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Original Article

Thermal Performance and Mechanical Properties of Concrete Blocks Incorporating Plastic Bottle Waste with Crushed Clay Bricks as Coarse Aggregates

Abla Marie-Josée Nadège Kougnigan[1], John Mwero[2], Raphael Mutuku[3]

[1]*Department of Civil Engineering, Pan African University, Institute of Basic Sciences, Technology and Innovation, Kenya.*
[2]*School of Civil and Resource Engineering, The Technical University of Kenya, Kenya.*
[3]*Buildings and Civil Engineering Department, Technical University of Mombasa, Kenya.*

[1]*Corresponding Author : kougnigann@gmail.com*

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Abstract - *This research examines the mechanical characteristics and thermal performance of concrete masonry blocks made from clay waste bricks that have been crushed and used as coarse aggregates and incorporated plastic bottles. The study uses plastic bottles of 350 ml of volume and clay brick waste as a complete replacement for traditional aggregates to produce lightweight concrete. The blocks utilized in the study were 150mmx200mmx400mm in size. The blocks underwent testing for various properties such as water absorption, ultrasonic pulse velocity, density, compressive strength, and thermal conductivity according to ASTM C140 standards. The incorporation of plastic bottles created 23% voids in the blocks for the density test, and the results revealed that the block's performance met the ASTM C129 standards for load-supporting blocks with regard to its capacity to absorb water (134.9 kg/m^3), lightness, and strength (12MPa). Additionally, the study revealed a decrease in thermal conductivity by more than 50% compared to conventional concrete blocks without bottles. In conclusion, based on the fact that the blocks studied met the mechanical standards for load-bearing masonry units, it is proposed that the construction sector consider incorporating these types of blocks in areas where heat insulation is necessary to reduce building energy consumption related to cooling.*

Keywords - *Clay bricks, Lightweight concrete blocks, Plastic bottles, Thermal conductivity.*

1. Introduction

Concrete is a prevalent artificial building material globally due to its abundant raw material source, versatility, ability to take on various shapes and sizes, robustness in harsh conditions, adaptability to different dimensions and shapes, and cost-effective maintenance over its lifetime [1, 4]. The concrete industry is having a harder time adhering to today's worldwide sustainable environmental standards [5]; to satisfy the high demand of an ever-growing population [6], more and more buildings are being constructed, and the amount of concrete used is anticipated to rise to over 18 billion tonnes per year in 2050 [7, 8]. Using local natural aggregate at such a high level will hurt the environment significantly in addition to deltas, river erosion, and the removal of natural sand and gravel from beaches [9, 10].

Also, the construction sector's material waste rate has increased due to the demolition of buildings for comfort and modernization, causing waste management and environmental issues [11, 12]; for example, in 2011, clay-brick waste is estimated to be about 30–50% of construction waste. According to available statistics, Shelter Clay Products, Minna, Nigeria, throws away 30,000 broken, burnt clay bricks (200m3) capable of generating 351m3 of lightweight concrete per year as trash [13]. However, many of these bricks can be utilized to build low-cost residences, lowering the company's expenditures of transporting them to a remote place as garbage while also addressing the environmental issue of solid waste disposal [14-18].

Waste management in both rich and low-income countries is of major concern to governments [19]. Numerous industries produce non-biodegradable solid waste, such as plastics, chemicals, agricultural waste, and industrial byproducts, in huge amounts every year. Plastic waste is a major contributor to pollution globally; according to UNEP (UN Environment Report 2022), plastic waste generates 300 million tons of waste annually [21]. However, plastics have some sustainable qualities, such as versatility, lightness, hardness, and resistance to chemicals, water, and impacts [22], which can make them suitable for construction alongside traditional materials such as bricks [11, 23-25].

Another major concern of the construction sector is building energy consumption management [26-28]. Most people do their daily activities indoors; buildings are where people spend their everyday lives. But, because of the high thermal conductivity of building materials, buildings in hot climates become so hot and uncomfortable for the inhabitants [29]. Seeking thermal comfort, building users nowadays use a lot of electrical appliances such as air coolers, air conditioners, and fans [30]. This results in buildings with high energy consumption and carbon dioxide production, leading to global warming [31-38].

Durable materials with good heat-shielding qualities and structural stability are necessary for energy-efficient construction. In order to lessen heat transmission, building insulation materials such as lightweight clay bricks, insulating concrete blocks, polymer foam boards, and pumice, made in various combinations, are utilized. [39].

