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Compressive loading and response time behavior of concrete containing refractory brick coarse aggregates

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Abstract

This research aimed to determine compressive stress and response time of using refractory brick waste as alternative natural coarse aggregates combined with blended cement in manufacturing sustainable concrete. The experiment was conducted by adding 15–50% aggregates volume of refractory bricks coarse aggregate (RBCA) to concrete mix in order to determine the suitability as coarse aggregates. The results showed that the slump values for the combination of standard concrete (SC) with all RBCA satisfied the design value of ± 20 cm and this showed easy handling and workability of the fresh concrete produced. Moreover, the peak stress and toughness were reduced as RBCA increased from 15 to 50% at both w/c of 0.52 and 0.49. The relationship between compressive stress and response time also showed that the travel time at the elastic, peak, and ultimate stages decreased as RBCA increased from 15 to 50% at both w/c. It was concluded that concrete mix with 50% RBCA did not meet the required criteria at w/c of 0.49 but those with 15–50% RBCA satisfied the minimum requirements at w/c of 0.52.

Keywords: Refractory brick stone aggregate (RBCA), Compressive strength, Compressive stress-response time behavior, Toughness

Introduction

The need for natural rocks and sand is increasing rapidly and continuously in recent decades due to the demand for large quantities of concrete to bolster the construction of massive buildings and infrastructure. The high demand is observed to have led to large-scale mining of rock and sand, thereby causing significant changes to nature balance as shown by the frequent occurrence of floods and landslides. For example, refractory brick (RB) is a fire-resistant and high-temperature-resistant material considered very important in constructing walls for ore processing furnaces, particularly those used in refining nickel ore. However, the quantity of RB by-products is increasing in line with the need for these furnaces and often placed in stacking yards which is the lowest stage of solid waste management. This shows that solid by-products need to be recycled to reduce the expenditures incurred through the current landfilling operations and the pressure placed on the environmental equilibrium by extensive rock and sand mining.

The application of RB by-products to replace natural rocks as coarse aggregates in concrete is very important in reducing disastrous mining activities. Several research have been generally conducted on the potential application of this material as acceptable aggregates or relevant additive in concrete production Khatab et al., [13], Khattab et al., [15], Khattab & Hachemi, [14], Nematzadeh & Baradaran-Nasiri, [19]. For example, Nematzadeh and Baradaran-Nasiri [19] reported that the increasing usage of RB by-products as fine aggregates improved compressive strength of concrete at higher temperatures. Another research by Khatab et al. [13] provided critical evidence for the replacement of 30% ordinary crushed rock (OCR) used as coarse aggregates in concrete by RB by-products. Moreover, an experimental research conducted by Khattab et al. [15] and Khattab and Hachemi [14] discussed considerable details about the viability of replacing 20% OCR with this material as coarse aggregates to produce sustainable concrete through experimental evaluation of the mechanical and physical features. Most recently, the findings from Jureje et al. [12] indicate that the inclusion of refractory coarse aggregate in concrete mixes at various percentages has a nuanced effect on compressive strength. Specifically, when the refractory coarse aggregate constitutes 15% of the mixture, there is a slight reduction in compressive strength compared with the control concrete. However, as the proportion of refractory coarse aggregate increases to 30% and 50%, this reduction in compressive strength becomes less significant, suggesting a marginal impact on strength at higher proportions of refractory coarse aggregate. Additionally, the study highlights the importance of the water-to-cement (w/c) ratio in mitigating the loss of compressive strength associated with the addition of refractory brick aggregate. Another study by Pertiwi et al. [22] suggests that the performance of concrete paving blocks can be enhanced by increasing the percentage of alumina waste refractory brick used as a replacement for sand in the mixture. The authors argued that the higher alumina content in the refractory bricks plays a crucial role in promoting pozzolanic reactions during the hydration process of the concrete. Pozzolanic reactions involve the reaction of silica and alumina with calcium hydroxide in the presence of water, forming additional calcium silicate hydrate (C-S–H) gel. This gel contributes to the strength and durability of concrete by filling in voids and enhancing the binding properties of the material.

Concrete is basically produced using 60% to 75% aggregates and coarse type constitutes approximately 45% Meddah et al. [17],Irmawaty et al. [11],Sandra et al. [23]. The resilience of a concrete structure to withstand compressive loads is intricately defined by the potential collapse mechanisms which are substantially associated with the inherent properties of the constituents Ozturan & Cecen [21],Zhou et al. [30]. One of the qualitative methods often used to assess the compositional materials associated with the collapse mechanism is the loading-response time relationship as previously stated in the experiments conducted by Kim et al. [16] and Ali et al. [1].

The stakeholders in the construction materials sector, including cement and concrete producers, have been attempting to reduce the carbon footprint for decades. This has led to the suggestion of fly ash or pozzolanic materials derived from different by-products as additives to provide sustainable blended cement for construction Schneider et al. [24]. An example is the Portland Composite Cement (PCC) which is presently common in the Indonesian market SNI, [27]. The results of several laboratory research confirmed that PCC-based concrete and mortar had favorable mechanical properties Caronge et al. [8],Djamaluddin et al. [9]. Moreover, blended cement has been used to promote different scientific approaches in several research to reduce the abundance of fly ash produced through the widespread usage of coal as a fuel source for power plants.

