

Physical and Mechanical Properties of Concrete using Recycled Clay Bricks as Coarse Aggregate

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Abstract: Rising construction waste due to demolition work, natural disasters, and development is becoming a prominent issue. To tackle this, Recycled Crushed Brick Masonry Aggregate (RCBMA) can be an ideal replacement for the limited Natural Coarse Aggregates (NCA) in the production of concrete, potentially assisting in managing construction waste and reducing the depletion of NCA. As such, this study focused on assessing the suitability and establishing the optimum percentage of RCBMA as a replacement for NCA in concrete. To do so, five different concrete mixes were prepared where NCA was replaced by RCBMA at different percentages (0, 25, 50, 75, and 100%). The effect of RCBMA on concrete was studied and analyzed for physical and mechanical properties including concrete slump, compressive strength, density, water absorption, and flexural strength. From the results, the workability of the concrete mixes were reduced by as much as 21.8 and 44.9% at 50 and 100% RCBMA replacement, respectively. Meanwhile, the water absorption increased with higher RCBMA replacement from 1.43 at 0% replacement to 7.76 at 100% replacement, indicating greater porosity at higher RCBMA replacement levels. The compressive strength was reduced with a rise in RCBMA replacement due to the lighter weight of RCBMA as compared to NCA. This reduction was as much as 48.72 and 63.14 at 50 and 100% RCBMA replacement of NCA. The same can be said about the flexural strength and density of concrete, where higher RCBMA replacement led to lower flexural strength and concrete density. It was concluded that a 25% RCBMA replacement does not severely affect the workability and mechanical strength of concrete (16.8 and 17% reduction in compressive and flexural strengths, respectively, as compared to the control samples) and thus can be used for structural concrete applications. The findings from this study illustrate the possibility of using RCBMA as a partial replacement for NCA, potentially assisting in reducing construction and demolition waste sustainably.

Keywords: Recycled Brick, Crushed Bricks, Sustainable Concrete, Compressive Strength, Flexural Strength, Workability

Introduction

At the turn of the current century, a greater awareness of the urgent need to protect the environment crystallized by the agreement of all 191 United Nations (UN) member states at the time to implement the Millennium Development Goals (MDGs), a 15-year plan to tackle some of the major problems in the world. Goal 7 of the 8 MDGs was to ensure environmental sustainability by reducing CO₂ emissions into the atmosphere and protecting natural resources. After the relative success of the MDGs, the UN member states decided to sign a more comprehensive 15-year plan, called

the Sustainable Development Goals (SDGs), with 17 main targets to be achieved by 2030. Many of the SDGs were geared towards sustainable cities and infrastructure (Goals 9 and 11) and important action on climate change (Goals 13). Further international agreements, such as the Paris Climate Change Agreement in 2016, highlight the urgent need to curb CO₂ emissions and find sustainable solutions to modern infrastructure. Researchers and engineers play an important role to achieve such a sustainable vision; for instance, Portland Cement (PC) production alone emits nearly 1.5 billion tons of CO₂ into the atmosphere (Amran *et al.*, 2020a; Dhakal, 2009;

Madheswaran *et al.*, 2013), which is approximately 6% of the overall emissions from various sectors as shown in Fig. 1. Similarly, the rapid growth in the use of construction materials worldwide presents a considerable challenge to the environment (Amran *et al.*, 2020b; Martín-Antón *et al.*, 2017). It has been reported, for instance, that about 25,000 million tons of concrete are produced annually, which emits between 1250 and 3250 million tons of CO₂ into the atmosphere (Siddique *et al.*, 2018; Zhang *et al.*, 2019). This, without a doubt, contributes to the greenhouse gas effect and the depletion of the ozone layer.

In addition, Natural Coarse Aggregates (NCA), an important construction material that constitutes up to 80% of concrete volume (Noaman *et al.*, 2021), are getting ever more scarce and the quarrying process negatively impacts the environment. Also, quarries consume huge amounts of water to produce natural aggregates (Wong *et al.*, 2018), contributing to the depletion of water. On a separate note, it has been reported that schools could require up to 3,000 tons of aggregates by the time construction is finished (Adamson *et al.*, 2015) and the number of aggregates needed could rise to 300,000 tons for larger projects such as a sports stadium (Adamson *et al.*, 2015). The existing excavated aggregates used are non-renewable as they take ages before they reform again. Additionally, with an increase in urbanization and infrastructural demand, more NCA will be required (Huang *et al.*, 2018; Mahpour, 2018). Therefore, it becomes imperative to find alternative sources to NCA that can be used in construction.