As a result, there is a lot of interest in lightweight construction materials that have outstanding thermal qualities and satisfy all usage criteria for residential, commercial, and institutional structures. In most structures, the construction industry uses much concrete. If concrete blocks are improved by proper processing, they may have much reduced thermal conductivity and transmittance characteristics, which results in less heat loss through building walls. [40].

Our objective, therefore, is to assess the mechanical characteristics and thermal properties of concrete blocks made from clean crushed clay bricks and incorporating plastic bottles. The study's findings regarding the concrete blocks' capacity to absorb water, their compressive strength, density, and thermal conductivity are presented in this paper.

2. Methodology

2.1. Preliminary Tests and Materials Preparation

This study uses crushed clay bricks as Coarse Aggregates (CA) from Kenya Clay Products; Ordinary Portland Cement (OPC) class 42.5N; Sika Visco flow- 615 KE superplasticizer from SIKA Kenya Limited; from nearby garbage sites were gathered identical-shaped plastic bottles, and river sand as Fine Aggregates (FA) were from Meru, Kenya.

2.1.1. Fines Aggregates

The fine aggregates, river sand, were sundried to eliminate moisture. The sand was then subjected to a series of tests, including sieve analysis, moisture content, specific gravity, silt content, and bulk density. The tests were carried out in line with ASTM standards; Table 1 and Fig. 1 display the results.

2.1.2. Coarse Aggregates

The coarse aggregates used in this study were broken or rejected clay tile bricks during and after firing by manufacturers from Kenya Clay Products. Kenya Clay Products is the National firm supplying the whole country. As a result of its high manufacturing pace, the firm generates a huge amount of waste. The waste was collected and brought to the JKUAT University Civil Engineering Laboratory, where it was crushed with a hammer and sieved. According to ASTM standards, the coarse aggregates were tested for their properties using sieve analysis, aggregate impact value, specific gravity, aggregate crushed value, and bulk density. Table 2 displays the outcomes of these tests. Before casting, the coarse aggregates were washed through a 2.36 mm ASTM sieve and soaked in water for 24 hours. Fig. 2 presents the coarse aggregates' particle size distribution. Clean potable water was used to produce the blocks.

2.1.3. Cement

The cement's physical characteristics were evaluated after BS EN 196-3 (2016) guidelines; Table 3 displays the tests' results.

2.1.4. Super-Plasticizer

This study used the Sika Visco flow- 615 KE super-plasticizer, having a 1.08 specific gravity and a 34% solid content; it has a yellowish tint.

2.1.5. Plastic Bottles

The plastic bottles were gathered from nearby garbage sites, soaped and washed in water for this study. After being dried under the sun, the bottles were tied with soft wires two by two before being placed in the molds into two different arrangements A1 and A2. Fig 3 and 4 present the bottle arrangements in the results of the mold.

Table 1. Fines aggregates' characteristics

Test	Results	ASTM Requirements
Water absorption	1.49%	<2.3
Specific gravity	2.777	2.4 - 2.9
Silt content	4.53%	<6
Moisture content	0.7%	--
Finesses modulus	2.6	2.1 – 4
Bulk density	1456 kg/m3	1120 - 1680 kg/m^3
Voids	34.8%	<40%

Table 2. Properties of coarse aggregates' characteristics

Test	Results	ASTM Requirements
Water absorption	19.74%	<2.3
Specific gravity	2.605	2.4 - 2.9
Aggregate crushed value	15.19 %	<10%
Aggregate impact value	57.56 %	<30%
Compacted bulk density	1063.68 kg/m^3	-
Loose bulk density	921.78.67 kg/m^3	-
Voids	38.63%	<40%

Table 3. Cement properties

Test	Results	ASTM Requirements
Normal consistency	36%	-
Specific gravity	2.8	<2.9
Final setting time	249 min	<10 hours
Soundness	7 mm	<10 mm
Initial setting time	130 min	>60 min