The aforementioned above literatures show the advantages of using refractory brick aggregate in concrete mixes, both as coarse and fine aggregate. However, it acknowledges a potential challenge due to refractory bricks that are porous in nature as well as had low strength value, which might impact the bond between aggregate and the cement matrix, potentially reducing the concrete ability to withstand compressive loads. Hence, this study endeavors to examine the influence of compression time on the variations in stress within concrete containing RBCA. By observing the compressive strength values over time, this study aims to examine how the bond between RBA and the cement matrix evolves and its impact on the concrete mechanical properties. This research provided methods to specifically calculate the time required by a specimen to collapse under load, and the relationship was further used to determine the behavior of the specimen.

The novelty of this study was to experiment with the production of sustainable concrete using RBCA by-products and to quantitatively assess some important features such as compressive strength as well as load and response time behavior. The purpose was to determine the usability of this material in producing concrete in combination with blended cement.

Materials and experimental procedures

Materials

This research was focused on expanding the perception of blended cement, including the PCC type, as a sustainable building material considered easily accessible on the national market and useful in producing all concrete mixes. Crushed OCR process was used as fine aggregates (FS), while OCR from the exterior surface of corresponding nickel ore mining areas were split into smaller coarser pieces with a maximum favorable size of 20 mm as coarse aggregates.

The sieve diameters of the FS, OCR, and RBCA complied with the SNI 03–2834, [26] gradation criteria for concrete aggregates as presented in Fig. 1. RBCA was obtained from the furnace partition of the nickel refinery in Sorowako, Indonesia, manually crushed, and sieved to acquire the desired 10–28 mm size and quantity needed as coarse aggregates. The physical properties of aggregates used are listed in Table 1. The physical appearance of FS, OCR, and RBCA is shown in Fig. 2. Meanwhile, the chemical components of RBCA are listed in Table 2 with MgO Al_2O_3, SiO_2, and Fe_2O_3 identified as the key compounds. These compounds were categorized as reactive due to their exposure to high burning temperatures. It was further discovered that RBCA used in this research was mostly dominated by MgO and Fe_2O_3. Moreover, the physical properties showed lower specific gravity and this indicated the importance of higher water absorption rate to RBCA compared to OCR. The pores found along the surface of RBCA were responsible for the high-water absorption rate. This led to the immersion of the material into water for 4 h followed by air curing to achieve saturated surface dry (SSD) before its application as coarse aggregates. The

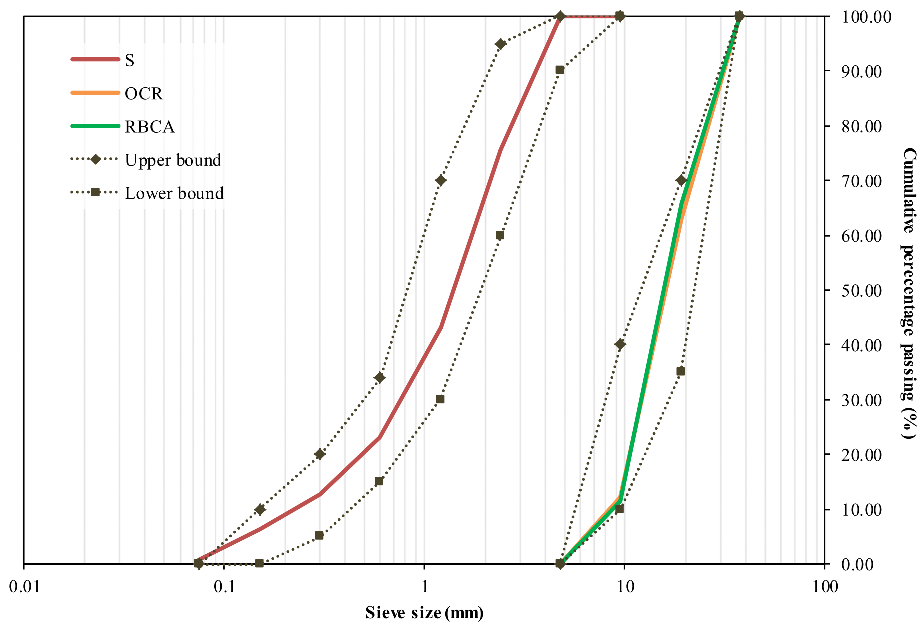


Fig. 1 Sieve analysis of aggregates

Table 1 Physical properties of aggregates

Property	FS	OCR	RBCA	Test procedure
Specific gravity in SSD condition	3.01	3.11	2.93	ASTM C127-88, [3] and ASTM-C-128, [2]
Water absorption (%)	0.44	0.35	2.92	
Fine modulus	3.71	7.26	7.21	ASTM C136—06, [5]
Los Angeles abrasion (%)	-	17.40	62.2	ASTM C131/C131M-14, [4]