Many researchers have encouraged the usage of recycled aggregates to curb the harm of the construction industry to the environment (Guo *et al.*, 2018; Huda and Shahria Alam, 2015; Zhang *et al.*, 2019). Also, recycling aggregates in the construction industry can help ensure a circular economy and assist countries to achieve their CO₂ reduction targets more rapidly (Cantero *et al.*, 2018; Gálvez-Martos *et al.*, 2018). Newman (1946) reported that crushed clay brick can be an ideal substitute for NCA in concrete. Furthermore, researchers have revealed that bricks and concrete can account for up to 75% of the total waste from construction sites (Formoso *et al.*, 2002) and 10-30% of all waste thrown away in landfills in the US (Adamson *et al.*, 2015). Bricks are used heavily in residential buildings and they contribute largely to demolition and construction waste (Formoso *et al.*, 2002; Kumar *et al.*, 2017). Also, due to rapid urbanization, it is expected that demolition and construction waste will continue to rise over the next few years. For example, in China, demolition and construction waste rose from 88 million tons in 2000 to 3.9 billion tons in 2015 (Ding *et al.*, 2016; Guo *et al.*, 2018). This only suggests that more brick waste will be generated over the years and appropriate recycling methods should be explored.

Bricks are considered waste if they break during production, or they are collected from construction and demolition sites (Demir and Orhan, 2003; Sadek, 2012). Recycling such bricks would solve an important issue and reduce the strain on landfills (Lennon, 2005). Also, recycling could prove to be a cheaper alternative to landfilling; for example, it has been reported that reprocessing one ton of bricks, blocks, and concrete would cost about \$21 per ton; while landfilling, on the other hand, would cost a staggering \$136 per ton in comparison (Lennon, 2005). Reusing bricks in the fabrication of concrete can moderate the demand for NCA (Abed *et al.*, 2020; Adamson *et al.*, 2015) and solve the problem of dealing with construction waste (Leite and Santana, 2019). Moreover, due to their lighter weight compared to NCA, the use of bricks can help produce lightweight concrete, which ultimately results in savings in energy and cost due to lower self-weight (Al-shannag and Charif, 2017).

Recycled bricks have been used previously as base filler in roads (Etxeberria *et al.*, 2007a) and the lack of understanding of the behavior of concrete made with bricks has limited their use in the past (Debieb and Kenai, 2008). Previous studies have shown that crushed bricks have the potential to act as aggregates to form ordinary concrete (Dang and Zhao, 2019; Hoque *et al.*, 2020) and due to their lower specific gravity in comparison to NCA, greater replacement of the latter by Crushed Brick Aggregates (CBA) causes a reduction in density. For example, an up to 18% reduction in density was observed at 30% CBA replacement of NCA (Alwash and Al-Khafaji, 2018).

Furthermore, several studies have reported that the replacement of NCA with CBA causes a 10-35% fall in the compressive strength when coarse aggregates are substituted and 30-40% when fine aggregates are replaced (Debieb and Kenai, 2008; Khalaf and Devenny, 2005; Noaman *et al.*, 2021). On the contrary, Adamson *et al.* (2015) reported a rise in concrete compressive strength with an increase in CBA replacement; while Khalaf (2006) noted that the compressive strength for concrete with NCA and another with CBA was almost identical. Pinchi *et al.* (2020) tested the compressive strength of concrete samples with CBA as a replacement for NCA by up to 27% and found that the optimum replacement percentage was 21%, where a 4.07% increase in compressive strength at 28-days was observed.

As for the concrete tensile strength, it has been reported that an increase of about 11% in concrete with crushed clay bricks was observed as compared to ordinary concrete (Akhtaruzzaman and Hasnat, 1983). Meanwhile, it has been reported that the flexural strength of concrete mixes with CBA as a partial replacement for NCA reduces in comparison to the control mix (Alwash and Al-Khafaji, 2018) and this reduction was in around 16% at 40% CBA replacement of NCA

(Alwash and Al-Khafaji, 2018). Furthermore, Maroliya (2012) observed that increasing the replacement of NCA with CBA causes a decrease in the elastic modulus. For example, the elastic modulus of concrete with CBA was 30-40% less than that of normal concrete with granite aggregate and 28.2% less than that of concrete with limestone aggregate.

As for permeability, concrete with recycled CBA had a similar or two times higher permeability when compared to that of natural concrete. Also, the higher the permeability of the crushed clay bricks, the lower the concrete compressive strength (Dang and Zhao, 2019; Hoque *et al.*, 2020). The water permeability of concrete with CBA decreased by about 11% when a plasticizer was used. Meanwhile, it was shown that using burnt CBA as a 100% replacement for coarse aggregates resulted in an increase in water absorption at 28-days from 2.83 to 7.83% (Azunna and Ogar, 2021), indicating higher water absorption of the burnt CBA.

Moreover, the use of recycled aggregates in concrete leads to higher chloride ingress and subsequently lower durability and the possibility of steel corrosion in reinforced members (Liang *et al.*, 2021). As for its workability, Etxeberria *et al.* (2007b) reported that replacing over 50% by weight of NCA with crushed clay brick aggregates leads to poor workability in the new concrete mixes. This adverse effect on workability was also observed by (Aliabdo *et al.*, 2014; Bektas *et al.*, 2009; Noaman *et al.*, 2021).

