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Basic Engineering Properties of Concrete with Refractory Brick as Coarse Aggregate: Compressive Stress-Time Relationship Assessment

U. Jureje, M. W. Tjaronge, M. A. Caronge*

Civil Engineering Department, Universitas Hasanuddin, Makassar, Indonesia

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ABSTRACT

This study aims to investigate the use of refractory brick (RBA) by-products as a substitute for coarse aggregate in sustainable concrete production. Concrete mixes with water-to-binder (w/c) ratios of 0.52 and 0.49 and containing 0%, 15%, 30%, and 50% RBA as a partial replacement for ordinary crushed stone (OCS) were produced. The following properties were examined in this study: workability, compressive strength, stress-time relationship, toughness index, performance criteria, and cost analysis. The test results showed that an increase in the RBA percentage in the concrete mixtures positively contributed to concrete workability. Moreover, the compressive strength and all phases in the compressive stress and time relationship decreased as the percentage of RBA in the concrete mixture increased. However, at 15%RBA, the toughness index value was comparable to that of the reference concrete, whereas based on the performance criteria, the replacement of OCS with 15%RBA for both water-cement ratios met the minimum requirements. Meanwhile, cost comparison analysis discloses that material and production costs can be reduced by approximately 51.84% and 1.5–6.5%, respectively. Based on the analysis of all the test results, 15%RBA exhibited insignificant differences in value compared with the reference concrete. Thus, the use of 15%RBA as an OCS replacement is an acceptable and viable option for producing sustainable concrete.

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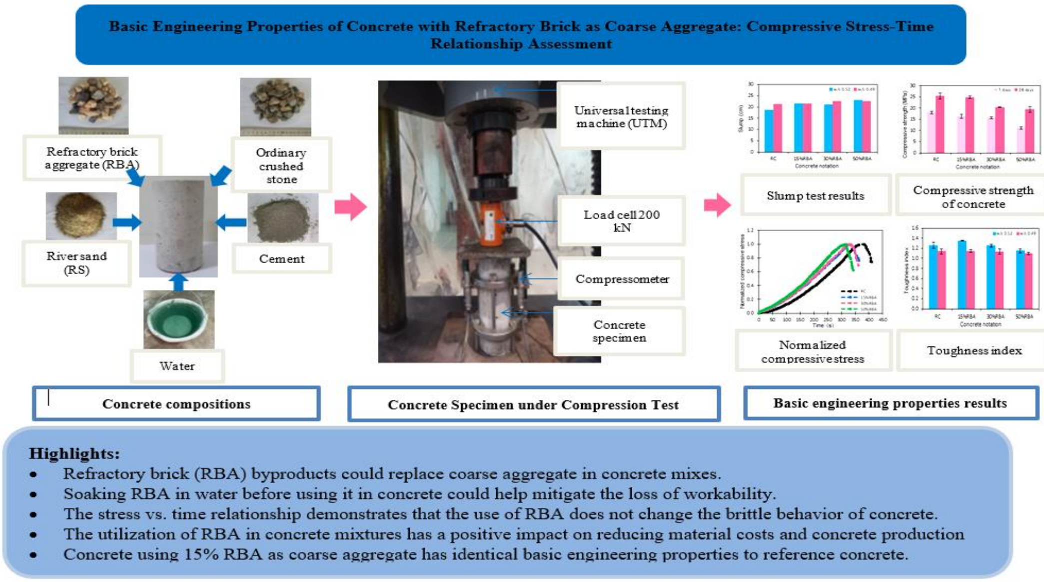
Graphical Abstract



Basic Engineering Properties of Concrete with Refractory Brick as Coarse Aggregate: Compressive Stress-Time Relationship Assessment

Highlights:

- Refractory brick (RBA) byproducts could replace coarse aggregate in concrete mixes.
- Soaking RBA in water before using it in concrete could help mitigate the loss of workability.
- The stress vs. time relationship demonstrates that the use of RBA does not change the brittle behavior of concrete.
- The utilization of RBA in concrete mixtures has a positive impact on reducing material costs and concrete production
- Concrete using 15% RBA as coarse aggregate has identical basic engineering properties to reference concrete.

