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Quarry Dust and Kenaf Core: An Ideal Waste By-Product as Alternative Fine Aggregate for Producing Lightweight Cement Brick

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Abstract

In response to growing environmental concerns and a scarcity of natural resources, finding sustainable alternatives to sand cement bricks has become a critical challenge. This study explores the feasibility of using quarry dust (QD) and kenaf core (KC) as eco-friendly replacements for conventional fine aggregates to produce lightweight cement bricks. Eight mixed proportions of bricks were manually prepared using a cement-to-fine aggregate ratio of 1:6 (volume ratio) and a water-to-cement ratio of 0.6, with conventional sand cement bricks as the baseline. The bricks were tested for density, compressive strength, water absorption, initial absorption rate, and thermal conductivity. The results revealed that QD significantly enhances compressive strength and density, achieving values of up to 35.14 MPa and 2,076 kg/m^3, representing a 70.6% improvement in strength compared to conventional sand cement bricks, which have a compressive strength of 20.6 MPa. Conversely, KC demonstrated its ability to reduce brick weight and thermal conductivity, with values as low as 527 kg/m^3 and 0.12 W/mK, respectively. These findings underscore the trade-off between strength and thermal performance when using KC. The study identifies an optimal mix of 25% KC and 75% QD, producing lightweight, non-loadbearing bricks with a density of 1,576 kg/m^3, compressive strength of 5.34 MPa, water absorption of 15.6%, initial absorption rate of 12 g/min./193.55cm^2, and thermal conductivity of 0.51 W/mK. While KC's incorporation delayed setting times and increased brittleness, adhesives or additives are recommended to mitigate these challenges and enhance practical applications. This research contributes to the advancement of sustainable construction by providing a viable pathway for developing eco-friendly, lightweight bricks that meet industry standards for non-loadbearing applications while addressing critical environmental and resource challenges.

1. Introduction

The increasing emphasis on sustainability within the construction industry has necessitated the search for environmentally friendly and economically viable alternatives to traditional building materials. Sand cement bricks, commonly utilised in construction, pose substantial environmental challenges, including resource depletion, habitat destruction, and pollution due to the extraction of natural sand [1]. Moreover, the rising costs and scarcity of natural sand amplify the urgency to identify sustainable substitutes that balance environmental preservation with functional performance [2].

Quarry Dust (QD), a by-product of rock quarrying, is a promising material extensively investigated for its potential as a partial replacement for sand in construction applications. Studies have shown that QD can enhance concrete and bricks' compressive strength and durability [3], [4]. However, its higher density raises concerns regarding its effect on lightweight construction requirements. Despite its established benefits, a significant research gap exists in understanding the performance of bricks when QD is used exclusively as a fine aggregate, particularly in conjunction with complementary materials that may mitigate its density challenges.

Kenaf Core (KC), derived from agricultural waste, has emerged as a lightweight, renewable alternative in construction. Previous studies suggest that incorporating KC into cement bricks may improve thermal insulation and reduce overall weight, aligning with sustainability goals [5]. However, research on the combined use of QD and KC as sole fine aggregates remains limited. Furthermore, the existing literature has not adequately addressed critical aspects such as fresh density, initial absorption rate, and comprehensive performance evaluations for these alternative materials [6].

The integration of QD and KC in cement bricks addresses two pressing challenges: reducing dependence on diminishing natural sand resources and repurposing industrial and agricultural waste. In Malaysia, where rapid urbanisation exacerbates ecological and resource concerns, the exploration of these materials is particularly relevant [7]. While previous studies have investigated QD's ability to enhance strength and sustainability, they largely overlook its implications for lightweight brick applications. Similarly, KC has been evaluated for its benefits in composite materials. However, its role as a primary fine aggregate alongside QD demands further exploration to establish practical guidelines for mix proportions and production techniques.

This study aims to bridge these gaps by providing a detailed evaluation of lightweight cement bricks utilising QD and KC as alternative fine aggregates. Adhering to ASTM C109/C109M–08 [8], the research investigates key physical properties, including hardened density, compressive strength, water absorption, and thermal conductivity. By focusing on bricks suitable for non-loadbearing applications, this study contributes to the ongoing discourse on sustainable construction materials, offering insights into the optimisation of QD and KC for practical and environmentally responsible building practices.

2. Materials and Methods

2.1 Materials

The primary raw materials studied in this research encompass Ordinary Portland Cement (OPC) as the binder, water crucial for cement, and fine aggregates comprising QD and KC, forming the fundamental materials assessed in this investigation. OPC labelled CEM I 42.5N, obtained from Ipoh, Perak, Malaysia. It has a bulk density of 1,197.56 kg/m^3 and a specific gravity of 3.15. Chemical analysis (Table 1) reveals Calcium Oxide (CaO) as its major component at 63.80% by weight, consistent with OPC's composition, which is rich in calcium silicates for binding alongside minor elements.

