were satisfactory and well within the range of this standard.

As expected, Fig. 13 indicates that the 20.17 kg weight of the control block was heavier than all the other hollow blocks produced using the four different substituted materials. In addition, the perlite hollow blocks weighted the least (15.19 kg) compared to the control blocks. This is a difference in weight by 5 kg (25 %). Furthermore, the weight of the scoria block is 15 % lighter than the control block, which is 17.06 kg. The vermiculite and polystyrene blocks were lighter than the control block by 6 % and 3 %, respectively.

4.3. Thermal properties

The thermal properties of concrete blocks are inextricably linked to the density, composition of the concrete, and the existence of air gaps within the concrete. The thermal conductivity of concrete is substantially higher than that of air. Hence, the presence of air gaps inside the concrete lowers its thermal conductivity [20]. Additionally, the insulation effect of the blocks is greatly affected by the thermal conductivity of the inclusions used in place of the conventional components. Two samples of each block types were analyzed independently and then joined by mortar to determine the impact of the thermal bridge generated by the joint mortar on this study. Their performance were also evaluated against that of a commonly used three-holed market block from the building industry. Table 6 and Table 7 provide the results for the thermal characteristics of the single and double blocks of all block types. It was found out that the market block has an average thermal conductivity (λ-value) of 0.738 W/m.k. Meanwhile, the thermal conductivity of the control blocks (our design without insulating materials) was reduced by 53 % (0.344 W/m.k) when contrasted with that of the market, which demonstrates that the block design shape has a significant influence on the block performance [58,59]. 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. This accounts for a 1 % reduction in thermal conductivity due to the fact that the amounts of vermiculite particles and polystyrene used were only 5 % and 14 %, respectively. In addition, the scoria and perlite blocks showed the greatest reduction in thermal conductivity of all the samples. Comparing the thermal conductivity of scoria blocks and perlite blocks with the market blocks, it was found out that they were reduced by 59 % (0.303 W/m.K) and 57 % (0.314 W/m.K), respectively. Furthermore, they were reduced by 12 % and 9 %, respectively, when compared to the control block. The results for the two blocks connected with cement mortar showed a similar trend to the single blocks in terms of a reduction in the equivalent thermal conductivity for the produced hollow blocks (53 % control, 60 % perlite, 54 % vermiculite, 61 % scoria, and 56 % polystyrene) as contrasted with the hollow market block, which had the highest thermal conductivity of 0.929 W/m.K. Further, as a result of the thermal bridge effect, the market block's thermal conductivity was almost 20 % higher than the single block, whereas it was only 5 % and 9 % higher than the other types, as shown in Fig. 14

In addition, all structures in Saudi Arabia are currently required by law to have a thermal insulation installed. The Saudi Building Code required a minimum R-value of 2.92 m^2.K/W for external walls [60]. Fig. 15 shows that the R-values for individual blocks produced in this study vary from 0.271 to 0.661 m^2.K/W, demonstrating a considerable enhancement in the thermal resistance that may reach up to 144 % on scoria blocks compared to the market blocks with a resistance of 0.271 m^2.K/W. The results of the R-value calculations would not meet the criteria of the Saudi Building Code, even if the thermal properties of these blocks have improved significantly. As a result, polystyrene boards and other forms of insulation may need to be added to the building envelope to achieve the desired thermal requirements.

Table 8 compares the lowest scoria blocks developed to other types of masonry blocks in terms of thermal conductivity. The scoria blocks have highly efficient thermal performance, as they were found to have significantly reduced thermal conductivity by 77 % compared to the normal hollow concrete blocks. Furthermore, when compared to the other types of insulated blocks, such as hollow blocks made of lightweight concrete (HBLC), hollow clay blocks (HCLB), hollow concrete blocks with body-added perlite and polystyrene, sawdust and lime sludge hollow blocks, the scoria insulation hollow block shows an impressive reduction of the thermal conductivity by almost 2–52 %.