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*Corresponding Author Email: *ma-caronge@unhas.ac.id* (M. A. Caronge)

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1. INTRODUCTION

The large-scale construction of buildings and infrastructure in urban areas, which are mostly composed of concrete and mortar, requires large amounts of sand and naturally crushed stone or ordinary crushed stone (OCS). Concrete is manufactured with an aggregate proportion of approximately 60–75% of the overall volume, with approximately 45% coarse aggregate (1, 2). Each year, approximately 13.12 billion tons of aggregates are globally utilized (3). Related to the conditions mentioned above, it is necessary to keep abreast of major changes in reuse and recycling technology so as to significantly reduce the use of virgin materials as building materials and to provide added value to non-hazardous waste (4).

Refractory brick (RB) by-products are non-hazardous and non-toxic solid by-products that can be used as fire-resistant and high-temperature furnace walls. The number of RB by-products will continue to grow in line with the need for furnaces. Approximately 28 million tons of RB by-products are generated each year (5). In general, the utilization of RB by-products as aggregates or additives for concrete production has been extensively studied (6-9).

Efforts to add value to by-products and provide sustainable cement have encouraged cement manufacturers to adopt fly ash or pozzolanic materials from other by-products as cement substances to produce blended cement (10). Such cement recognized as sustainable cement and is available in the national market as Portland composite cement (PCC) and used to produce reliable concrete and mortar (11).

The robustness of concrete structures to compressive loads is characterized by the mechanisms of compressive failure that may occur, which depend on the constituent properties of the concrete. One of the qualitative assessments used to evaluate the failure mechanism is through the loading response time behaviour described in the scientific literatures (12, 13).

The investigational method utilized throughout this study to develop a link between stress and related time responses is proposed as a novel approach to the assessment of hardened concrete containing RB and blended cement under compressive load.

2. MATERIALS AND METHODS

2. 1. Materials

PCC blended cement that available on the market serves as the principal binder in the manufacture of all concrete mixtures in this study. The PCC cement used has a specific gravity of 3.07 and fulfills the Indonesian requirement for PCC.

Fine aggregate is natural sand mined from rivers and defined as river sand (RS). Ordinary stone spanning numerous surfaces in the same nickel-obtaining location was crushed into a smaller, coarser shape and then regarded as coarse aggregate. In the present study, such aggregate was defined as ordinary crushed stone (OCS) in the process of producing regular concrete. The Refractory Brick Aggregate (RBA) used in this study was acquired from the kiln walls of a nickel slag ore furnace in Sorowako, Indonesia. The RBA were crushed manually and sieved to obtain the required size and amount to produce coarse-aggregate RBA with a size range of 10–28 mm.

The grain size distribution of RS, OCS, and RBA complies with the concrete mix gradation standard according to ASTM C33 (14). The grain size distribution of RS, OCS, and RBA is shown in Figure 1, and the physical appearance of RS, OCS, and RBA is shown in Figure 2. Meanwhile, the physical properties of RS, OCS, and RBA are listed in Table 1.

The primary chemical compound components of RBA are Al_2O_3 (17.52%), SiO_2 (35.11%), and Fe_2O_3 (19.55%), all of which can be characterized as reactive owing to their high combustion temperatures. Based on the physical properties listed in Table 1, RBA possesses lower specific gravity and higher water absorption than OCS. Such high water absorption was due to the presence of pores on the surface of the RBA. The property causes the RBA abrasion value greater than OCS, which is 36% for RBA and 17.5% for OCS, as summarized in Table 1.

Owing to the high water absorption of RBA, prior to their inclusion in the concrete mix, the RBA were pretreated by immersion in water for 4 hours and then air-dried until saturated surface dry (SSD) conditions. This

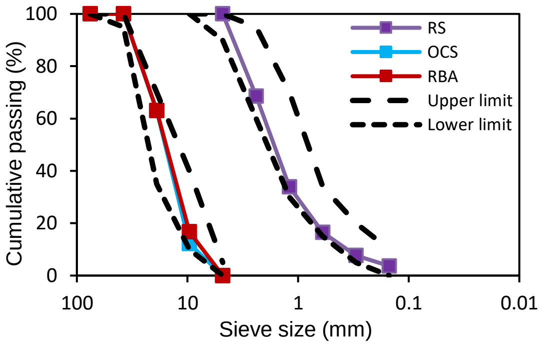


Figure 1. Gradation of aggregate grain size

(a) RS (b) OCS (c) RBA

Figure 2. Physical appearance of the aggregate

TABLE 1. Physical properties of aggregates

Item	Specific gravity	Water absorption (%)	Fineness modulus	Los angeles abrasion (%)
RS	3.02	0.45	3.70	-
OCS	3.13	0.36	7.25	17.50
RBA	2.92	2.91	7.20	36.00
Testing standard	ASTM C127 (15) and ASTM C128 (16)		ASTM C136 (17)	ASTM C131 (18)

approach is in accordance with the methodology applied by previous researchers (6). This approach mitigates the loss of water during mixing owing to the high water absorption of RBA.