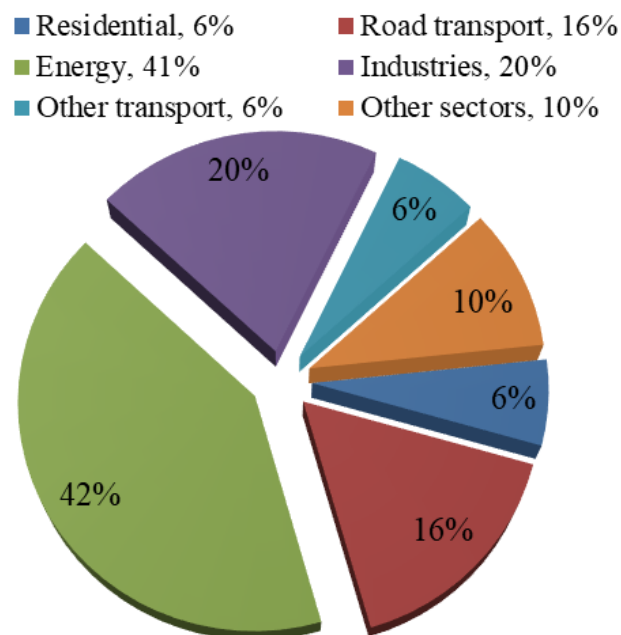


Fig. 1: CO₂ emitted by various sectors (Amran *et al.*, 2020a)

As such, the objective of this study is to contribute to the existing literature on the mechanical and physical properties of concrete with recycled crushed clay brick as a replacement for NCA to help reduce the depletion of natural mineral aggregates and reduce construction waste. This includes reporting the concrete compressive strength, concrete flexural strength, concrete density, and water absorption. From these results, a recommendation on the optimum quantity of crushed clay brick aggregates is given.

Experimental Work

This study investigated five different concrete mixes with varying percentages of Recycled Clay Brick Masonry Aggregates (RCBMA). The materials utilized in the concrete mix design were cement, water, sand, coarse aggregate, and RCBMA to get a solid blend. These materials were mixed and cured in the laboratory. The RCBMA was used to replace NCA and the concrete mixes were labeled as M0, M25, M50, M75, and M100, indicating 0, 25, 50, 75, and 100% natural aggregate replacement, respectively.

Recycled Materials

The RCBMA used in this study was obtained from a warehouse in Kuala Lumpur, Malaysia, that underwent demolition as shown in Fig. 2. While carrying out the demolition process, an effort was made to get the cleanest bricks through source separation methods and the demolished clay brick specimens that were later used as aggregates are shown in Fig. 3. Moreover, the chemical composition of the extruded brick specimens is listed in Table 1 as given by the supplier.

Properties of Cement and Water

Grade 25 Ordinary Portland Cement (OPC) was utilized to bind the various concrete mixes. The physical and chemical properties of the OPC used are given in Tables 2 and 3, respectively. The Specific Gravity (SG) of cement was determined to be 3.15 as given in Table 2. Furthermore, tap water (27°C) with a density of 1000 kg/m³ was utilized in the concrete mix design. The water-cement ratio (w/c) was kept at 0.55 to ensure concrete mixes with appropriate workability.

Properties of Aggregates

The fine aggregates used in this study were crushed river sand with a particle size of less than 4.75 mm (Fig. 4). As for the coarse aggregates, both NCA and crushed RCBMA, as shown in Fig. 5, were utilized in the mix designs. The size of the coarse aggregates was between 4.75-19 mm.

Superplasticizer

Super Plasticizers (SP) are typically used in concrete mix designs to enhance workability and lower the quantity of water required for mixing. In this study, Sikament-163 (Fig. 6), made up of sodium salt (sulfonated) naphthalene formaldehyde condensate, was used as an SP to ensure adequate workability with no additional water and no direct influence on the concrete's compressive strength.

Sieve Analysis

The different sieve sizes were arranged in descending order (largest opening on top). The aggregates were then placed on the uppermost sieve and the sieves were subsequently shaken. The weight of aggregate retained on each sieve was noted and the percentage passing for each sieve was computed. Accordingly, the results for the NCA are shown in Fig. 7, while that for the RCBMA are shown in Fig. 8.