Table 1 *Chemical analysis of OPC*

Chemical Composition	Weight (%)
Calcium Oxide (CaO)	63.80
Silicon Dioxide (SiO_2)	19.30
Aluminium Oxide (Al_2O_3)	5.05
Iron Oxide (Fe_2O_3)	4.44
Sulfur Trioxide (SO_3)	4.05
Magnesium Oxide (MgO)	1.98
Potassium Oxide (K_2O)	0.43
Titanium Dioxide (TiO_2)	0.22
Sodium Oxide (Na_2O)	0.19

The water used in this study was sourced from the local supply network in Batu Pahat, provided by Ranhill SAJ Sdn Bhd, which handles water treatment and distribution in Johor, Malaysia. The treated water, with a pH of 6, was used for mixing purposes. Meanwhile, the QD for this research came from Medan Kuari Sdn. Bhd. in Minyak Beku, Batu Pahat, Johor, Malaysia, and was used as received without any additional treatment. The KC was utilised as an agricultural waste by-product from kenaf plants in Kelantan. It underwent processing at the CPMC LKTN facility in Kg. Air Tawar, Tok Bali, Pasir Putih, Kelantan, by the Lembaga Kenaf dan Tembakau Negara (LKTN) in Kota Baharu, Kelantan, Malaysia. This process involved extracting kenaf fibre from the bast, leaving KC as a waste by-product. The KC, with particle sizes passing 5mm, was employed in its as-received form. Sieve analysis following BS 812-103.1:1985 [9] determined the fine aggregate grading, as illustrated in Fig. 1.

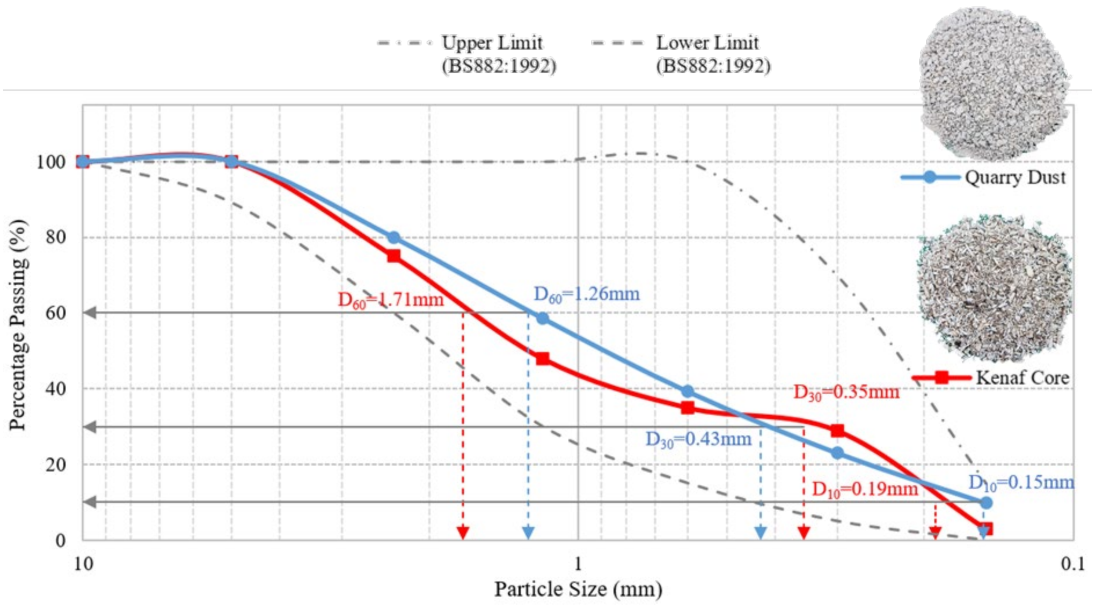


Fig. 1 *Particle size grading of quarry dust and kenaf core in compliance with BS882:1992*

Particle size analysis revealed that QD and KC had effective sizes (D_{10}) of 0.15mm and 0.19mm, respectively, with grain size diameters (D_{60}) of 1.26mm and 1.71mm and D_{30} values of 0.43mm and 0.35mm. Their coefficients of uniformity (C_u) were 8.3 for QD and 9.3 for KC, classifying both as clean sands. The materials predominantly passed through the No.4 sieve but were retained by the No.200 sieve, aligning with [10]. This particle size distribution differs from previous studies [6], [5] and [11], which used QD and KC with particle sizes exceeding 5mm and passing 3mm, respectively.

2.2 Mix Proportions

The bricks produced in this study adhere to BS EN 771-3 [12], maintaining dimensions of 215mm x 103mm x 65mm. To ensure precise raw material preparation, a 1:6 volume ratio for cement-to-fine aggregate, alongside a water-to-cement ratio of 0.6, as per JKR 20800-0226-20 [13], was converted into weight equivalents through loose bulk density. The mixing process was meticulously conducted using a mechanical mixer.

During the trial batch, an 18% reduction in the final wet volume of the fresh mix was observed, mainly due to friction between fine aggregates, which caused particles to compact more closely as water acted as a lubricant, reducing voids in the mix. Hand tamping during compaction further contributed to the 18% volume reduction, leading to an overall reduction factor of 1.59. While studies have suggested prewetting the QD before casting [14] and reported a reduction factor of 1.54 [15], this research highlights that preparing 1 m^3 of a wet mixture requires 1.59 m^3 of dry mix, considering the extent of void reduction. The study formulated eight mix proportions (P1 to P8), with P1 (100% QD) and P8 (100% KC) serving as controls. The impact of KC substitution with QD was assessed from 5% to 30%, while conventional Sand Cement Bricks (SCB) from A'Formosa Decoration Sdn Bhd were used as the comparative baseline. The specific quantities of raw materials utilised for each mix are detailed in Table 2.