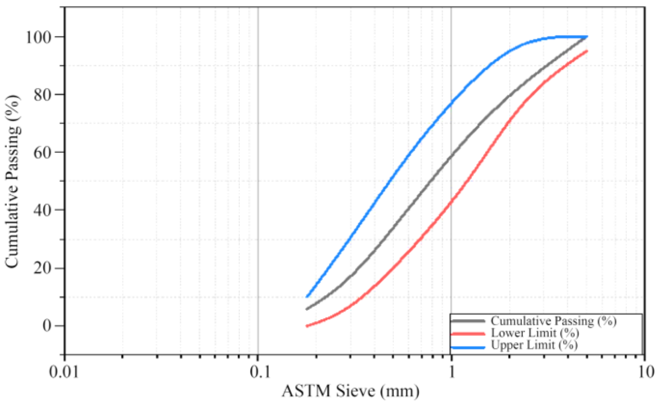


Fig. 1 Fine aggregates' particle size distribution

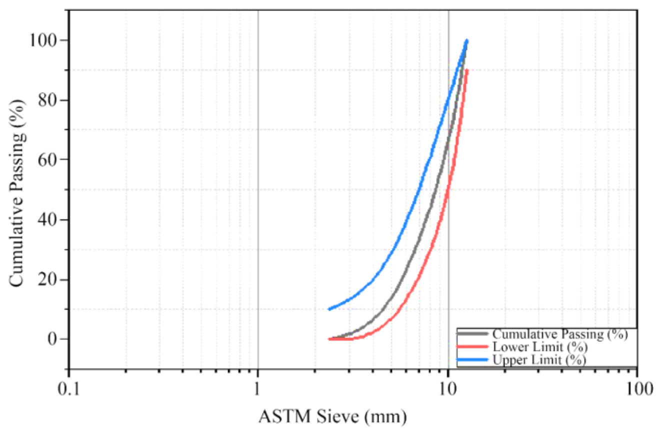


Fig. 2 Coarse aggregates' particle size distribution

2.2. Mix Design

A self-compacting concrete mix proposal [41] was used for the concrete mix design, with a 28-day target strength of 20 MPa. Table 4 displays the mix design for 1m3 of concrete, and Fig. 9 the fresh concrete.

Table 4. Properties of coarse aggregates' characteristics

Items	Proportions (kg/m^3)
Cement	422
Fine aggregate	916
Coarse aggregate	821
Water	190
Sp	3

2.3. Preparation and Curing Samples

The concrete blocks used had a size of 400x200x150 mm, as illustrated in Fig 3. The height and diameter of the plastic bottles that were utilized were 160 mm and 63 mm, respectively, and were arranged in two distinct configurations, which are depicted in Fig. 4 and 5. The concrete has been poured directly within the mold without any need for additional vibrating.

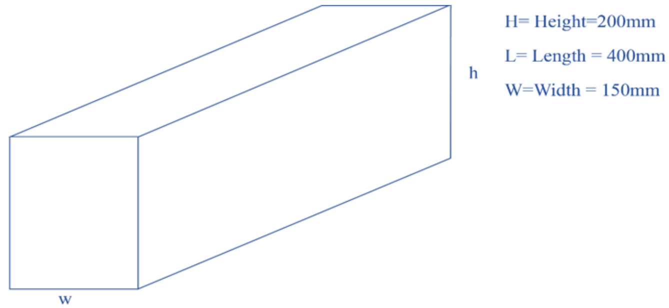


Fig. 3 Size of the concrete block

Source: Robleh (2021)

1st Arrangement

2nd Arrangement

Fig. 4 Upper view of the bottles' arrangement

2.4. Tests Methods

2.4.1. Workability Test

The slump was done to observe the fresh concrete's flow in accordance with ASTM C143/C143 M-10. Fig 9. presents the fresh concrete.

2.4.2. Compressive Strength

The concrete blocks incorporating plastic waste were tested on the 7-day, 14-day, and 28-day compressive strength tests according to ASTMC140. Fig. 11 was plotted based on the age of the concrete blocks.

2.4.3. Density and Absorption Tests

28 days after the production of the concrete blocks underwent water absorption and density tests, which were carried out in accordance with ASTM C642.