Table 7
Average thermal properties of the double blocks (two connected blocks).

Type of Blocks	Thermal conductivity (W/m.K)	Improvement in k value (%)	Thermal resistance R (m^2.K/W)	Increase 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 (100 %)	0.362	61.03	0.557	157.87
Polystyrene (14 %)	0.405	56.40	0.498	130.55

This makes the scoria insulation hollow block an ideal option for construction projects that prioritize energy efficiency and thermal insulation. The results of this study indicate that the scoria insulation hollow block has a superior thermal performance compared to other

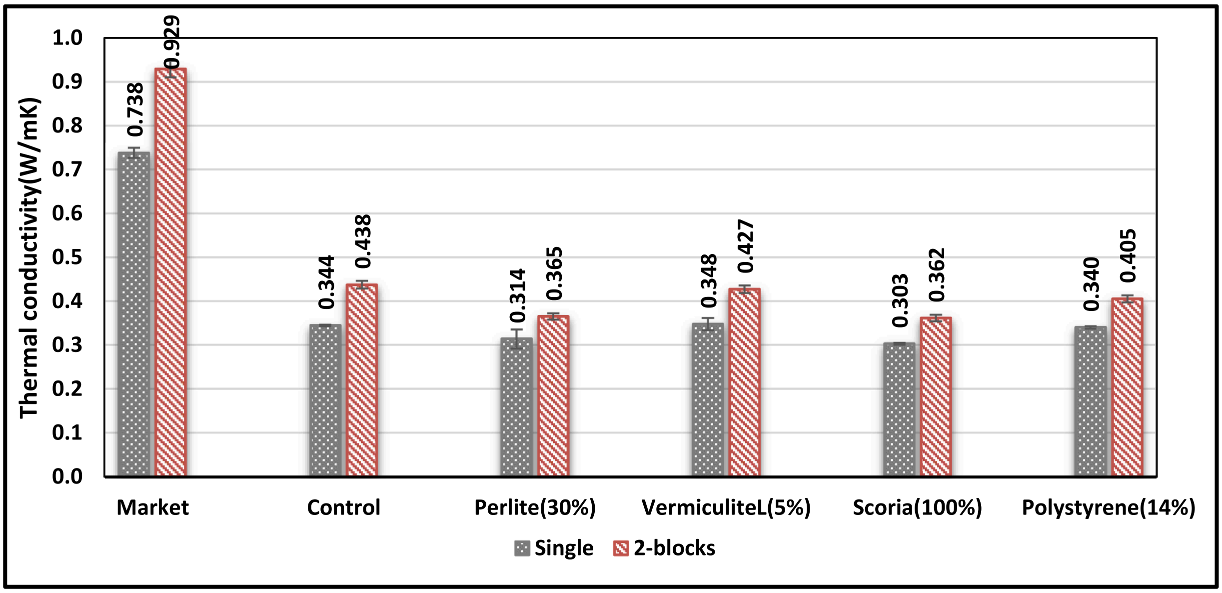


Fig. 14. Comparison of single and double blocks' thermal conductivity.