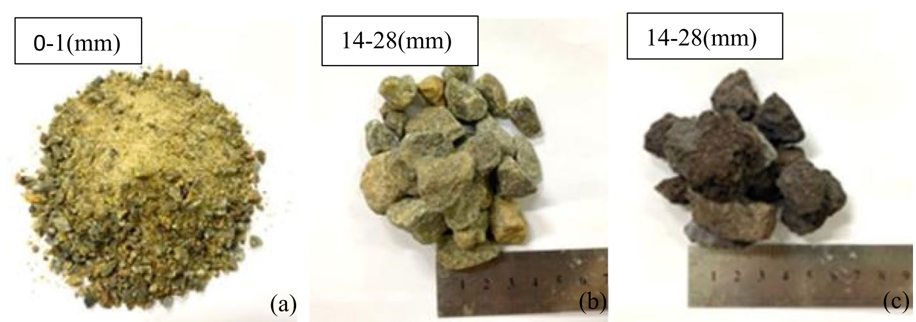


Fig. 2 Physical and geometric appearance of aggregates: **a** FS, **b** OCR, and **c** RBCA

observation was based on the approach applied in a previous research Khatab et al. [13] to minimize water loss in RBCA during the mixing process. Moreover, the ability of RBCA to withstand mechanical action was observed to be lower than for OCR based on the Los Angeles abrasion test conducted González-Fonteboa et al. [10]. It

Table 2 Chemical compounds of RBCA

Compounds	RBCA
Magnesium oxide (MgO)	8.689
Iron oxide (Fe_2O_3)	51.242
Chromium oxide (Cr_2O_3)	27.35
Sulfur trioxide (SO_3)	4.869
Nb_2O_5	0.079
Aluminum trioxide (Al_2O_3	2.539
Calcium oxide (CaO)	1.959
Loss of ignition (LOI)	1.813
In_2O_3	0.008
TiO_2	0.813
ZrO_2	0.079
NiO	0.57
MnO	0
SnO_2	0.051
Potassium oxide (K_2O)	0
Silicon dioxide (SiO_2)	4.611
Insoluble residue	-
Others	-
P_2O_5	0.739
ZnO	0.05

Table 3 Concrete mix proportion

Mix No	Specimen ID	w/c	Water (kg/m^3)	Cement (kg/m^3)	FS (kg/m^3)	OCR (kg/m^3)	RBCA (kg/m^3)
1	SC	0.52	227	438	722	1085	0
2	RBCA-15		227	438	722	922	155
3	RBCA-30		227	438	722	760	311
4	RBCA-50		227	438	722	543	518
5	SC	0.49	228	466	711	1070	0
6	RBCA15		228	466	711	909	153
7	RBCA-30		228	466	711	749	306
8	RBCA-50		228	466	711	535	511

was further stated that the weak features of the material could reduce compressive strength of concrete.

Mix Properties and specimen preparation

Concrete mixture was designed to achieve a grade of 21 MPa and 25 MPa with w/c 0f of 0.52 and 0.49, respectively, using the trial mix procedure. The process focused on using RBCA wastes to produce eight different concrete mix compositions where RBCA was varied at 0%, 15%, 30%, and 50% of the total aggregates volume as presented in Table 3.

The fresh concrete was mixed evenly in the laboratory using an electric mixer and immediately poured and compacted in a cylinder mold with a diameter of 100 mm and a height of 200 mm. The cast concretes used as specimens were maintained at a temperature of 25 ℃ for 1 day in the laboratory, removed from the mold, and soaked in water at the same temperature of 25 ℃ until the specimens were ready to be tested.

Methods

Workability of fresh concrete

The slump test is traditionally one of the approaches to evaluate the workability of fresh concrete. Therefore, ASTM C143/C143M-12 [6] was adopted in this research as the basis for the qualitative and quantitative evaluation.

Compressive strength

Compressive strength was tested using cylindrical concrete specimens with a diameter of 100 mm and a height of 200 mm and cured in water for 7 and 28 days. The test was conducted in line with ASTM C39/C39M—14 [7] and the process was achieved by using a universal testing machine (UTM) with a capacity of 1000 kN to apply a compressive load on the diametrical surface of the specimen at a speed of 0.25 MPa/second until it fails. Concrete compressive strength (f'c) was eventually quantified using the following Eq. (1):

$$f\prime c = P/A \tag{1}$$

Fig. 3 The instruments deployed to figure out the compressive stress process: **a** compressive strength test and **b** computerized devices set

where f'c is compressive strength (MPa), P is compressive load (N), and A is compressive area of the specimen (mm^2).

Compressive stress was determined using the instruments presented in Fig. 3, and this included a load cell tied to an ensemble of computerized devices to record the load value per time. The purpose was to establish a straightforward correspondence between response time and compressive stress. The test was conducted by representing each mixture with three identical specimens at each age, and the average result was used as the reference value in the subsequent phase of analysis.

Toughness

Toughness and toughness index have been used to analyze the ability of concrete to withstand post-peak compressive loads, and this is traditionally based on the relationship between stress and strain Munir et al. [18]. Toughness rate was calculated using certain variables obtained from 28-day-old specimens such as compressive strength and time in order to comprehensively understand the behavior of concrete under compressive loads. It is important to state that toughness is a quantifiable measurement normally used to determine the energy absorption capacity of concrete during loading. This was achieved by calculating the area under compressive stress and time curve from the start to 80% post-peak stress and previously applied in a previous research Yan et al. [29]. The principles and formulas applied to determine toughness and toughness index are presented in Fig. 4 and Eq. 1.