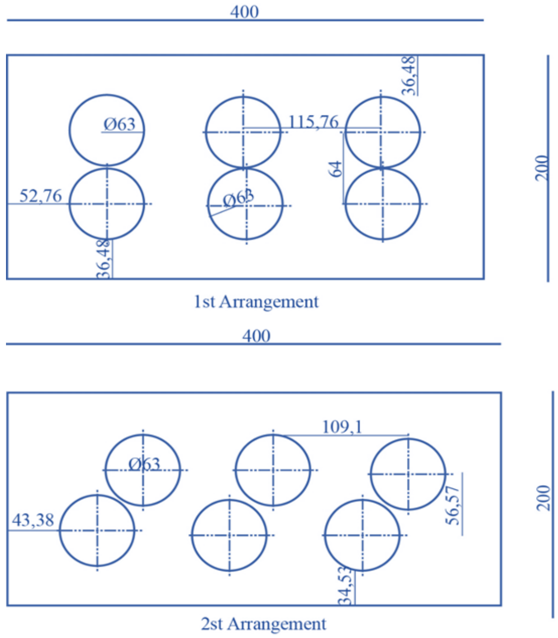


Fig. 5 Sketch

2.4.4. Thermal Conductivity Test

The concrete blocks' thermal conductivity was evaluated using the steady state method, which considers the transfer of heat zones in one dimension from high to low-temperature zones. The test was done in accordance with ASTM D 5930 - 17. 30 blocks were tested at 28 days of age. The testing was carried out using the heat flow meter apparatus (Fig. 6 and 7), which adheres to the ASTM C177 standards. The thermal conductivity is determined as follows:

$$q = -K\frac{\partial T}{\partial x} \quad (1)$$

$$Q = q\ A \quad (2)$$

$$Q = -KA\frac{\partial \mathrm{T}}{\partial \mathrm{x}} \quad (3)$$

$$K = \frac{Q \times L}{A \times (T_2 - T_1)} \quad (4)$$

Where:

- L = length of specimen;
- Q = heat flow;
- A = cross-sectional area;
- K = material thermal conductivity;
- $\frac{\partial T}{\partial x}$ = temperature gradient;
- T2 and T1 = temperatures.

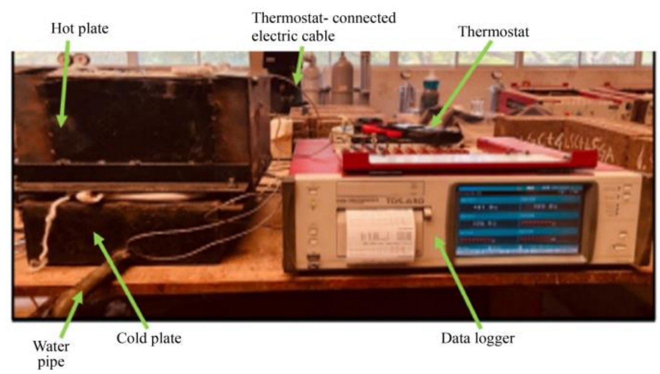
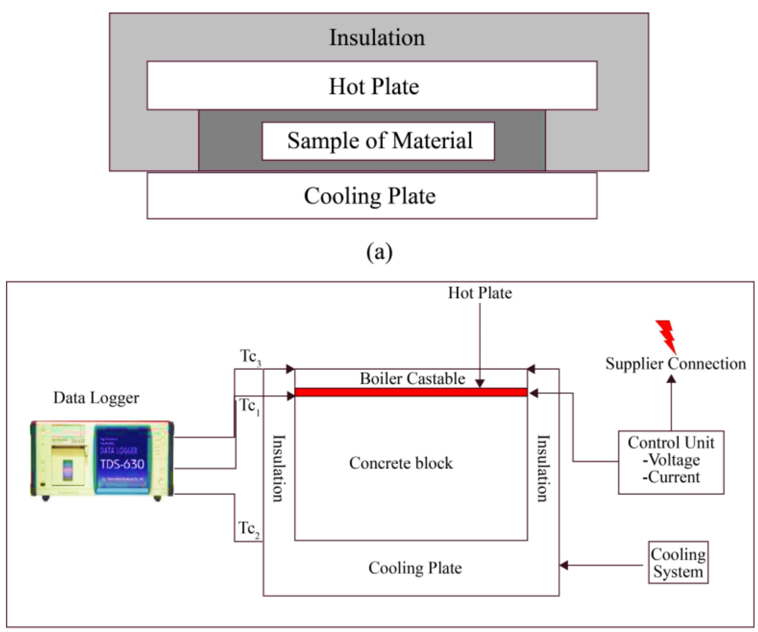


Fig. 6 Thermal conductivity setup (original picture)
Source: Robleh (2021)



(b)

Fig. 7 (a) and (b) Thermal conductivity setup (schematic)

2.4.5. Ultrasonic Pulse Velocity

Following the procedures indicated in ASTM C597, after 28-day curing, the UPV test was done on the concrete blocks using two transducers and the Ultrasonic Nondestructive Tester and two transducers. The test was carried out in three directions. The setup and methods of the UPV test are depicted in Fig 8.