Table 2 *Designation of mix proportions and their corresponding formulations*

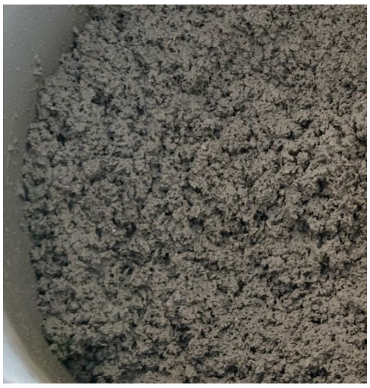
Code	Mix Proportions Design			Mix Ratio (Volume Basis)					Dry Mix Proportions in Weight Equivalent (kg/m³)			
	W-CR	C-AR	KC (%)	Cement	:	QD	:	KC	Cement	Water	QD	KC
P1	0.6	1:6	0	1	:	6	:	0	272	163	1,655	0
P2			5	1	:	5.7	:	0.3	272	163	1,572	8
P3			10	1	:	5.4	:	0.6	272	163	1,489	16
P4			15	1	:	5.1	:	0.9	272	163	1,407	24
P5			20	1	:	4.8	:	1.2	272	163	1,324	32
P6			25	1	:	4.5	:	1.5	272	163	1,241	40
P7			30	1	:	4.2	:	1.8	272	163	1,158	49
P8			100	1	:	0	:	6	272	163	0	162

2.3 Sample Preparation

The preparation of samples began with the precise weighing of all raw materials using an electronic balance, following the proportions specified in Table 2. The mixing process involved combining QD, KC, and cement in a pan mixer to produce a dry compound. Water was gradually added to ensure a thorough blending of the fine aggregate and cement slurry. This process was repeated for each mix proportion, as shown in Fig. 2.

(a)

(b)



(c)

Fig. 2 *Batching and mixing process (a) Weighed raw materials; (b) Mixed dry compound; (c) Well-blended mix*

The steel moulds were coated with oil to prevent adhesion, and the fresh mixture was cast into the moulds. Hand-tamping, in accordance with ASTM C109/C109M–08 [8], was performed by compacting each layer with 32 tamping strokes, repeated across three layers. Excess material was removed, and the surface was levelled, as illustrated in Fig. 3.

(a) **(b)**

Fig. 3 *Casting process (a) Cast using manual hand tamping; (b) Troweled out and levelled the surface*

After casting, the samples were allowed to rest undisturbed for 24 hours before demoulding. Following the methodology outlined in previous studies [16], the demoulded samples were systematically labelled and placed under plastic sheets for a curing period of seven days. After this initial curing phase, the samples were subjected to air curing until the 28th day, as depicted in Fig. 4. It is important to note that the samples containing KC exhibited a delayed setting time, requiring a prolonged demoulding period of four days post-casting, which deviated from the conventional 24-hour timeline.

(a) **(b)** **(c)**

Fig. 4 *Curing process (a) Fresh mix in steel mould; (b) Curing under the plastic sheet; (c) Air curing under room ambient surface*

A total of 120 samples were prepared for testing, with each mix (P1 through P8) subjected to various assessments. Fresh density measurements were recorded immediately after batching, with three readings taken per mix. For the 7-day compressive strength test, three samples from each mix were tested, resulting in a total of 24 samples. Similarly, 24 samples were allocated for the 28-day hardened density test, and these same samples were subsequently used for the 28-day compressive strength test. Water absorption was evaluated on 24 samples after 28 days of curing. Thermal conductivity was measured on 48 samples (six from each mix), with two samples required per thermal conductivity measurement. The results for thermal conductivity are based on the average of three readings, with each reading involving two samples. Since this test is non-destructive, 40 of these specimens were later used for the initial rate of absorption (IRA) tests. The IRA results were based on the average of five samples per mix, as stipulated in ASTM C67-11 [17].

2.4 Test and Measurement

The brick samples were assessed using several standard tests, beginning with the freshly mixed density test, in accordance with ASTM C138/C138M-13 [18]. This procedure involved a cylindrical metal container with a known volume of 0.0028 m^3. The mix was divided into three equal parts, with each segment compacted by 25 strokes from a tamping rod, accompanied by side taps to eliminate air voids. The surface was levelled using a flat plate, and density measurements were recorded from three different readings to ensure accuracy and consistency.

The 28-day hardened density test followed BS EN 12390-7 [19], where the mass of the samples was measured using digital balances with an accuracy of 0.01%. This test provided critical data on the mass and volume characteristics of the bricks, which are essential for evaluating their physical properties and suitability for construction applications.

The compressive strength test, conducted following ASTM C140-11a [20], involved the application of a uniform load to the samples using a 3,000 kN capacity compression test machine. The test was performed at both 7 and 28 days, with a constant loading speed of 3.0 kN/s. Excess moisture was removed from the samples before testing, and the samples were placed between the machine's lower and upper platens for compression. This procedure ensures an accurate assessment of the structural integrity and performance of the bricks under compressive load.

Water absorption, a key indicator of the durability of the bricks, was measured following ASTM C140-11a [20]. The samples were conditioned at a temperature of 24 ± 8°C until equilibrium was reached. Subsequently, they were immersed in water at 26.7°C for 24 hours, drained for 60 ± 5 seconds, and weighed. Afterwards, the samples were dried in a ventilated oven set to 110 ± 5°C for 24 hours, and the weight change was recorded. The difference in mass before and after drying indicated the bricks' ability to absorb water.