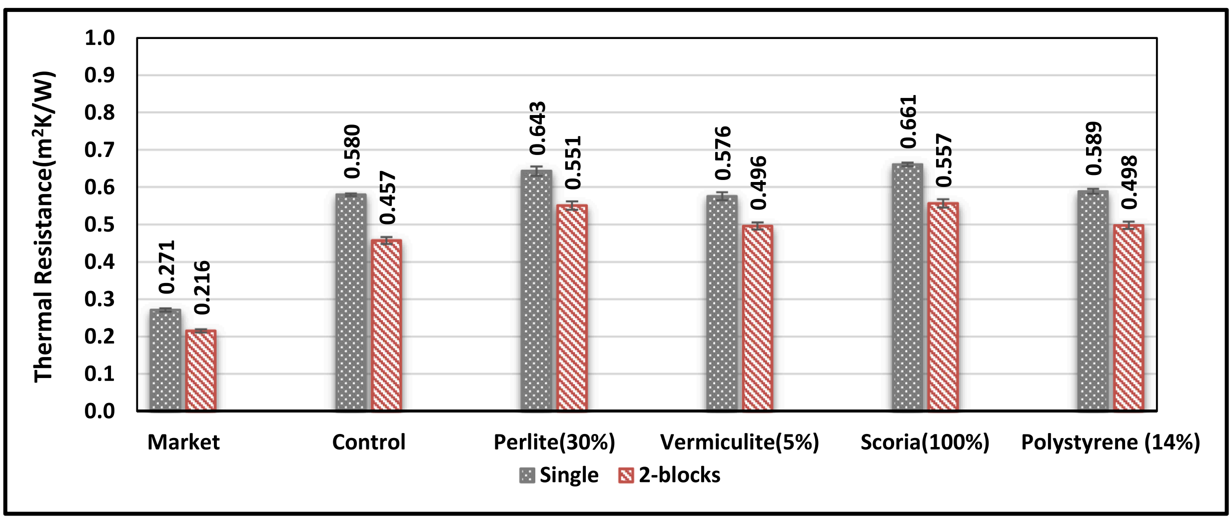


Fig. 15. Single and double block thermal resistance.

types of masonry blocks making it a highly sought after material for sustainable construction projects.

4.4. Energy-Efficient and economic analysis

In order to assess the economic visibility of each wall per square meter, the cost of each product in the mix design, the operational cost, and the profit rate were determined based on the market price of the masonry blocks in eastern Saudi Arabia. The costs of the masonry hollow block walls are shown in Table 9, which includes the costs of all the materials [21]. Market concrete blocks currently cost \$0.42 each, while the control blocks in this study cost \$0.41 each. The 0.01 \$/Block disparity between the estimated and market pricing values enforced the confidence about the validity of the price calculation. Newly cast blocks are cheapest in scoria, roughly at 0.46 \$/block, and in polystyrene at 0.50 \$/block, respectively. The price of perlite is reflected in its blocks, which cost the most at \$1.11 per block (see Table 9).

All the blocks experimented 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 considered. One should figure out how much energy the air conditioner uses by using Eq. (1), which is based on the thermal resistance (m^2 °C /W) of the wall, D. This is equivalent to 2185 K days based on a temperature of 24.5 °C at Dhahran, eastern Saudi Arabia, and the air conditioner's thermal performance coefficient (C = 2.16) [17,64]:

$$E = \frac{0.024 \times D}{R \times C}\ \mathrm{kWh/m^2} \tag{1}$$

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

$$EC = ET \times E \tag{2}$$

While the net present value (NPV) 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) [17]:

$$NPV = PWF \times EC + BC \tag{3}$$

The PWF may be calculated using the formulae in Eq.(4), where (i =

Table 8
Comparison of the thermal conductivity for different hollow concrete blocks.

Author	Type of Blocks	Thermal conductivity (W/m.K)	Improvement in λ-value (%)
This work	Scoria	0.362	–
Krstic et al. [61]	Hollow blocks made of lightweight concrete (HBLC)	0.370	2
	Concrete with recycled crushed brick and ground polystyrene (RBC-EP)	0.380	2
	hollow clay blocks (HCLB)	0.480	25
Al-Hadhrami et al. [17]	Hollow concrete block with body added perlite	0.489	26
Aftab et al. [62]	Hollow clay block with body added polystyrene	0.473	23
	Normal hollow blocks	0.976	63
Aljabri et al. [63]	Normal hollow blocks	1.600	77
	Hollow block with polystyrene	0.626	42
	Hollow block with vermiculite	0.760	52
Blanco et al. [54]	Hollow blocks with lime sludge	0.630	43
	Hollow blocks with saw dust	0.600	40