Fig. 8 UPV test

Source: Robleh (2021)

3. Results and Discussions

3.1. Compressive Strength

Fig. 9 and 10 present the fresh concrete and the blocks tested.

Fig. 9 Fresh concrete

Fig. 10 Compressive strength test on the blocks

The compressive test results are plotted in Fig 11.

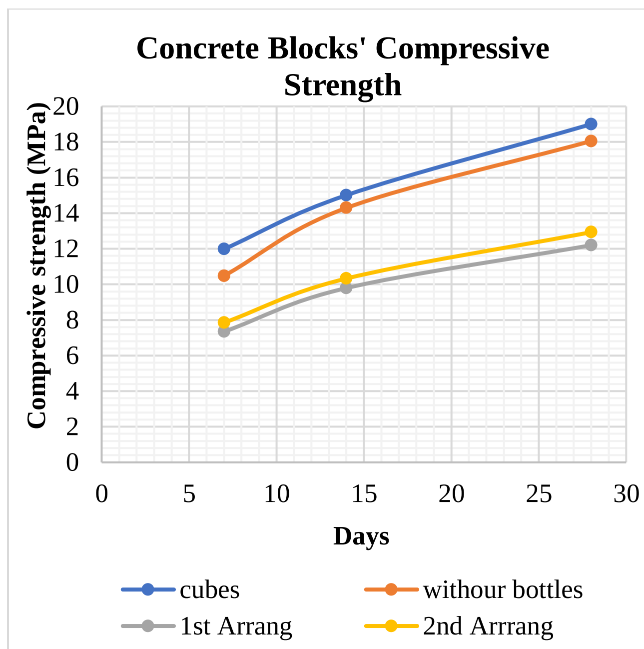


Fig. 11 Concrete blocks' compressive strength

The 28-day compressive strength performance of concrete cubes was 19MPa. The 28-day compressive strength of concrete blocks with bottles and the blocks without bottles was 12MPa and 18.05MPa, respectively. Concrete hardening, or curing, refers to the process via which the concrete gains strength and hardness over time. However, the blocks with bottle curves are flatter than that of bottle-free concrete blocks.

According to [23] [25], this could be explained by the fact that the walls of the sides of the blocks with bottles are too thin; the blocks may fail to collapse as a whole but buckle locally instead (as shown in Fig 12).

Fig. 12 Local failure of concrete

As shown in Fig. 11, the compressive strength of the concrete blocks with bottles is lower than that of the concrete blocks without bottles. After testing, and as reported by [25], [42], the net area of the concrete influences the concrete blocks' compressive strength.

The fact that the compressive strength [43], [44] was given on the gross area of the blocks might have contributed to the lower strength of the blocks [45]-[47] because the area carrying the load is much smaller than assumed due to the voids introduced by the bottles in the blocks.

Similar researchers [23], [48] stated that the decrease in compressive strength of the blocks with bottles compared to the bottle-free blocks, as shown in Fig. 11, can be explained by the presence of voids introduced by the bottles in the blocks the presence of holes weakens the block and reduces its ability to resist compressive forces.

The 28-day compressive value of blocks with the 1st and 2nd arrangements is 12.46 MPa and 12.89 MPa, respectively. The strength reduction compared to blocks without bottles is 48.59% for 1st arrangement and 43.99% for 2nd arrangement. There is a slight difference in the compressive strength for either arrangement of the bottles in the concrete blocks.

As reported by [49], concrete blocks' compressive strength is influenced by a number of variables, including their size and distribution of voids. Concrete blocks with uniform voids (2nd arrangement) throughout their length have a more homogeneous structure and can distribute stress evenly, resulting in higher compressive strength.

Conversely, blocks with voids concentrated at specific points (1st arrangement) are more likely to experience concentrated stress in those areas, leading to localized failure and lower compressive strength. Additionally, the shape and size of voids can also affect the compressive strength, with larger voids reducing the strength of the block.

For both arrangements of bottles, the blocks met ASTM C129's requirements for a strength of 5 MPa for concrete masonry units.

3.2. Density and Water Absorption

Table 5 and Fig. 13 and 14 show the concrete blocks' density and water absorption results. According to ASTM C90 standards, all the concrete blocks with bottles might be categorized as masonry blocks that are lightweight when their dried density is 1680 kg/m3 or less, as reported in ASTM C90, 2016.