The Initial Rate of Absorption (IRA) test, as per ASTM C67-11 [17], was performed to determine how quickly the bricks absorb water, which is important for assessing mortar and grout bonding efficiency. The test involved drying the samples at 110 ± 5°C for 24 hours, followed by cooling and weighing. The samples were then placed alongside a saturated reference brick in a tray, and water was added for exactly 1 minute ± 1 second. The rate of absorption was calculated based on the weight difference before and after the water contact, providing critical data on the porosity and permeability of the bricks.

Finally, thermal conductivity was evaluated using the Transient Line Method (TLM) in accordance with ASTM D5930-09 [21]. This method uses a thermoelectric sensor to measure the effective thermal conductivity (λ_eff) of the material. The sensor, placed between two samples, applies a heat pulse, which induces a transient temperature response in the material, as illustrated in Fig. 5. This response was recorded in real-time using the Linseis Transient Hot Bridge (THB-100), allowing the effective thermal conductivity to be determined. The data were subsequently analysed to offer valuable insights into the thermal behaviour of the bricks.

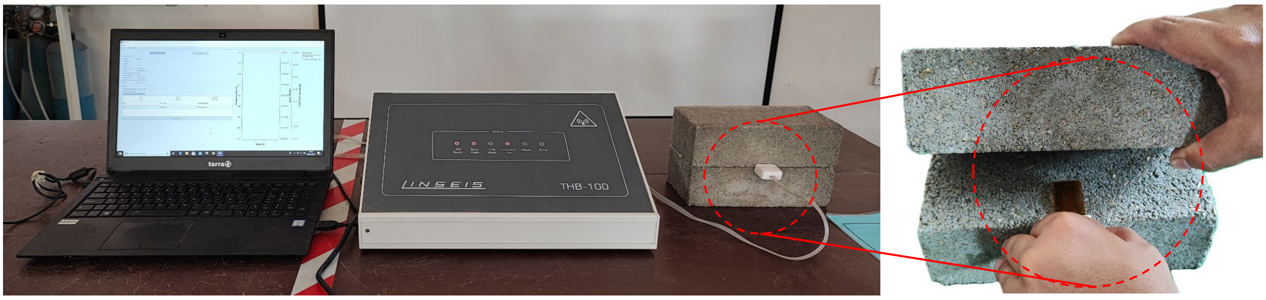


Fig. 5 *THB-100 setup for thermal conductivity measurement*

3. Results and Discussion

3.1 Fresh and Hardened Density

Fig. 6 presents the density analysis of various brick compositions, both freshly mixed and after 28 days of curing. According to ASTM C90-16a [22], lightweight bricks must maintain a hardened density below 1680 kg/m^3 after 28 days. As a baseline, the Sand Cement Brick (SCB) exhibited a density of 2008 kg/m^3 at 28 days. The P1 mix, which consisted solely of QD, showed a modest 3% decrease in density over time, from 2140 kg/m^3 at the fresh state to 2076 kg/m^3 at 28 days. This result indicates that the P1 mix is less suitable for lightweight brick applications, consistent with findings reported in[6], [11] and [23].

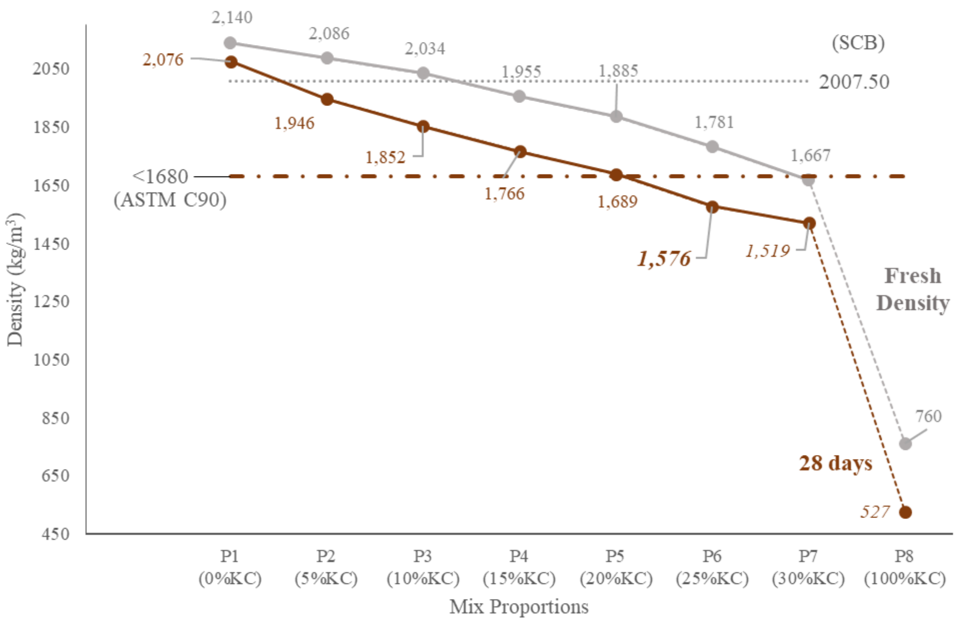


Fig. 6 *Density changes from fresh to hardened state with varying mix proportions*

In contrast, mixtures P2 to P7, which incorporated KC, exhibited a notable average reduction in density of 10% from their fresh to hardened states. This suggests that KC incorporation effectively reduces brick density, with the extent of reduction varying depending on the percentage of KC used. Notably, the P8 formulation, consisting entirely of KC, showed a substantial 44% reduction in density at 28 days compared to its fresh density.