(a) Before demolition



(b) After demolition

Fig. 2: Source of RCBMA



Fig. 3: Clay brick specimens



Fig. 4: Fine aggregates



Fig. 5: NCA and RCBMA



Fig. 6: Superplasticizer

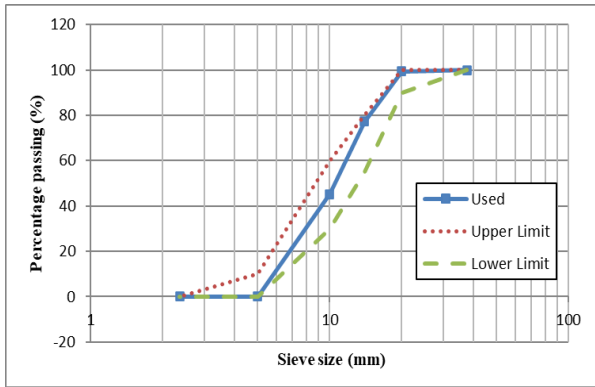


Fig. 7: Sieve analysis of NCA

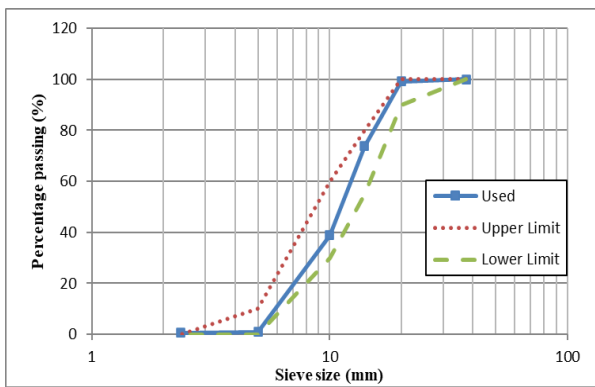


Fig. 8: Sieve analysis of RCBMA

Specific Gravity

To determine the SG of NCA and RCBMA, air-dried samples-1 kg each and passing the 19 mm sieve but retained on the 4.75 mm sieve-were first obtained. The samples were then carefully washed to remove any dust; after which, the samples were soaked in water for 24 h. After taking out the aggregate samples from the water, the aggregates were placed over a clean cloth and rolled to remove any visible water. Next, the mass of the Saturated Surface Dry (SSD) aggregates was measured (W_s). The samples were subsequently placed in a wire basket and were submerged in water. Next, their weight was measured using a double beam balance (W_w). The basket was then taken out from the water and the aggregates were placed in an oven for 24 h at a temperature of $105 \pm 5^\circ\text{C}$. After that, the aggregates were taken out from the oven, cooled and their mass was subsequently measured (W_d). The procedure was carried out three times in total to record the average values. The SG and water absorption were determined as follows and their respective values are given in Table 4:

$$\text{Apparent SG} = W_d / (W_d - W_w) \quad (1)$$

$$\text{SG(SSD)} = W_s / (W_s - W_w) \quad (2)$$

$$\text{SG(oven dry condition)} = W_d / (W_s - W_w) \quad (3)$$

$$\text{Water absorption} = (W_s - W_d) / W_d \% \quad (4)$$

Preparation of Mix Design

Five different concrete mixes (M0, M25, M50, M75, and M100) were prepared with NCA being partially replaced by RCBMA at 0, 25, 50, 75, and 100%, respectively. The mix proportions for grade C25 concrete were determined and a summary is given in Table 5. In the mix designs, the w/c was kept at 0.55 while the percentage of superplasticizer added was kept at 1.4% of the weight of cement. In addition, SSD aggregates were utilized in the concrete mix design, and the batching process was done by weight of cement, water, and aggregates. The mix proportions for cement, water, and fine aggregates were kept constant, while the proportions of NCA and RCBMA were varied depending on the mix design. For instance, mix design M0 had 0% RCBMA replacement (i.e., no RCBMA), mix design M50 had 50% RCBMA replacement (i.e., an equal amount of NCA and RCBMA) and M100 had 100% RCBMA replacement (i.e., no NCA).

The mixing process was conducted using a concrete mixer with a 1.0 m^3 capacity. After thorough mixing, the concrete was placed in metal molds as illustrated in Fig. 9(a). While placing the concrete in the molds, a poker vibrator was utilized to ensure compact concrete samples. The molds were then covered with a plastic sheet for 24 h. After that, the molds were disassembled and the concrete samples were then placed in a curing tank (temperature ranging between 19 and 22°C) as shown in Fig. 9(b) to continue the curing process. In total, 45 concrete cubes of 150 mm size were prepared as part of this study. Fifteen cubes were set to determine the 7-day compressive strength, while another 15 cubes were used to determine the 28-day compressive strength. The remaining 15 cubes were utilized to determine the water absorption at 28-days. For each mix design, the results were averaged from the readings of three cubes. In addition, 15 concrete prisms (3 for each mix design) of $100 \times 100 \times 500 \text{ mm}$ size were prepared to determine the flexural strength at 28-days. Table 6 summarizes the prepared cube and prism samples used in this study, together with the number of curing days. Moreover, the mix proportions used in each concrete cube and prism are detailed in Tables 7 and 8, respectively.