2.5 %), (e = 2 %), and (n assumed to be 40 years) represent the discount rate, inflation rate, and the block's lifetime in Saudi Arabia, respectively [17,65,66]:

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

$$\mathrm{PWF} = \mathrm{n} \times (\mathrm{i}+\mathrm{e})\mathrm{for\,e} = \mathrm{i} \tag{5}$$

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 10 and Fig. 16. The energy consumption for the market block wall was 112.40 kWh/m^2, which was dramatically dropped by almost 53.13 % by developing the innovative blocks. Insulation blocks could reduce energy consumption by up to 60 %. When the market blocks are used, the anticipated cost will be 7.5 US dollars per square meter per year, according to the energy pricing of the Saudi Electricity Company (6.67 cents/kWh). As a result of implementing the control block, the price per square meter drops to \$3.54, with a savings of \$3.95 (or more than 50 %). The findings confirmed that scoria is the best alternative of block, saving up to 68.81 kWh/m^2 and 4.6 \$/m^2 per year, about 2.6 times less than the market wall, followed by the perlite block wall.

A payback period analysis is performed to determine the payback period for the different types of walls and divide the cost increase in the block by the yearly energy savings to get it back. This yearly cost saving for each square meter of wall surface equals the difference in the annual energy costs between the walls constructed with the developed blocks and those available in the market. The annual cost growth for walls equate the 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 1.76 and 1.86 years,

Table 9
Cost analysis of a masonry wall for 1 m^2.

Materials	Material cost per unit for the manufactured block walls										
	Materials	Control		Perlite		Vermiculite		Scoria		Polystyrene	
	kg/$	kg	$	kg	$	kg	$	kg	$	kg	$
Cement	0.060	195	11.70	250	15	250	15	195	12	195	11.70
Water	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	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									
Profit ($)		0.13									
Total cost/brick ($)		0.41		1.11		1.02		0.46		0.50	
mortar cost ($/m^2)		0.04									
wall cost ($/m^2)		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

Table 10
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 (100 %)	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

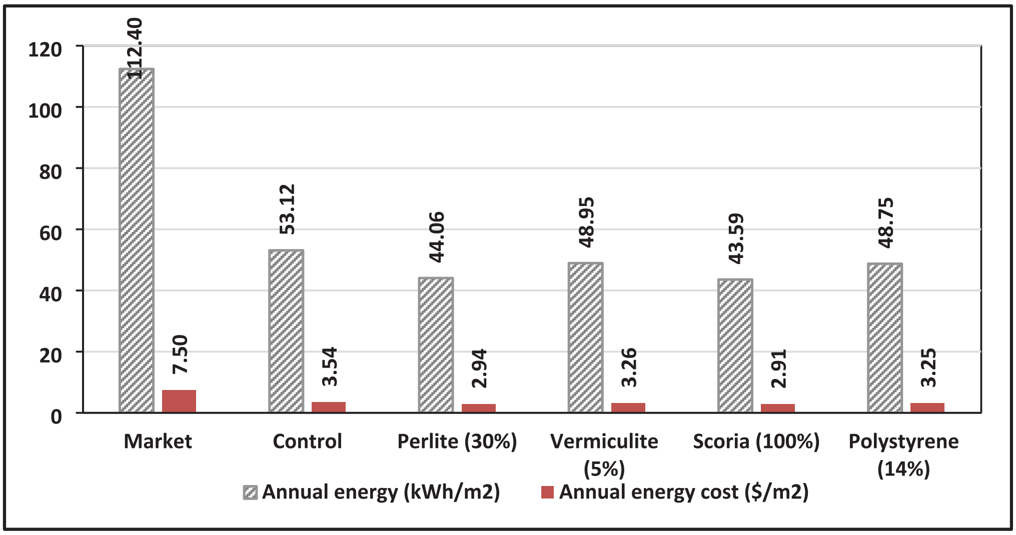


Fig. 16. Annual energy consumption and cost for the developed masonry walls.

respectively. When selecting thermal insulation block types, payback durations and energy-saving 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.