Specifically, the P6 mix, composed of 25% KC and 75% QD, achieved a density of 1576 kg/m^3 at 28 days, meeting the desired lightweight brick density standard. This finding highlights the effectiveness of higher proportions of KC in the mix without the need for additional sand, which contradicts previous recommendations for optimal mix designs that suggested limiting the amount of KC, as indicated in [6] and [11]. The results suggest that KC can replace a portion of QD in brick compositions while still maintaining compliance with lightweight brick standards. In summary, this study confirms that KC is a promising material for the production of lightweight bricks, with the P6 mix being identified as the most effective proportion.

3.2 Compressive Strength

The compressive strength test results for various brick formulations at 7 and 28 days, as shown in Fig. 7, highlight the impact of different mix proportions on brick performance. The Standard Cement Brick (SCB) demonstrated a compressive strength of 20.6 MPa at 28 days, meeting the ASTM C129-06 [24] minimum requirement of 4.14 MPa for non-loadbearing bricks. The control sample P1, composed entirely of QD (100%), achieved an outstanding compressive strength of 35.14 MPa at 28 days, exceeding the required threshold and surpassing SCB. Remarkably, P1 attained 75% of its 28-day strength by the seventh day, signifying rapid early strength development. This rapid strength gain in P1 can be attributed to the intrinsic properties of QD, which contains fine particles that enhance particle packing, reduce porosity, and improve the hydration process. The finer texture of QD accelerates the pozzolanic reaction, leading to the rapid formation of calcium silicate hydrate (C-S-H) gel, the primary contributor to early strength development. Moreover, the uniform distribution of QD particles promotes better bonding with the cement matrix, minimising microcracks and contributing to superior mechanical properties.

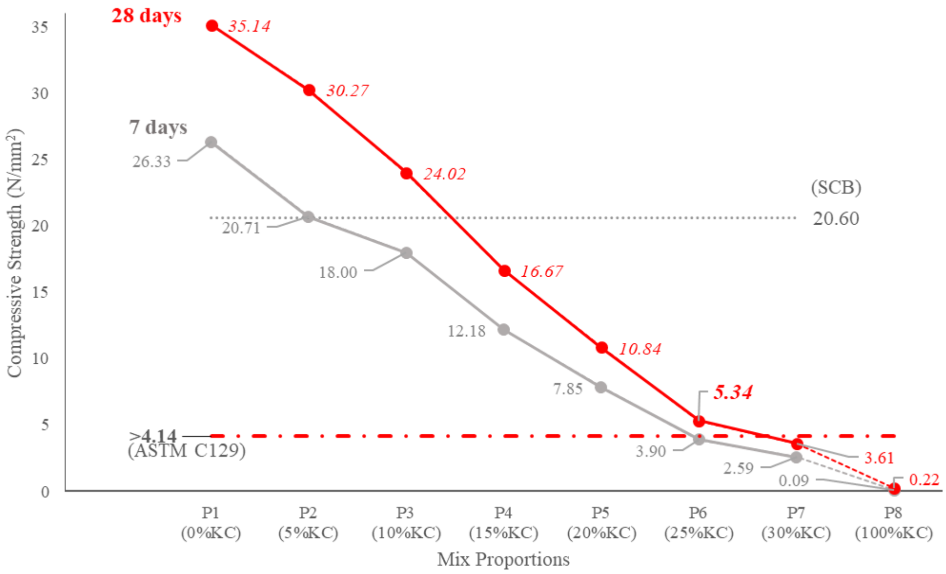


Fig. 7 *Comparison of compressive strength at 7 and 28 days for different mix proportions*

In contrast, mixtures P2 to P7, incorporating 5%-30% KC, achieved an average of 72% of their 28-day strength at seven days, slightly lower than P1 but still within an acceptable range for brick applications. These formulations exhibit a trade-off between early strength and sustainable material usage. The decrease in early strength relative to P1 is likely due to the introduction of KC, which is inherently less dense and has higher porosity than QD. The porous structure of KC tends to reduce the density of the overall matrix, slightly delaying the hydration process.

For P8, a mix composed entirely of KC, the strength development trend is markedly different. P8 achieved only 40% of its 28-day strength at seven days, with a final compressive strength of just 3.61 MPa, falling short of the ASTM C129-06 [24] requirements. The reduced performance of P8 aligns with findings in [5], which identified increased material porosity as a critical factor influencing strength when higher proportions of KC are used. The higher porosity in KC-dominant mixes leads to more excellent water absorption and reduced compaction, resulting in lower overall strength.

Among the KC mixes, P6 (25% KC and 75% QD) stands out with a compressive strength of 5.34 MPa at 28 days. This formulation meets the ASTM C129-06 [24] requirements, balancing sustainable material use with adequate strength. The slight retardation in strength development observed in KC-containing mixes may also be influenced by the lignocellulosic nature of KC, which can partially hinder the hydration process by absorbing moisture.

In summary, QD's superior performance in P1 highlights its suitability for achieving high strength in lightweight cement bricks, particularly in non-loadbearing applications. Meanwhile, KC, though reducing compressive strength, provides an avenue for incorporating agricultural waste into sustainable construction materials. The findings emphasise optimising the QD-to-KC ratio to balance strength, sustainability, and practicality in brick production.