Results and discussion

Workability

The slump rates obtained for concrete mixtures are depicted quantitatively in Fig. 5. It was discovered that standard concrete (SC) ranged between 18.51 and 21.21 cm for w/c

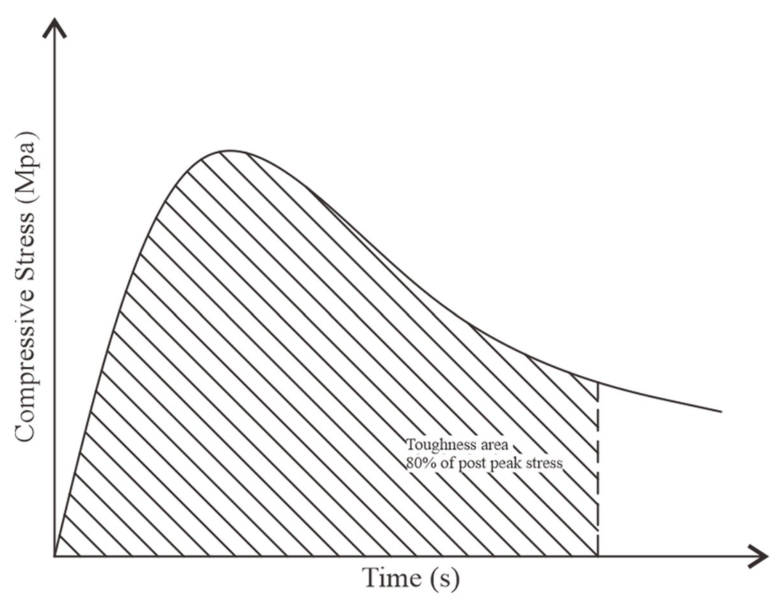


Fig. 4 Toughness area

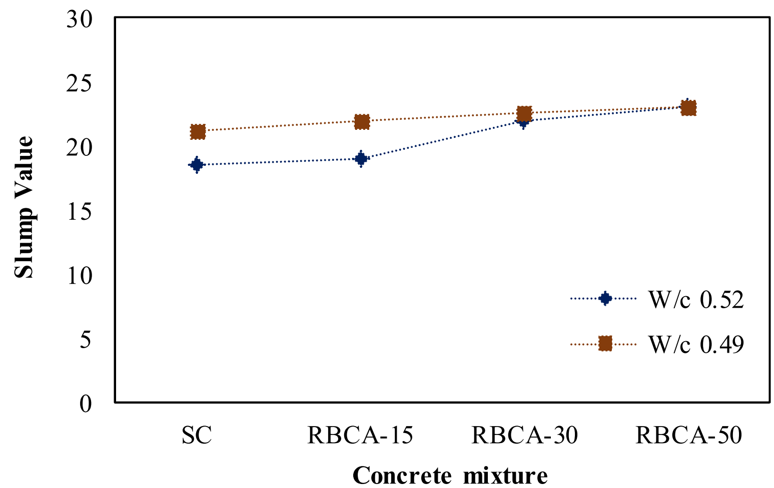


Fig. 5 Slump values of the fresh concrete for SC and RBCA

of 0.52 and 0.49, respectively. Meanwhile, the values changed due to the introduction of RBCA into concrete mixtures as shown by an increment of 2.65%, 18.31%, and 24.26% recorded for RBCA-15, RBCA-30, and RBCA-50, respectively, at w/c of 0.52 as well as 3.59%, 5.73%, and 7.78% at w/c of 0.49 compared with SC.

The increment in slump value was possibly associated with the immersion of RBCA in water for 4 h and its subsequent drying before being added to concrete mix while maintaining a consistent water-to-cement ratio. This was observed to be in line with the results of other previous research that the addition of recycled materials to concrete mixes as coarse aggregates increased the slump value Sheen et al. [25]. However, the values recorded for both SC and all RBCA combinations satisfied the ± 20 cm slump design, and this indicated good workability and easy handling of the fresh concrete on the field.

Compressive strength

The effect of different variations of RBCA on compressive strength of concrete was assessed at 7 and 28 days for w/c of 0.5 and 0.49. The value was observed to have increased for all samples except the one with the partial substitution of OCR with RBCA. This was shown by the 15.26 MPa and 21.58 MPa recorded for SC at the age of 7 and 28 days for w/c of 0.5 and 18.01 MPa and 25.36 MPa for w/c of 0.49, respectively. Meanwhile, the samples with RBCA variations of 15%, 30%, and 50% showed a decrease in compressive strength by 7.20%, 10.50%, and 21.09% for w/c of 0.5 and 5,89%, 28.23%, and 38.52% for w/c of 0.49, respectively, compared with SC. The reduction was further recorded at 28 days to be 0.13%, 13.59%, and 26.64% for w/c of 0.5, as well as 2.95%, 20.77%, and 34.64% for w/c of 0.49, respectively, compared with SC.