Comparison of the net present values (NPV) of the produced walls, which estimates the long-term profit of the blocks, shows that the scoria block wall had the least NPV of all the blocks considered in this investigation. It was 60 % less than the market block. In addition, the market concrete block's NPV is 272 $\$/m^2$, which could be decreased to \$131 per square meter by altering the design of voids in the 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 the commercial concrete blocks. The such enhancement will certainly lower the net present value from 272 to 109 $\$/m^2$, nearly 2.5 times, as illustrated in Fig. 17. Therefore, the traditional block walls should be replaced with volcanic scoria walls in Saudi residential and commercial construction.

4.5. Emissions of released carbon dioxide (CO_2) and fuel consumption

The increased exterior wall thermal resistance minimizes heat transmission into the construction industry; hence, fuel consumption and air pollution could also be reduced. Fuel combustion may be modelled using the following generic Equation [67]:

$$C_aH_bO_dS_eO_f + \beta X(O_2 + 3.76N_2) \rightarrow aCO_2 + \left(\frac{b}{2}\right)H_2O + (\beta - 1)XO_2 + eSO_2 + YN_2 \quad (6)$$

Oxygen equilibrium principles are used to determine X and Y parameters, which are represented by the following equations [67]:

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

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

By neglecting the emissions of CO_2, SO_2, and NOx, using Equation (9), one may estimate the quantity of products released from the burning

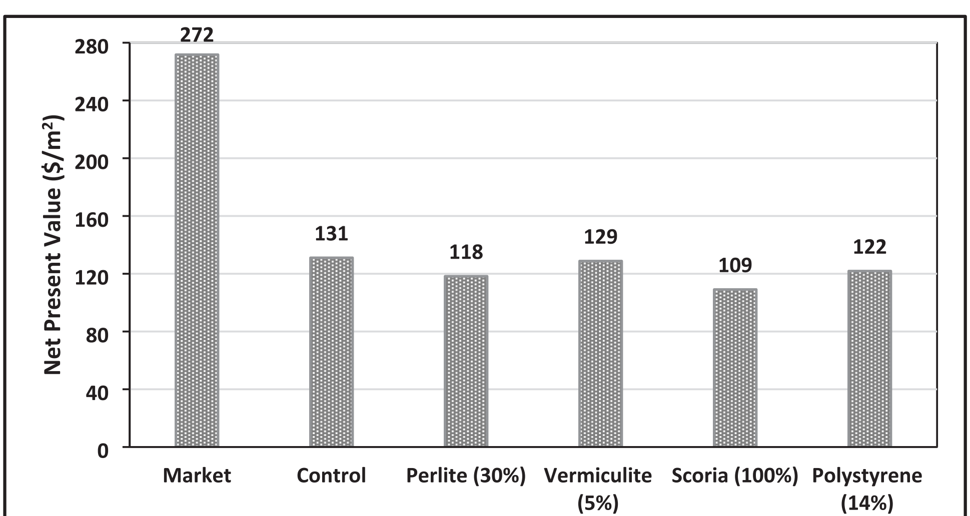


Fig. 17. Net present value using different masonry wall.

Table 11
Variables used to calculate 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	$C_{3.7}H_{4.1}$

of 1 kg of fuel [68]:

$$M_{CO_2} = \frac{aCO_2}{M} \equiv kg\frac{CO_2}{kg}/kgfuel \tag{9}$$

Fuel's weight in kilograms per kilomole (kg/kmol) may be calculated using the Equation below [68]:

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

Using the Equation below, we can figure out the emission of CO_2 [68]:

$$M_{CO_2} = \frac{44a}{M} m_{FA} \tag{11}$$

According to this Equation, m_{FA} is the total amount of fuel consumed each year, which can be calculated using the wall's thermal resistance (R_{wall}), the fuel efficiency of the space heating system (η_s), the daily temperature at the location of study (D), and the lower heating value of the fuel (LHV) [67]:

$$m_{FA} = \frac{86400D}{R_{wall}.LHV.\eta_s} \tag{12}$$

Table 11 summarizes the results of the emission computation, including all the parameters that were considered.