3.3 Water Absorption

Fig. 8 shows the water absorption with varying mix proportions at 28 days. ASTM C90-16a [22] indicates that lightweight bricks should exhibit a water absorption rate of less than 18% at 28 days. To provide context, the SCB serves as our reference point with a water absorption rate of 7.1%. Notably, P1, comprising 100% QD, demonstrates a slightly higher water absorption rate of 7.9% at 28 days, indicating a marginal increase in water absorption compared to the baseline. In contrast, mixtures P2 to P8, incorporating KC into the mix, exhibited progressively higher water absorption rates at 28 days, with P8 reaching 40.5%. These findings are consistent with the earlier studies, which state that water absorption increases with increased KC proportions [5], [6], [11]. This phenomenon occurs because increased KC proportions produce greater material porosity and enhanced water absorption capabilities [25].

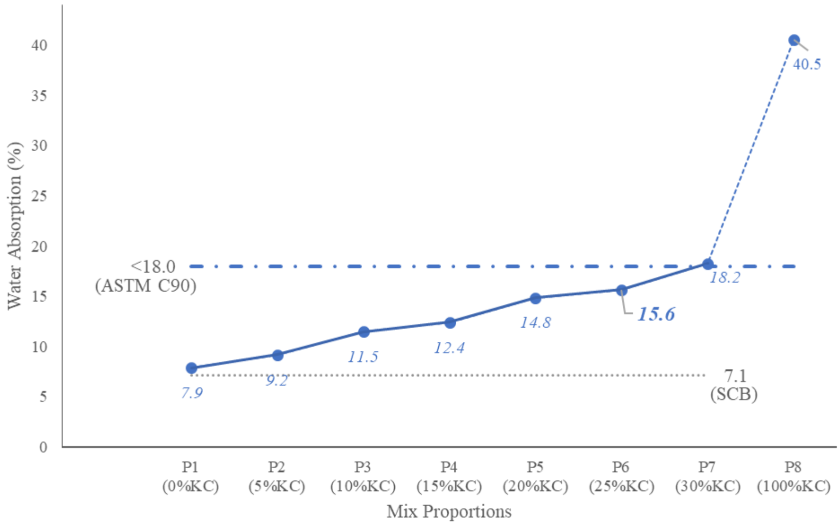


Fig. 8 *Comparison of water absorption with varying mix proportions at 28 days*

Among the compositions, P6, consisting of 75% QD and 25% KC, achieved the desired water absorption rate of 15.6% at 28 days, highlighting its potential for producing lightweight cement bricks with improved water resistance. This discovery underscores the effectiveness of using a 25% proportion of KC as a replacement for QD, contributing to the desired water absorption characteristics of the bricks. In conclusion, the results emphasise the importance of selecting an appropriate composition to meet water absorption standards, with P6 emerging as the ideal choice. This finding holds significant implications for constructing lightweight cement bricks that resist excessive water absorption.

3.4 Initial Rate of Absorption (IRA)

Fig. 9 shows the initial absorption rate variations with increasing KC content. ASTM C67-11 [17] indicates that full-size bricks should ideally exhibit an IRA falling between 10 to 30 g/min./193.55cm^2. The SCB is the baseline with a 37 IRA. Notably, P1, composed of 100% QD, exhibited an IRA of 34, just marginally below the SCB baseline. Conversely, P3 to P7, which introduced KC into the mix, consistently achieved IRA values within the desired range, signifying the feasibility of reducing QD content and integrating KC to meet IRA standards. Among the compositions, P2 to P6 excel by attaining the desired IRA values, ranging from 26 to 12 IRA. These outcomes underscore the potential of utilising KC as a partial substitute for QD in brick mixtures, thus ensuring compliance with the essential IRA criteria for full-size bricks.

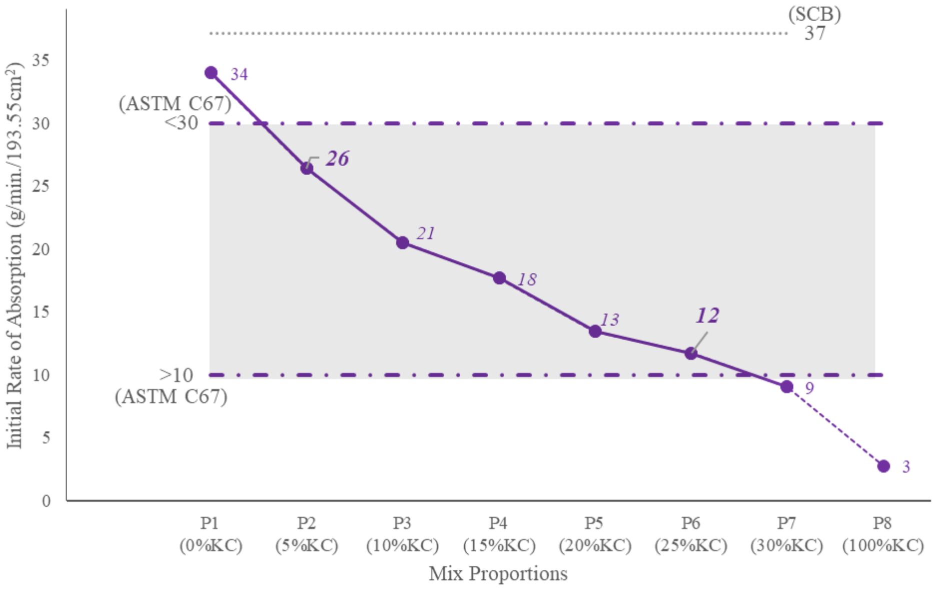


Fig. 9 *Initial absorption rate variations with increasing KC content at 28 days*