Fresh and Hardened Concrete Properties

Slump Test

The slump test was done immediately on the fresh concrete following BS EN 12350-2 (2019). The slump cone used was 300 mm high, with a base and top diameter of 200 and 100 mm, respectively. The cone was filled with fresh concrete in three equal layers and each layer was stroked with a 19 mm diameter rod 25 times. Upon filling the cone with concrete and removing any excess concrete

at the top level, the cone was lifted vertically to permit the concrete to slump. The slump height was recorded as shown in Fig. 10.

Concrete Density

The concrete density was determined at 7-and 28-days of curing following BS EN 12390-7 (2019). The mass of the cubes was measured using an electric weighing balance and the concrete density, ρ , was computed using the following expression;

$$\rho = M / V \quad (5)$$

where M is the mass (kg) and V is the volume (m^3).

Compressive Strength

The concrete compressive strength was measured following BS EN 12390-3 (2019) on 150 mm cubes at 7-and 28-days. Thirty minutes before testing, the cubes were removed from the curing tank and their outer surface was wiped with a clean cloth to remove any excess moisture. After that, the cubes were placed in the compressive testing machine as depicted in Fig. 11 and tested under load-control conditions using a loading rate of 0.3 MPa/s. The maximum load applied to the cubes at failure was noted and the compressive strength, CS, of the cube specimens was calculated as follows:

$$CS = F / A_c \quad (6)$$

where F is maximum failure load (N) and A_c is the cross-sectional area of the cubes (mm^2).

Flexural Strength

The concrete flexural strength was obtained in line with BS EN 12390-5 (2019) on $100 \times 100 \times 500$ mm concrete prisms at 28-days. Thirty minutes before testing, the concrete prisms were taken out from the curing tank and any excess moisture on their surface was removed. Similarly, the bearing surfaces of the supports and rollers in the flexural strength testing machine were wiped as well to ensure that any loose sand was removed before testing. The prisms were then tested on a span of 450 mm by applying two equal loads placed at two points (one-third of the supported span) as illustrated in Fig. 12. The test was carried out in load-control conditions using a loading rate of 0.04 MPa/s. The flexural strength, FS, of the concrete prism specimens were calculated using the following expression:

$$FS = (P_{max} L) / (bh^2) \quad (7)$$

where P_{max} is the maximum load on the concrete prism (N), L is the distance between the supports (mm) and b

and h are the width and height of the concrete prism's cross-section (mm), respectively.

Water Absorption

The concrete water absorption was determined for 150 mm size cube samples after 28-days of curing. Initially, the samples were taken out from the curing tank and were left to drain for 2 min. After that, noticeable water was removed with a clean cloth and their saturated weight was recorded. Next, the concrete cube samples were oven-dried at $105 \pm 5^\circ C$ for 24 h before their dry weight was recorded. The percentage of water absorption, WA, was determined as follows:

$$WA = (W_w - W_d) / W_d \times 100 \quad (8)$$

where W_w is the saturated surface dry weight (kg) and W_d is the oven-dry weight (kg).



Fig. 9: Preparation of concrete samples: (a) in molds; (b) curing



Fig. 10: Slump test



Fig. 11: Compressive strength test

Table 1: Components of whole brick specimens

Element	Percentage content by weight
SiO ₂	50-60%
Al ₂ O ₃	20-30%
CaO	2-5%
Fe ₂ O ₃	≤ 7%
MgO	≤ 1%

Table 2: Physical properties of OPC

Property	Result	Requirement as per IS:8112-1989
Normal consistency	28%	-
Initial setting time	48 min	Min 30
Final setting time	165 min	Max 600
SG	3.15	-
Soundness	1	Max 10
OPC grade	25	-

Table 3: Chemical properties of OPC

Oxide composition	Values
CaO	62.1%
SiO ₂	21.14%
Al ₂ O ₃	5.23%
Fe ₂ O ₃	4.42%
MgO	1.14%
SO ₃	2.3 %
LOI	1.5%

Table 4: Specific gravity of NCA and RCBMA

Parameter	NCA	RCBMA
Apparent SG	2.63	2.51
Bulk SG (SSD basis)	2.52	2.10
Bulk SG (OD basis)	2.45	1.82
Absorption capacity (%)	2.71	14.99

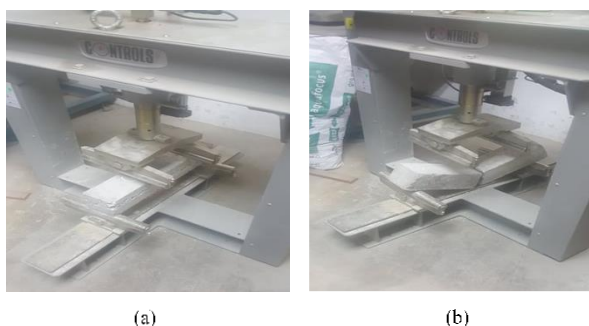


Fig. 12: Flexural strength test setup

Table 5: Summary of mixed design

Quantities	Cement (kg/m ³)	Water (kg/m ³)	Fine aggregates (kg/m ³)	Coarse Aggregates (kg/m ³)	Superplasticizer by weight of cement, 1.4%
Per 1 m ³ (to nearest 5 kg)	309.000	170.000	646.000	1255.000	4.3300
Per trial mix of 0.003375 m ³ ratio	1.043	0.574	2.181	4.234	0.0150
Per trial mix of 0.005 m ³ ratio	1.545	0.850	3.230	6.275	0.0220
Ratio	1.000	0.550	2.090	4.060	0.0140