Six different types of blocks with four different types of fuels were used to assess the environmental consequences of thermal insulation walls. Table 11 lists the chemical formulas for many types of fossil fuels, including oil, natural gas, coal, and liquid petroleum gas (LPG). The fuel usage and CO_2 emissions are estimated based on the annual heating demand determined with dynamic approaches. Fuel usage and CO_2 emissions are reduced when the thermal resistance improves. Therefore, the control and scoria blocks may cut down fuel consumption by approximately 53 % and 60 %, respectively. On the other hand, when used in place of the market concrete blocks on the wall, the maximum consumption will be 43.2 kg/m^2 per year. The use of perlite blocks would also lower the usage by 58 %. Oil may be replaced with any fossil fuel, including coal, and the resulting percentages are relatively static (see Fig. 18). Therefore, the kind of wall, not the type of gasoline, is the most important factor in determining fuel consumption.

For LPG, oil and coal, the carbon dioxide emissions of the market concrete wall were 56, 67, and 135 (kg/m^2.year), respectively, whereas the CO_2 emissions of natural gas was 59 m^3/m^2. year (see Fig. 19). If the control concrete block is used, the emissions of LPG, oil, and coal may will be decreased to 26, 31, and 63 (kg/m^2.year), respectively. Furthermore, the emissions of natural gas could be reduced to 28 m^3/m^2.year. 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 CO_2 emissions by 2.4 times. It is noted that the oil fuel consumption is lower than gas used for all types of walls. However, it generates more CO_2 than gas does. Fig. 19 demonstrates that the carbon dioxide emissions of all fuel types were reduced by 2.1 times compared to the market wall. The volcanic scoria block can reduce CO_2 emissions by 2.4 times compared to the market wall and 1.15 times compared to the wall of control, while the Perlite block wall is the second best in terms of reducing CO_2 emissions. The idea is that these new walls will be better for the environment and cheaper than the traditional masonry walls.