The results showed that compressive strength of concrete mixture was reduced as more content of OCR was replaced with RBCA. The acceptable explanation for this trend was associated with the higher porosity value of RBCA compared to OCR as shown by the absorption values of 0.35 and 2.92%, respectively, in Table 2. This was in line with previous investigations conducted by replacing natural coarse aggregates with recycled materials characterized by high porosity yielded similar results Khatab et al. [13],

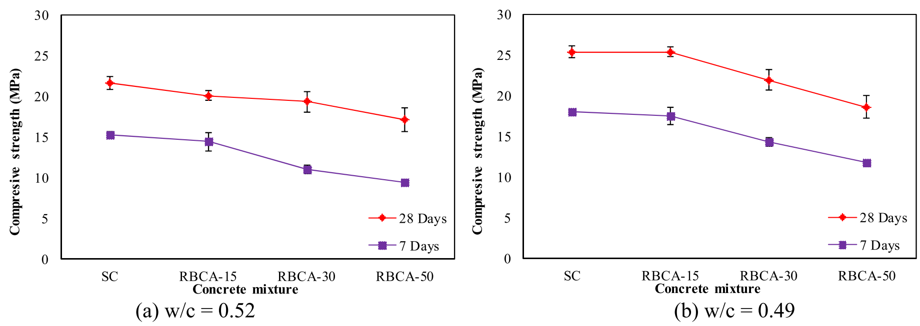


Fig. 6 Concrete compressive strength at different RBCA contents

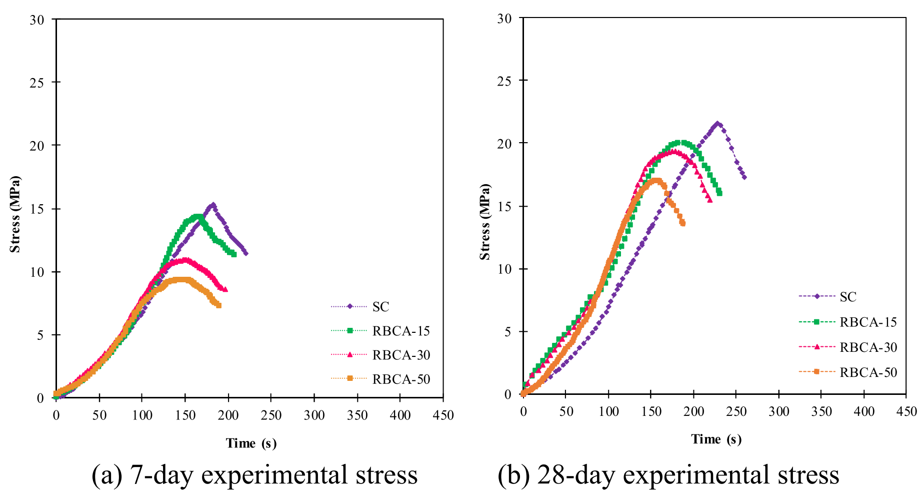


Fig. 7 Experimental stress and response time behavior (w/c = 0.52)

Nepomuceno et al. [20]. Compressive strength values recorded in this research satisfied the 17 MPa minimum required by SNI [28] for general usage, but 21 MPa is required for specialized moment-resisting frames and structural walls. It was also observed that compressive strength increased from 7 to 28 days of age for both w/c of 0.49 and 0.52 irrespective of RBCA content in the mix. This showed the ability of the blended cement to hydrate and harden to bind conventional and RB coarse aggregates (Fig. 6).

Relationship between compressive and response time

The relationship between compressive stress and response time for SC and RBCA samples is presented in Figs. 7 and 8. Several peak stresses were observed between the mixtures with and without RBCA, but all the samples had similar linear and nonlinear ascending stages up to the peak stress followed by descending stages. This showed the existence of similar physical properties for both RBCA and OCR which enabled strong mortar adhesion and further generated brittle behavior in all samples. Moreover, the normalized compressive stress–response time curve was used to comprehensively analyze the role of compressive stress in achieving the elastic, peak, and ultimate stages of both SC and concrete incorporating RBCA quantitatively (Figs. 9 and 10). This led

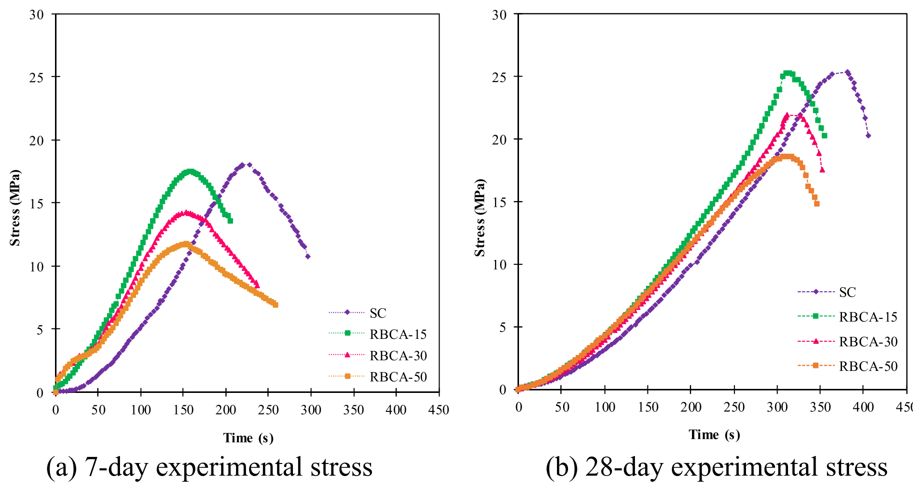


Fig. 8 Experimental stress and response time behavior (w/c = 0.49)