Table 6: Total concrete cubes and prisms tested

Mix design	Grade of concrete cubes and prisms (MPa)	Number of cubes and curing days			
		Cubes for compressive strength tests		Prisms for flexural strength tests	Cubes for water absorption tests
		7-days	28-days		
M0	25	3	3	3	3
M25	25	3	3	3	3
M50	25	3	3	3	3
M75	25	3	3	3	3
M100	25	3	3	3	3
Total		15 cubes	15 cubes	15 prisms	15 cubes

Table 7: Quantity of the materials used in cubes for various mix designs

Mix design	Cement (kg)	Water (kg)	FA (kg)	NCA (kg)	RCBMA (kg)	Ratio by mass (RCBMA: NCA)	w/c ratio	Superplasticizer (kg)
M0	1.043	0.574	2.181	4.234	(0%)	0	0.55	0.000
M25	1.043	0.574	2.181	3.387	1.059 (25%)	1:3	0.55	0.015
M50	1.043	0.574	2.181	2.540	2.117 (50%)	1:1	0.55	0.015
M75	1.043	0.574	2.181	1.694	3.176 (75%)	1:0.33	0.55	0.015
M100	1.043	0.574	2.181	0.000	4.234 (100%)	0	0.55	0.015

FA = Fine Aggregates; NCA = Natural Coarse Aggregates; RCBMA = Recycled Clay Brick Masonry Aggregates

Table 8: Quantity of the materials used in prisms for various mixed designs

Mix design	Cement (kg)	Water (kg)	FA (kg)	NCA (kg)	RCBMA (kg)	Ratio by mass (RCBMA: NCA)	w/c ratio	Superplasticizer (kg)
M0	1.545	0.85	3.23	6.275	(0%)	0	0.55	0.000
M25	1.545	0.85	3.23	5.020	1.255 (25%)	1:3	0.55	0.022
M50	1.545	0.85	3.23	3.765	2.5 (50%)	1:1	0.55	0.022
M75	1.545	0.85	3.23	2.510	3.765 (75%)	1:0.33	0.55	0.022
M100	1.545	0.85	3.23	0.000	6.275 (100%)	0	0.55	0.022

FA = fine aggregates; NCA = natural coarse aggregates; RCBMA = recycled clay brick masonry aggregates

Results

Slump

The slump values for the fresh concrete mixes are given in Fig. 13. The recorded slump results for M 25, M 50, M 75, and M 100 mix designs were 10.3, 21.8, 33.3, and 44.9% lower than that of the control mix (M0). Similar findings were also reported by Kasi and Malasani (2016) where greater replacement of NCA by CBA resulted in a reduction in a concrete slump.

Density

Figure 14 presents the recorded concrete densities at 7 and 28-days. As the RCBMA replacement of NCA increased, the density dropped accordingly for 7 and 28-days. For instance, the density of the reference mix (M0) at 28-days was 2520 kg/m³ and this dropped by 13.25% and 15.95% for M 50 and M 100, respectively. These results are in agreement with the observations of Alwash and Al-Khafaji (2018), where greater CBA replacement of NCA resulted in lower density. The results in Fig. 14 also show that the density at 28-days was higher than that at 7-days regardless of the RCBMA replacement rate.

Compressive Strength

The average compressive strength for M0 at 28-days was 31.2 MPa, the highest compared to other mixes as shown in Fig. 15. The 28-day compressive strength of M25, M50, M75, and M100 was 25.95 MPa, 16 MPa, 13.5 MPa, and 11.5 MPa, indicating a drop of 16.83, 48.72, 56.73, and 63.14%, respectively, when compared to M0. This inverse trend of lower compressive strength with higher RCBMA replacement of natural aggregates was observed in several previous studies (Debieb and Kenai, 2008; Khalaf and Devenny, 2005; Noaman *et al.*, 2021).

Flexural Strength

The flexural strength results at 28-days are illustrated in Fig. 16 where the control samples (M0) had the highest average flexural strength of 4 MPa. The reduction in flexural strength, as compared to the control samples, was 17, 22, 27.5, and 37.5% for the M25, M50, M75, and M 100, respectively. Similar results were also observed by Debieb and Kenai (2008), where the flexural strength decreased by about 33% when NCA was fully replaced by secondary aggregates.