3.5 Thermal Conductivity

Fig. 10 illustrates the variations of thermal conductivity with increasing KC content. The figure shows that the standard SCB exhibits a thermal conductivity of 0.93 W/mK, aligning with BS EN 1745:2012 [26] which specifies a thermal conductivity below 0.98 W/mK. Introducing KC as a partial substitute for QD significantly impacts thermal conductivity. The P1 mix, composed entirely of QD, records 1.02 W/mK, surpassing the threshold. However, conductivity decreases as KC content increases. The P2 mix, with 5% KC replacement, achieves 0.86 W/mK, falling within the desired range. Notably, mixes from P2 to P8 exhibit thermal conductivities below the 0.98 W/mK requirement.

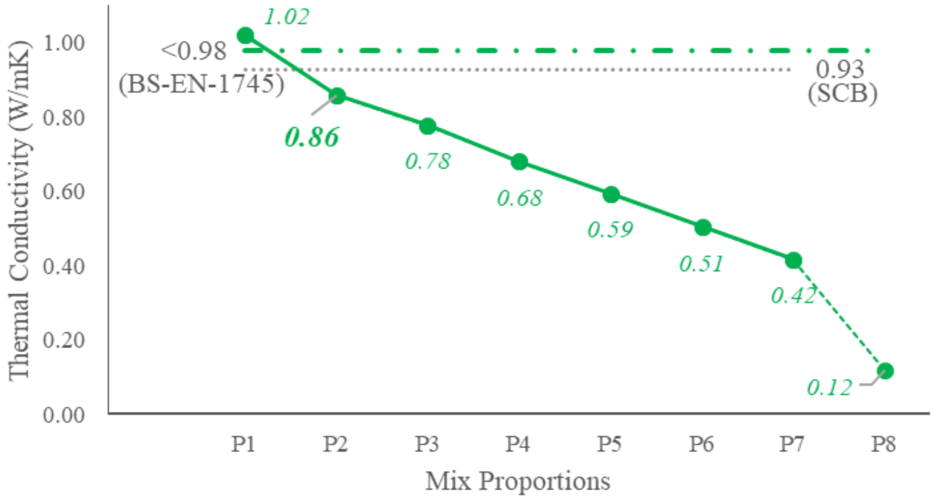


Fig. 10 *Thermal conductivity gradually decreases as the proportion of KC increases*

This study employed the Transient Line Method (TLM) to assess thermal conductivity, in contrast to the Hot Plate Method (HPM) used in previous studies [5]. The use of TLM resulted in significantly higher thermal conductivity values. TLM uses a transient heat source and records temperature changes, offering greater accuracy and versatility for testing various materials, including non-uniform or anisotropic substances [27]. In contrast, HPM applies constant heat, making it suitable for materials with uniform properties but somewhat less precise compared to TLM [28].

These findings underline the effectiveness of KC as a partial replacement for QD in brick production, leading to a significant reduction in thermal conductivity, which is vital for maintaining energy-efficient building systems. The progressive decrease in thermal conductivity with increasing KC content is promising and demonstrates the potential to develop bricks that meet the required thermal standards.

3.6 Acceptable Mixing Proportions for Lightweight Cement Brick

The primary objective was to ascertain the ideal mix proportions for creating lightweight, non-loadbearing bricks meeting stringent standards. These parameters are essential for achieving bricks with low thermal conductivity that are practical for bricklaying. Defined standards dictate fundamental properties, demanding a hardened density below 1680 kg/m^3, compressive strength exceeding 4.14 MPa, an IRA between 10 and 30 ARI, water absorption below 18%, and a thermal conductivity not surpassing 0.98 W/mK, meticulously outlined in Table 3.

Table 3 *Standards and requirements for lightweight non-load-bearing brick*

Properties	Hardened Density (kg/m^3)	Water Absorption (%)	Compressive Strength (Mpa)	Thermal Conductivity (W/mK)	Initial Rate of Absorption (g/min/193.55cm^2)
Standard	ASTM C90-16a		ASTM C129-06	BS-EN-1745-2012	ASTM C67-11
Classification	Lightweight Brick		Non-loadbearing	Calcium Silicate Units	Full-size Brick
Requirements	<1680	≤18	≥4.14	≤0.98	10<IRA<30

The results reveal that mixtures with 0%, 10%, 15%, and 20% KC content fail to meet the desired hardened density criterion. Additionally, more than 30% of KC content fails to meet the compressive strength, IRA, and water absorption standards. Notably, all KC content percentages meet the thermal conductivity requirement, as indicated visually in Fig. 11, which delineates the boundaries set by standards.