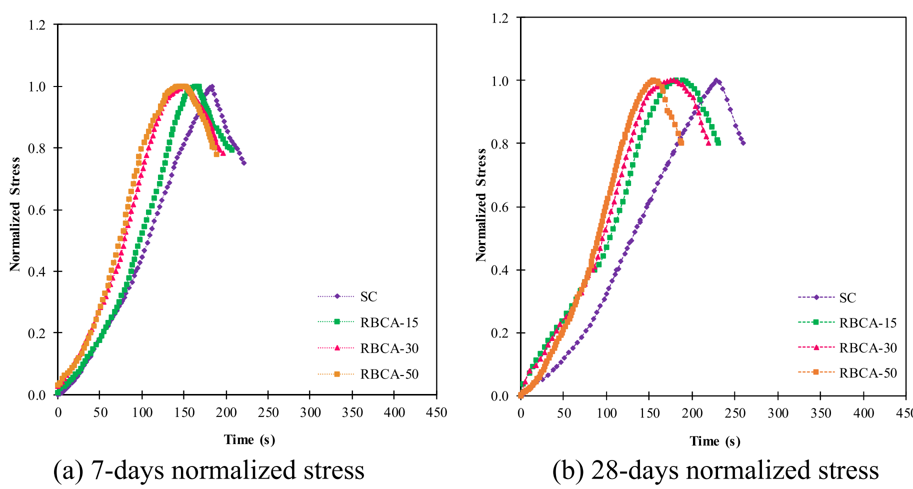
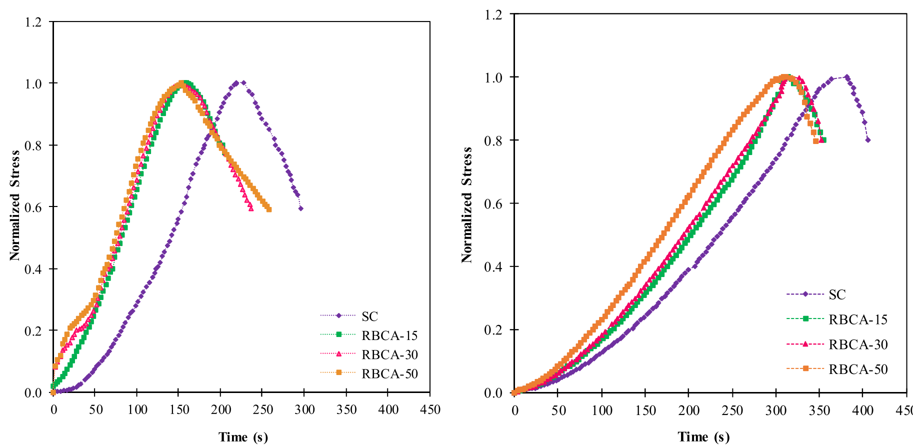


Fig. 9 Normalized stress and response time behavior (w/c = 0.52)

to the designation of 40% peak stress and 80% post-peak stress as the elastic and ultimate stages, respectively.

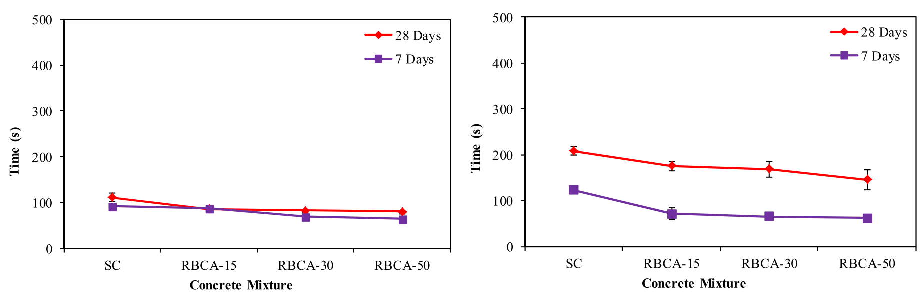
Elastic stage behavior

The relationship between compressive stress and response time is presented in Fig. 11 to measure the impact of RBCA addition in the elastic stages. It was discovered that response time of SC was 123.00 s and 207.67 s at w/c of 0.49 and 92.28 s and 111.67 s at w/c of 0.52 for 7 and 28 days, respectively, in the elastic stage. The addition of 15 to 50% RBCA changed response time from 62.33 s to 71.33 s and 145.50 s to 175.33 s at w/c of 0.49 and then 64.39 s to 87.00 s and 80.67 s to 86.27 s at w/c of 0.52 for 7 and 28 days, respectively. The results showed that response time in the elastic stage was highly dependent on the grade of coarse aggregates. The trend was further associated with the