Table 5. Density and water absorption of the concrete blocks

Bocks	Weight (kg)	Dry density (kg/m^3)	Water Absorption (kg/m^3)	Water Absorption (%)
A0	24.06	2004.83	170.7	8.5
A1	19.14	1595.60	134.90	8.45
A2	19.14	1599.10	134.90	8.45

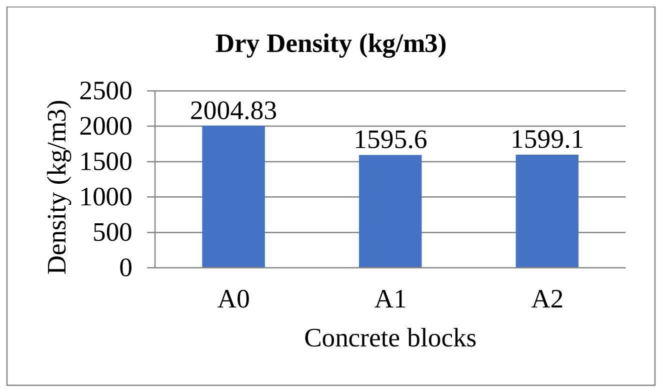


Fig. 13 Concrete block density results

The density for the concrete block without bottles was normal weight masonry block classification (density more than 2000 kg/m3) [50]. As noticed in Fig 13, blocks with bottles exhibited lower density compared to blocks without bottles; however, their density still falls in the range specified in standards for masonry units (ASTM C90, 2016).

The decrease in density can be explained by the 23% generated by plastic bottles inside the blocks [51]. This weight loss result is consistent with the findings recorded in [25], which established that the blocks with plastic bottles present a weight reduction and a lower density compared to bottle-free blocks.

As reported by [52], the voids due to the presence of plastic bottles in the blocks can significantly impact its thermal conductivity; materials with a lower density have lower thermal conductivity compared to denser materials with similar properties. This can be explained by the fact that the voids act as insulators, reducing the ability of heat to flow through the material [56]. Therefore, a hollow object is likely to have poorer thermal conductivity than a solid object of the same size and the same material.

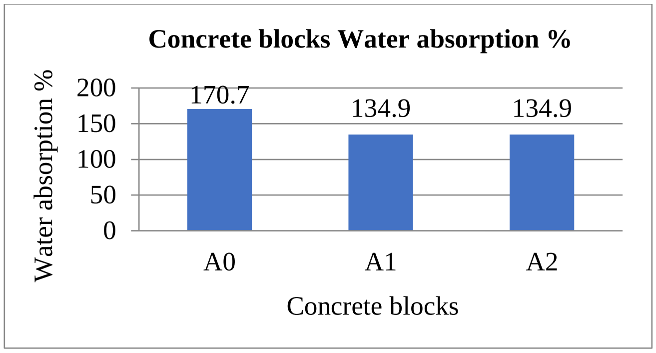


Fig. 14 Concrete blocks water absorption results

Fig 14 presents the concrete blocks' water absorption; the bottle-free concrete blocks' water absorption was 170.7kg/m^3 and was higher than that of concrete blocks with bottles, which had 134.9 kg/m^3 for the 1st and 2nd arrangements. According to [56], this difference in the weight of water absorbed is due to the incorporation of bottles, which has reduced the net volume of concrete materials responsible for water absorption in the other blocks [56]. ASTM C90 states that the highest amount of water absorbed by masonry units is respectively 320 kg/m3 and 240 kg/m3 for lightweight and normal-weight masonry units.

The water absorption of both arrangements of the concrete blocks with bottles (134.9 kg/m^3) was quite low compared to the upper limits of normal concrete blocks because of the hollow ratio incorporated by the plastic bottles in the concrete blocks [25], [56].

Consequently, the clay brick concrete blocks with and without bottles met the lightweight blocks' water absorption performance requirement.

3.3. Thermal Conductivity

Fig 15 presents schematically the Thermal Conductivity test outcomes for the concrete blocks. The data reflect a decrease in thermal conductivity for concrete blocks containing bottles, 53% for arrangement A1 and 55% for arrangement A2 compared with concrete blocks without bottles arrangement A0.