Water Absorption

Figure 17 illustrates the water absorption results at 28-days with an increasing percentage of RCBMA replacement. The findings show that the average water absorption of the control samples was 1.43% and the water absorption kept increasing, almost linearly, with a greater percentage of RCBMA replacement. The average water absorption for the M 25, M 50, M 75, and M 100 samples was 2.47, 3.59, 5.36, and 7.76%, respectively. The results are similar to that observed by Evangelista and Brito (2007) for concrete containing secondary aggregates.

Discussion

Slump

The workability of concrete suffered from higher RCBMA replacement. This is due to the lighter weight of RCBMA aggregates as compared to NCA, causing them to flow less under their self-weight. Moreover, the surface of RCBMA aggregates is rougher compared to NCA, which induces more friction in the fresh mix and results in a lower flow. Results from this study show that with up to 25% RCBMA replacement, the reduction in workability was minimal and the concrete can be used for structural applications.

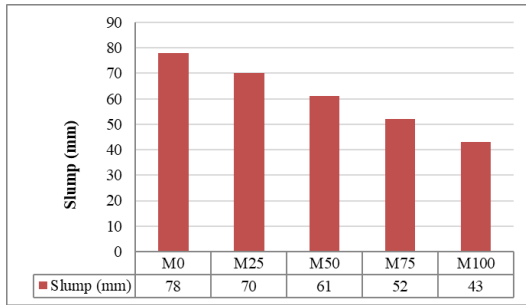


Fig. 13: Slump test results

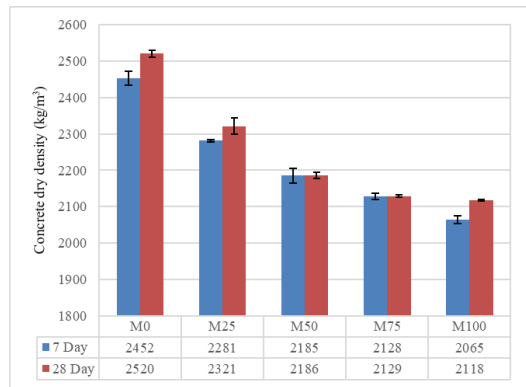


Fig. 14: Concrete dry density results

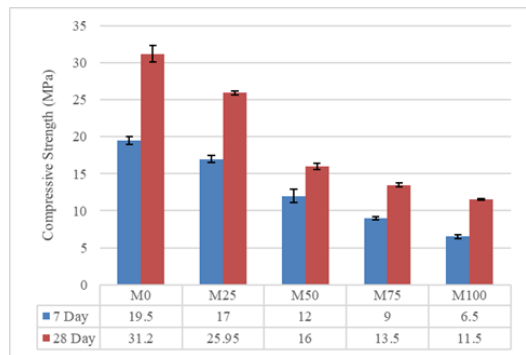


Fig. 15: Compressive strength results

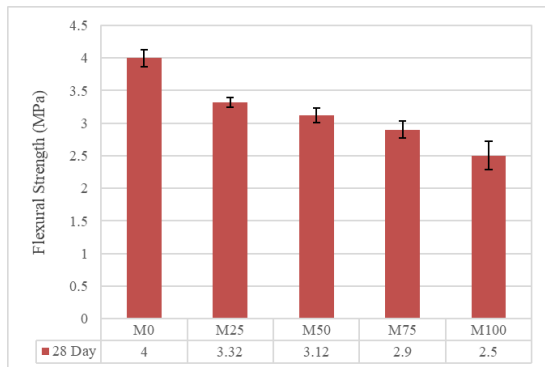


Fig. 16: Flexural strength results

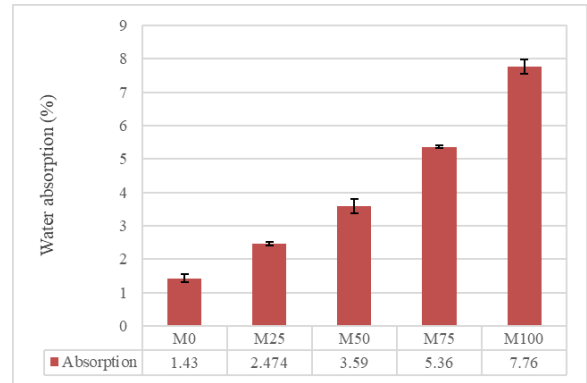


Fig. 17: Water absorption results

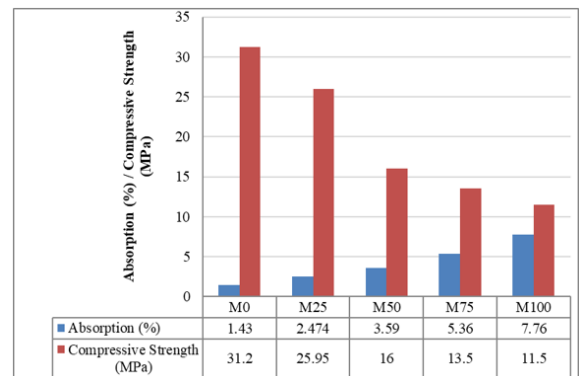


Fig. 18: Relationship between water absorption and compressive strength

Density

The reduction in density with higher RCBMA replacement of NCA was caused by the lighter weight of RCBMA as opposed to NCA, as indicated by the specific gravity of both in Table 4. Also, the rough surface of RCBMA is likely to induce more porosity in the mix and this contributes slightly to the reduction in density. The recorded densities for M 50, M 75, and M 100 were less than 2200 kg/m³, placing their values between that of normal density concrete (2200-2600 kg/m³) and low-density concrete (300-1850 kg/m³).