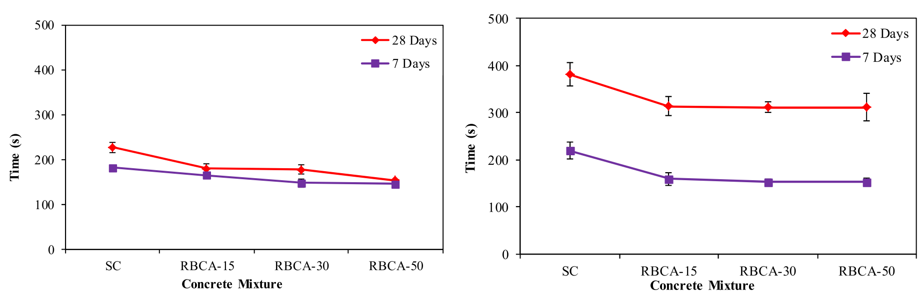
(a) 7-days normalized stress (b) 28-days normalized stress

Fig. 10 Normalized stress and response time behavior (w/c = 0.49)



(a) w/c of 0.52 (b) w/c of 0.49

Fig. 11 Compressive stress and response time to reach the elastic stage



(a) w/c of 0.52 (b) w/c of 0.49

Fig. 12 Compressive stress and response time to reach the inelastic stage to peak stress

influence of the grade on the capacity of concrete to manage elastic deformation caused by compressive stress.

Peak stress behavior at the inelastic stage

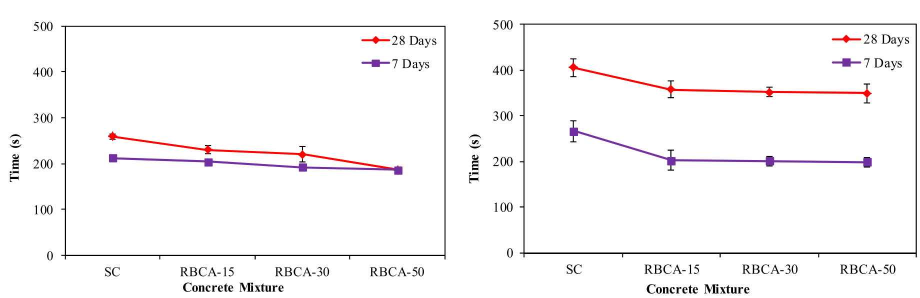
The relationship between compressive stress and response time is presented in Fig. 12 to measure the impact of RBCA addition in the inelastic stages. The results showed that the longest response times were in SC with 82.00 s and 228.00 s recorded at w/c of 0.52 as well as 219.97 s and 380.67 s at w/c of 0.49 for 7 and 28 days respectively. Moreover, the addition of RBCA from 15 to 50% changed the value from 146.67 s to 165.50 s and 155 s to 181 s at w/c of 0.52 for 7 and 28 days, respectively. The value also changed from 153.33 s to 159.67 s and 312.00 s to 314.00 s at w/c of 0.49 for 7 and 28 days, respectively. This showed that an increase in the percentage of RBCA added led to a reduction in response time. The results showed that the effort to resist compressive stress from the inelastic stage to peak stress was effectively managed through the use of magnesia-based RBCA.

Ultimate stage behavior

The effect of RBCA addition on the relationship between compressive stress and response in the ultimate stage is presented in the following Fig. 13. The addition of 15%, 30%, and 50% of RBCA reduced the reaction time to compressive stress in the ultimate stage by 3.80%, 9.46%, and 12.20% for w/c of 0.52 and 24.07%, 24.57%, and 25.32%, respectively, for w/c of 0.49 compared with SC at 7 days. The reduction at 28 days was recorded to be 10.98%, 15.22%, and 27.83% for w/c of 0.52 as well as 11.87%, 13.23%, and 13.97% for w/c of 0.49, respectively. The experimental data gathered after 28 days showed that the variation in response time between SC and RBCA did not exceed 30%. This was associated with the fact that all concrete mixtures shared an identical proportion of cement paste and mortar. The limited divergence in response times showed that mortar or cement paste, important for preserving the overall strength of concrete, played a significant role in determining the efforts to resists the post-peak stress stage used to represent the ultimate phase.

Toughness

The results presented in Fig. 14 showed that SC had the highest toughness values with 2845.291 MPa.s and 4626.44 MPa.s recorded for w/c of 0.52 and 0.49, respectively. Meanwhile, concrete treated with15%, 30%, and 50% RBCA decreased by 1.93%, 9.91%, and 39.33% for w/c of 0.52 and 10.70%, 19.14%, and 26.46% for w/c of 0.49, respectively.