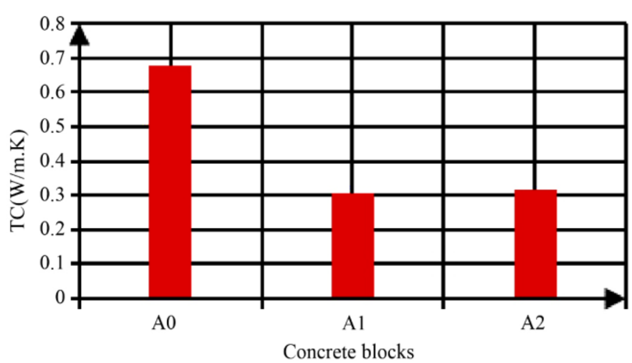


Fig. 15 Concrete blocks' thermal conductivity

The concrete blocks' temperature conductivity was 0.675 W/m.K, and the blocks with bottles were 0.308W/m.K and 0.314W/m.K for 1st and 2nd arrangements.

As reported by [25], [48], since the supply of heat energy and the specimens' block size and shape were the same, the reduction of thermal conductivity on the blocks could be explained by the bottle incorporation and arrangement.

According to [57]-[59], the heat flow was reduced by the plastic bottles by creating insulation. Incorporating plastic bottles into concrete blocks results in an increase in the volume of voids. These voids are filled with air, which has a lower thermal conductivity compared to concrete.

As a result, the presence of plastic bottles [53]-[55] leads to enhanced insulation. Similar trends in the literature were reported that adding plastic bottles to concrete lowers thermal conductivity [11], [23], [24]. Therefore, the result of this study agrees with previous studies and fulfills the goal set for the study to reduce thermal conductivity.

3.4. Ultrasonic Pulse Velocity

The test results for the concrete blocks are schematically presented in Fig 16.

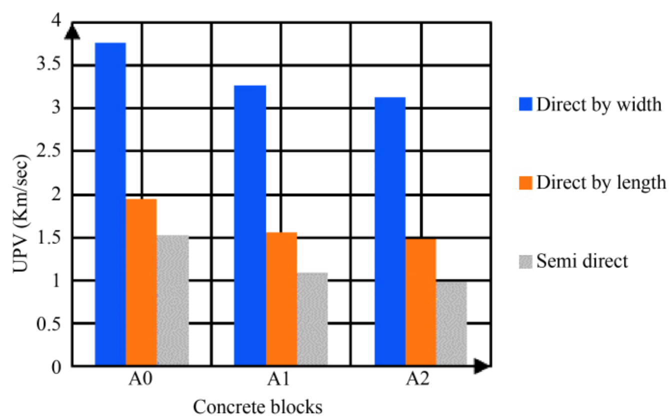


Fig. 16 UPV results of the concrete

According to these findings, the presence of plastic bottles in the concrete blocks has a huge impact on the UPV and can decrease the velocity of sound transmission. The UPV measures the speed at which sound waves travel through a material. The lower the UPV, the higher the sound insulation of the material. On the other hand, sound insulation measures the material's ability to block the transmission of sound waves through it. This could demonstrate that the masonry blocks with plastic bottles may have better sound insulation properties than traditional concrete blocks. As reported [25], ultrasonic pulse velocity (UPV) values predict the sound-insulating qualities of the material, and lightweight concrete with plastic can lower transmitting wave values compared to conventional concrete. Additionally, it is important to note that the UPV results are influenced by various factors, such as the arrangement and spacing of the bottles, the type of concrete mix used, and the curing time [20].

4. Conclusion

This study investigated the effect of incorporating plastic bottle waste into concrete blocks made with crushed clay bricks serving as coarse aggregates on their compressive strength, thermal conductivity, water absorption, ultrasonic pulse velocity, and density. The study's findings revealed that incorporating and arranging plastic bottles in the concrete blocks reduced their compressive strength. However, the blocks produced had compressive strength that met standard requirements for load-bearing blocks; hence, they are appropriate for use in buildings. Then again, these masonry blocks had several advantages compared to the normal concrete blocks, such as reduced weight (lightweight), improved sound insulation, and reduced heat transmission (heat insulation). All arrangements showed almost the same reduction in thermal conductivity. This paper highlights the potential uses of plastic bottle waste as a building material, promoting the reuse of waste materials like clay bricks in the construction industry while addressing heat insulation, which will contribute towards reducing building energy consumption for heating. In addition, the blocks give better insulation qualities while exhibiting acceptable strength. Hence, it is recommended to check fire resistance.

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