2. 2. Mix Proportions and Specimen Preparation

The design of concrete mixture is carried out through the trial mix process to obtain a proportional mixture composition for the target concrete strength (f'c) of 21 MPa and 25 MPa with w/c of 0.52 and 0.49, respectively. Eight concrete mix compositions were prepared using the RBA by-product as a partial replacement for OCS at 0%, 15%, 30%, and 50% by aggregate volume. The concrete mix design is presented in Table 2, and concrete mixing is carried out based on ASTM C192 (19). The concrete sample was manufactured using a 75-liter mixer. Then, the fresh concrete mixture was poured into an iron cylinder mold with a diameter of 100 mm and a height of 200 mm and compacted for 60 s using a vibrator machine. The concrete mixture was then left for 24 hours before the mold was opened, and the concrete samples were soaked in fresh water at a constant temperature of 20±2 °C until the testing day.

2. 3. Fresh Concrete Test

The slump test of fresh concrete was performed according to ASTM C143 (20). In this study, a target slump measuring 20±2 cm was used.

2. 4. Compressive Strength Test

The compressive strength test was performed using a universal testing machine (UTM) with a capacity of 1000 kN, as depicted in Figure 3, based on ASTM C39 (21). The load is applied to the surface of the specimen at a speed of 0.25 MPa/second until the specimen is crushed. To provide a straightforward alignment between the time response and compressive stress, a load cell coupled with a set of computerized devices was used to capture the load value and linked time during the compressive testing process. A concrete compressive strength test was performed on three specimens of each concrete mixture, and the average values of the three samples were adopted for quantitative assessment.

2. 5. Toughness Index

The toughness index is a parameter that describes the behaviour of a solid material such as concrete at post-peak stress and indicates the energy capability of the concrete to resolve the fracture of the material.

TABLE 2. The concrete mix designs

Notation	f'c = 21 MPa (w/c = 0.52)				f'c = 25 MPa (w/c = 0.49)			
	RC	15%RBA	30%RBA	50%RBA	RC	15%RBA	30%RBA	50%RBA
Water, (kg/m^3)	238	238	238	238	236	236	236	236
Cement, (kg/m^3)	458	458	458	458	487	487	487	487
RS, (kg/m^3)	755	755	755	755	743	743	743	743
OCS, (kg/m^3)	1132	962	793	566	1115	948	781	558
RBA, (kg/m^3)	0	159	318	531	0	157	314	523

Figure 3. Concrete specimen test setup

As depicted in Figure 4, the toughness index is calculated by dividing the area under compressive stress against time with details of the initial stress area up to 80% post-peak stress divided by the area from initial stress to peak stress, where in this study the y axis is compressive stress and the x axis is time. This calculation is based on previous studies (22, 23).

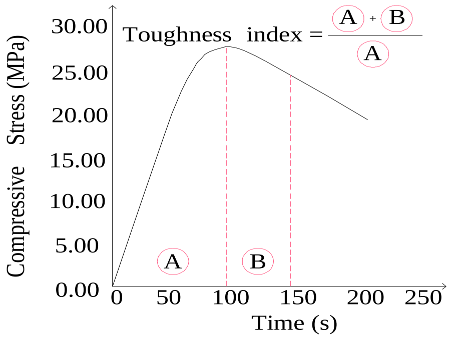


Figure 4. Definition of toughness index

3. RESULTS AND DISCUSSION

3. 1. Workability According to Figure 5, it is clear that the slump values achieved by the RC and all RBA mixtures meet the slump design of 20±2 cm, which indicates that the workability of fresh concrete can be easily handled in the field. Other studies also found that the use of brick waste as coarse aggregates in concrete mixes increases the slump (24). The visual observation depicted in Figure 6 revealed that bleeding and segregation did not occur. These qualitative results indicate good workability, which positively influences the pouring and compaction processes.