(a) w/c of 0.52 (b) w/c of 0.49

Fig. 13 Compressive stress and response time to reach the ultimate stage

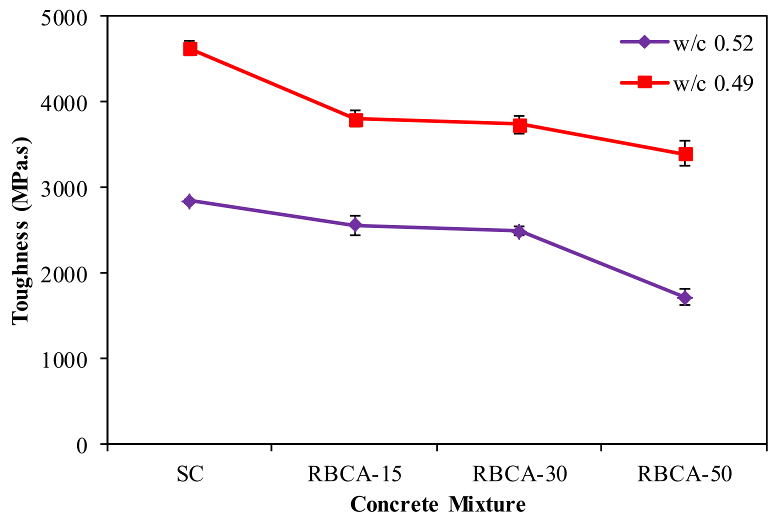


Fig. 14 Toughness value of RBCA

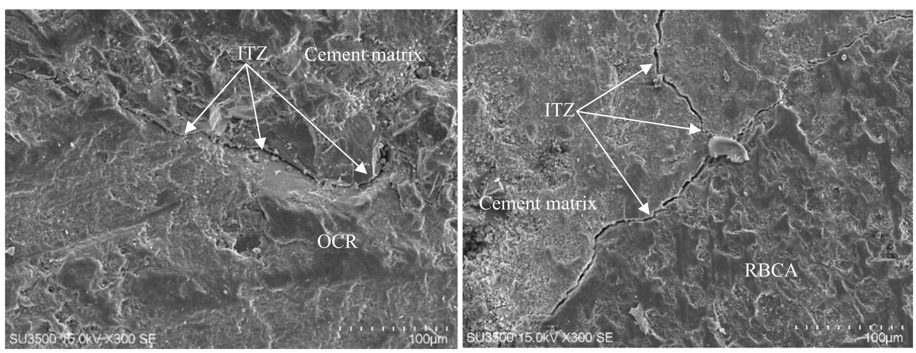


Fig. 15 Comparison the ITZ of SC (left) and RBCA concrete (right)

SEM analysis

Figure 15 compares the interfacial transition zone (ITZ) of SC and RBCA concretes through SEM analysis. Cracks are evident at the ITZ in both SC and RBCA concrete. However, cracks observed in RBCA concrete are notably more severe than that SC. This disparity is evident as cracks in RBCA concrete extend beyond the ITZ and propagate within the cement matrix. Such occurrences suggest a weakened cement matrix within the ITZ region due to RBCA absorb of free water and impeding the cement hydration process. Consequently, the ITZ in RBCA concrete exhibits reduced strength. This observation aligns with the findings from compressive loading and response time, indicating that an increase in RBCA content in concrete results in shorter durations to reach elastic, peak, and ultimate stress conditions compared to SC.

Advisability requirement (AR)

The establishment of advisability requirements for RBCA-containing concrete is important to ensuring its effective use as a conventional alternative in actual construction projects. This was achieved in this research with a focus on compressive stress and response

Table 4 Advisability requirement

Notation	OCR (%)	RBCA	f'c (MPa)		AR (%)	
			w/c = 0.52	w/c = 0.49	w/c = 0.52	w/c = 0.49
SC	100	0	21.58	25.36	-	-
RBCA-15	85	15	20.02	25.33	92.77	98.88
RBCA-30	70	30	19.31	21.91	89.48	86.40
RBCA-50	50	50	17.03	18.60	78.92	73.34

time behavior. The requirement was formulated by applying a concept used to allow the usage of pozzolanic material as a partial substitute for Portland cement, known as strength activity index (SAI) Sheen et al. [25],Yan et al. [29].

The advisability requirements were considered to be satisfied when RBCA-containing concrete had a minimum AR value of 75% compared with SC. This was observed to have been achieved by all RBCA combinations for w/c of 0.52 and RBCA-15, as well as RBCA-30 for w/c of 0.49, as shown in Table 4.

Conclusions

In conclusion, this research investigated the impact of using different quantities of RBCA materials on certain properties of concrete mix. The purpose was to determine the advisability of using RB by-products as coarse aggregates in concrete. The experiments conducted provided the following results:

1. The slump values of both SC and entire RBCA combinations satisfied the ± 20 cm required, and this showed good workability and easy handling of the fresh concrete produced in the field.
2. Peak stress and toughness values reduced as RBCA was increased from 15 to 50% at both w/c of 0.52 and 0.49 as presented in compressive stress and time curves.
3. The relationship between compressive stress and time response showed a reduction in the travel time at the elastic, peak, and ultimate stages as RBCA was increased from 15 to 50% at both w/c of 0.52 and 0.49.
4. According to the advisability requirements, concrete with RBCA 50% did not satisfy the required criteria at w/c of 0.49, while concrete with RBCA 15–50% fulfilled the minimum requirements at w/c of 0.52.

Abbreviations

RB	Refractory bricks
RBCA	Refractory bricks coarse aggregate
SC	Standard concrete
OCR	Ordinary crushed rock
PCC	Portland composite cement
FS	Fine aggregates
SSD	Saturated surface dry
AR	Advisability requirement

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Authors' contributions
All authors read and approved the final manuscript.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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