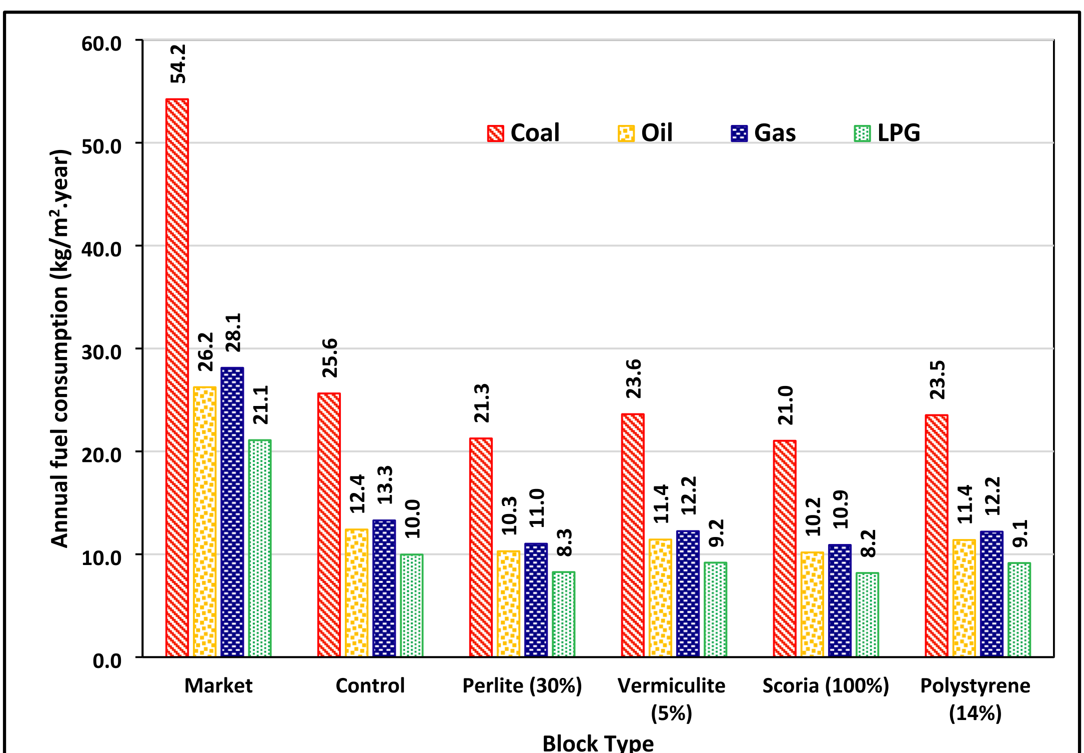
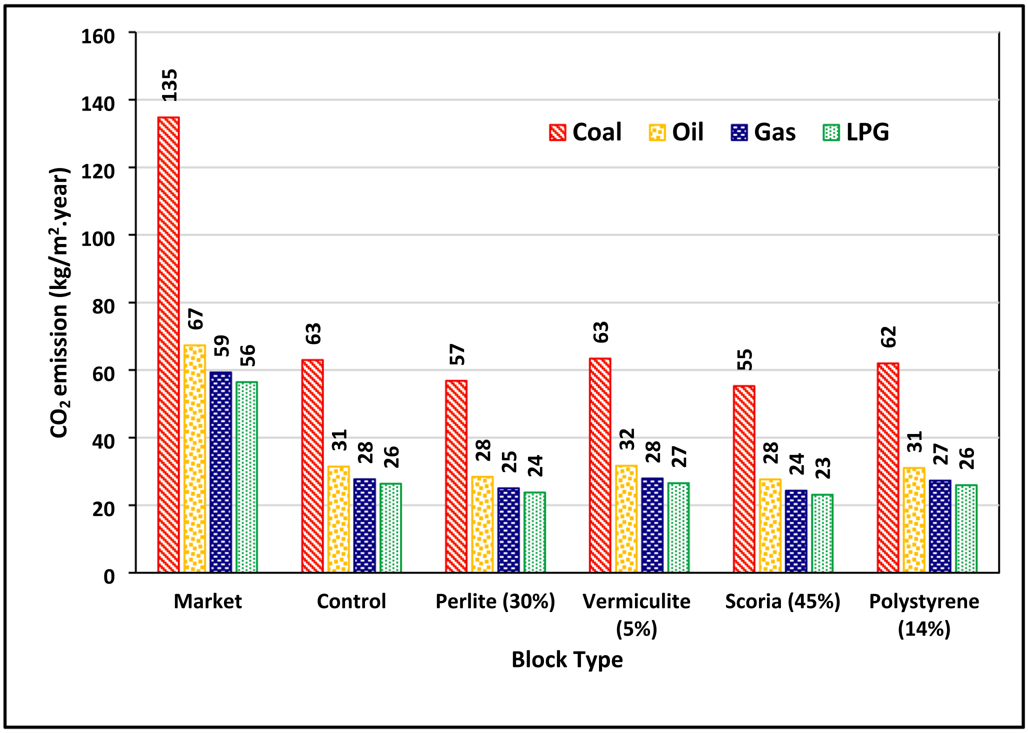


Fig. 18. Annual fuel consumption with various wall types.



Note that gas unit is (m^3/m^2.year)

Fig. 19. CO_2 emissions with different thermal insulation walls.