Compressive Strength

The reduction in compressive strength with higher RCBMA replacement of NCA is due to two main reasons: (a) The lower stiffness of RCBMA aggregates causes stress concentrations around them and the subsequent formation of microcracks, and (b) the higher porosity and entrapped air bubbles in concrete mixes with higher RCBMA replacement reduces their compressive strength.

The average compressive strength for M 25 was 25.95 MPa, or 83.2% of the average strength of the control samples, indicating that concrete for structural

applications is possible with up to 25% RCBMA replacement. This also seems to agree with Evangelista and Birto (2007), where the strength of concrete replaced by recycled aggregates (up to 30%) is generally 80 to 100% of the strength of concrete made with NCA. Concrete with RCBMA replacements greater than 25% can be used for non-structural applications due to its lower compressive strength as suggested by Aliabdo *et al.* (2014).

Flexural Strength

The factors that affect the reduction in flexural strength with higher RCBMA replacement of NCA are the same for compressive strength and mainly include the lower stiffness of RCBMA aggregates and the increased porosity and water absorption of concrete with higher RCBMA replacements.

Water Absorption

The increased water absorption observed with higher RCBMA replacement is due to higher overall porosity and more entrapped air bubbles in the concrete when a large proportion of NCA is replaced by RCBMA. In addition, a higher water absorption usually indicates a lower compressive strength, and this is shown clearly in Fig. 18.

Conclusion

Natural Coarse Aggregates (NCA) are becoming ever more scarce and the need to find alternative coarse aggregate sources has become highly imperative. Furthermore, the disposal of secondary aggregates, such as clay bricks, in a sustainable manner remains challenging. As such, this study focused on examining the suitability of Recycled Clay Bricks Masonry Aggregates (RCBMA) as a substitute for NCA in concrete mix designs. To do so, five different concrete mix designs were prepared with different levels of RCBMA replacement (i.e., 0, 25, 50, 75, and 100%). The study looked at the physical and mechanical properties of the mix designs and the workability was assessed based on the slump test that was done immediately after mixing. From the findings of this study, the following remarks were noted:

- The increase in RCBMA replacement in the concrete mix resulted in a reduction in a slump, indicating lower workability with added RCBMA replacement. However, at 25% RCBMA replacement, the decrease in workability was minimal compared to the control mix (10.3%) and the observed slump was still appropriate for structural applications
- The compressive strength of concrete decreased with a greater percentage of RCBMA replacement. Again, it was seen that a 25% RCBMA replacement could be

ideal to produce structural concrete where the average compressive strength observed was 25.95 MPa (a 16.8% reduction compared to the control mix with 0% RCBMA replacement)

- Similarly, the density of the hardened concrete samples was reduced with an increase in RCBMA replacement. But the reduction was less pronounced from one mixed design to the other. For instance, at 50 and 100% RCBMA replacements, the reduction in concrete density when compared to the control samples was 13.3 and 16%, respectively. This reduction in density was attributed to the lighter weight of the clay brick aggregates compared to the natural coarse aggregates
- An inverse trend was also seen between the flexural strength and increase in RCBMA replacement. For example, at 25% RCBMA replacement, the flexural strength was 3.32 MPa, which was reduced to 2.5 MPa when the RCBMA replacement was 100%
- The water absorption in the hardened concrete samples increased almost linearly with an increase in RCBMA replacement, indicating greater porosity with the addition of RCBMA. For instance, at 25% RCBMA replacement, the water absorption was 1.7 times higher than that of the control mix with no RCBMA

From the findings of this investigation, it can be concluded that RCBMA can be ideally used to substitute coarse aggregates in the production of concrete with up to 25% replacement. At such percentage replacement, acceptable concrete strength and workability were observed, which is suitable for many civil engineering applications. In addition, future research can focus on investigating the durability (i.e., sulfate attack, chloride ingress, resistance to sulfuric acid, etc.), shock resistance, and energy absorption of concrete with RCBMA as a replacement for NCA. Also, real-size beam and slab specimens can be tested to monitor their performance.

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Author's Contributions

Mohammad Yasir Abdul Hakim: Investigation, Formal analysis, Writing-original draft.

Siti Aminah Osman: Conceptualization, Resources, Supervision.

Mohamed El-Zeadani: Formal analysis, Writing-original draft.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and that no ethical issues are involved.

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