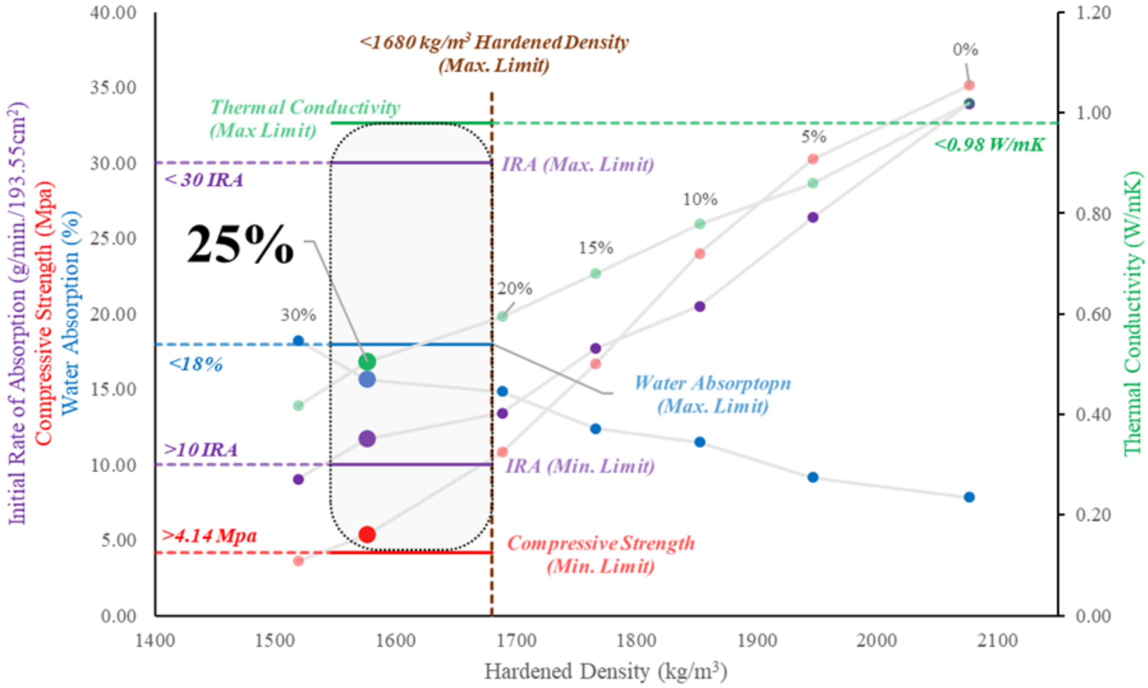


Fig. 11 *Chart of identifying optimal mix proportions based on the standards requirements*

Optimal compliance with all criteria is suggested in the mix containing 25% KC and 75% QD content. This proportion aligns impeccably with standards, offering a perfect composition to develop lightweight, non-loadbearing bricks that adhere to specified criteria. In summary, meticulous adherence to these specific criteria is pivotal. The findings assert the significance of the 25% KC and 75% content proportion, ensuring the creation of lightweight, non-loadbearing bricks that meet prescribed standards for practical and efficient bricklaying.

4. Conclusion and Recommendations

This study evaluated the potential of QD and KC as alternative fine aggregates in producing lightweight, non-load-bearing cement bricks. The findings demonstrate that QD and KC significantly influence the physical and mechanical properties of bricks, offering sustainable solutions to address the scarcity of natural sand.

The results indicate that using QD as a complete sand replacement yields superior compressive strength, with the control sample (P1) achieving 35.14 MPa at 28 days. This represents an improvement of approximately 70.6% compared to conventional sand cement bricks (SCB), which had a compressive strength of 20.6 MPa. The substantial increase in strength is attributed to QD's fine particle packing and pozzolanic properties, which enhance the hydration process and contribute to the material's mechanical performance. However, it was also observed that using QD increases IRA, necessitating pre-wetting during bricklaying to ensure proper bond strength.

In contrast, including KC in the mix reduces compressive strength but significantly enhances thermal performance. The optimal mix, consisting of 25% KC and 75% QD (P6), achieved a compressive strength of 5.34 MPa, which exceeds the ASTM C129-06 minimum requirement for non-loadbearing bricks. This mix also demonstrated improved thermal conductivity, reducing the value to 0.51 W/mK. This constitutes a 47.96% reduction compared to the thermal conductivity of conventional sand cement bricks, measured at 0.98 W/mK. Additionally, the P6 mix achieved a hardened density of 1,576 kg/m^3, making it suitable for lightweight applications. Despite these advantages, including KC delayed setting times, posing challenges for demolding and mass production efficiency.

To enhance the practicality of KC-based bricks, it is recommended that adhesives or additives, such as accelerators, be incorporated to address the delayed setting time observed with KC. This would mitigate production challenges and improve the viability of KC in large-scale brick manufacturing. Furthermore, given the higher water absorption rates observed in QD- and KC-based bricks, pre-wetting during bricklaying is strongly advised to ensure proper bond strength and durability.

In addition, future studies should include a detailed cost analysis to evaluate the economic feasibility of producing QD- and KC-based bricks compared to conventional sand cement bricks. Such an analysis would provide a comprehensive understanding of their potential for widespread adoption in the construction industry. Finally, further investigations into the long-term durability, thermal insulation efficiency, and lifecycle environmental impacts of QD- and KC-based bricks are necessary to validate their performance and sustainability over time.

By combining the strength-enhancing properties of QD with the thermal insulation benefits of KC, this study establishes a practical pathway for producing lightweight, non-loadbearing bricks that meet industry standards while addressing environmental and resource challenges. These findings contribute to advancing sustainable construction practices and offer a viable alternative to conventional sand-cement bricks.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Khairol Kamaruddin, Lokman Hakim Ismail;* ***data collection:*** *Khairol Kamaruddin;* ***analysis and interpretation of results:*** *Khairol Kamaruddin, Mohd Azuan Zakaria;* ***draft manuscript preparation:*** *Khairol Kamaruddin, Lokman Hakim Ismail, Mohd Azuan Zakaria. All authors reviewed the results and approved the final version of the manuscript.*

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