5. Conclusions

New masonry blocks were developed in the field using fully automated industrial processes for the use as exterior walls in industrial and residential structures. The blocks were made using lightweight materials such as vermiculite, scoria, and polystyrene instead of the coarse aggregates and perlite as the fine aggregates. The blocks were tested for compressive strength, water absorption, thermal conductivity, and resistance. They were also compared to the current market walls in terms of cost, oil usage, and CO_2 emissions to evaluate their ecological impact and long-term viability. This paper aimed to find a sustainable alternative to conventional concrete blocks that can be manufactured on-site and to explore the potentialities of using natural and industrial by-products to make greener concrete masonry units that meet the industry standards. The following conclusions may be drawn from the findings of the experimental program:

1. The newly designed blocks (made using perlite, vermiculite, scoria, and polystyrene) satisfied the non-load-bearing compressive strength requirement, as stipulated by ASTM C129. However, after 28 days of curing, the maximum reduction in the strength occurred on perlite and vermiculite blocks, which was 20% due to their high water-absorbing characteristics and their lightweight weak characteristics.
2. Perlite and scoria blocks lost a maximum density of 26.15% and 20%, respectively, when compared to the control block. Thus, they are considered as lightweight concrete blocks, whereas all the other types of produced blocks could be considered as medium-weight concrete blocks.
3. Vermiculite and perlite blocks had the highest water absorption of 214 and 199 kg/m^3, respectively, which were higher by 20% and 11%, respectively, compared to the control blocks. Absorption values of all block types were found to be within the permitted limit stipulated by ASTM C129.
4. The perlite hollow block was the lightest, with a 5 kg weight difference from the control block (20.17 kg), and the scoria block weighed 17.06 kg, which was 15 % lighter than the control ones.
5. In comparison to the hollow market blocks, the control block produced a 53.4 % lower equivalent thermal conductivity. Comparing the thermal conductivities of scoria and perlite blocks with the market blocks, it was found out that scoria and perlite blocks were lower 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 control block design wall could reduce energy consumption by about 53 % (i.e., 3.95 \$/m^2 annually) compared to the market block wall. Moreover, the scoria block wall was estimated to be 2.6 times lower cost than the market wall by saving 68.81 kWh/m^2 and \$4.6/m^2 annually.
7. The thermal resistance is increased by 158 % in the best wall (scoria block) compared to the commercial concrete blocks, thereby reducing the net present value from 272 to 109 \$/m^2 with a reduction of approximately 2.5 times.
8. In the case of market blocks, the annual oil consumption is 43.2 kg/m^2 per year, and CO_2 emissions is 135 kg/m^2. year. Scoria blocks might reduce these quantities to as low as 17.7 and 55 kg/m^2.year.
9. Perlite and vermiculite blocks have a high ability to absorb water, so avoiding using them in regions with very humid climates or coating their external surfaces with plaster or any type of polymer coating .

6. Recommendations

For future research on the developed blocks, the authors are suggesting the following valid recommendations:

1. Combining different materials like perlite as a replacement for cement and scoria instead of aggregate and filling the holes with polystyrene board to enhance the thermal resistance thereby leading to new and improved blocks with better thermal quality.

2. Using different curing methods like carbon dioxide to increase the rate of hydration and strength could result in producing more durable and stronger blocks.
3. Building a complete wall with plaster and measuring its thermal resistance in real-life conditions would provide more realistic and reliable data.

CRediT authorship contribution statement

Saeed M. Al-Tarbi: Writing – original draft, Methodology, Investigation, Formal analysis. **Omar S. Baghabra Al-Amoudi:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Mohammed A. Al-Osta:** Conceptualization, Methodology, Supervision, Writing – review & editing. **Waleed A. Al-Awsh:** Conceptualization, Methodology, Writing – review & editing. **M. Shameem:** Methodology, Writing – review & editing. **Mohammad Sharif Zami:** Methodology, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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