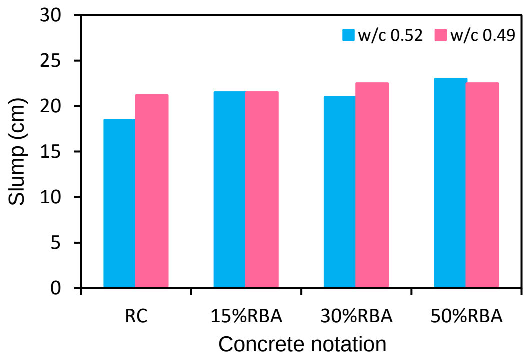


Figure 5. Slump values of the fresh concrete for different percentages of RBA

(a) RS (b) OCS

Figure 6. Visual observations of slump tests in fresh concrete

3. 2. Compressive Strength Figures 7 and 8 depict the effect of using RBA on the compressive strength. The results implied that the compressive strength increased with increasing curing times of 7 and 28 days for all samples. A similar trend was also found in the use of ceramic waste (RBA belongs to the ceramic subgroup) as aggregate in concrete mixtures (25). Furthermore, the trend of declining values in compressive strength occurred with the addition of RBA in the concrete mixture as an OCS partial substitution.

A possible rational explanation for the declining values in compressive strength along with an increase in the substitution of RBA for OCS in the concrete mix is due to the consequence of RBA being more porous compared to OCS, as detailed in Table 1.

Similar findings were obtained by a previous researcher who used recycled brick as a partial substitute for natural coarse aggregate in concrete. An increase in the use of recycled brick aggregate in concrete mixes resulted in a decline in the compressive strength values as a consequence of high water absorption and the weaker strength of the recycled aggregate (26).

As shown in Figures 7 and 8, the use of 15%RBA as a substitute for coarse aggregate in concrete mixes with w/c 0.59 and w/c 0.49 results in the minimum loss of compressive strength among variations of concrete

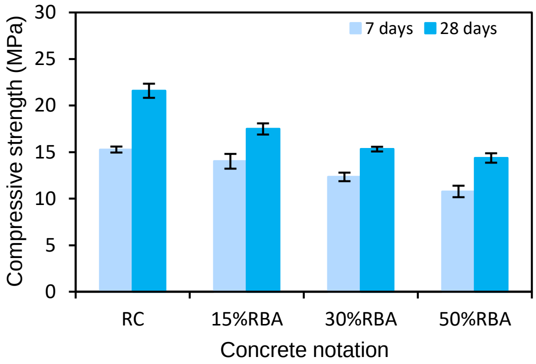


Figure 7. Compressive strength of concrete for w/c 0.59

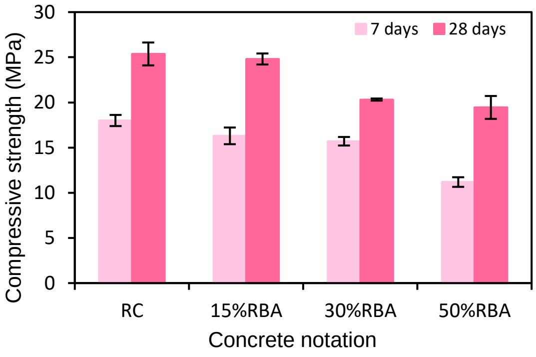


Figure 8. Compressive strength of concrete for w/c 0.49

mixtures modified with 30%RBA and 50%RBA when compared to RC.

3. 3. Compressive Stress and Time Pattern The findings shown in Figures 9 and 10 were obtained based on a compressive strength test that also measured the response time. As depicted in Figures 9 and 10, the pattern of the relationship between compressive stress and response time in all mixtures with and without RBA showed the same tendency. Two different phases can be clearly observed in all the mixtures: the rising phase, which shows a linear trend until it approaches the peak stress, and the declining phase of the post peak stress, which appears to immediately drop steeply.

This finding confirms that even though RBA is weaker than OCS, RBA has brittle properties that cause brittle behavior in concrete modified with RBA. So that the use of RBA in concrete mixtures in principle does not change the brittle behavior of the relationship between compressive stress and time. According to the cited literature, the coarse aggregate skeleton plays an essential role in carrying compressive loads. Hence, the quality of the coarse aggregate affects the brittle of concrete when carry compressive loads (2).

Furthermore, the relationship between the normalized compressive stress and response time was determined with the aim of thoroughly and quantitatively examining the action of compressive stress in attaining the elastic, peak, and ultimate phases of both RC and concrete containing RBA. The elastic and ultimate phases were specified in this study as stress at 40% peak stress and 80% post-peak stress, respectively.

3. 4. Elastic Phases According to Figures 9 and 10, because the quality of coarse aggregates affects the ability of concrete to control elastic deformation due to compressive loading, the response time in the elastic phase is heavily dependent on the coarse aggregate quality. The more rapid rate of reaching the elastic phase in all the RBA containing concretes was attributed to the declining robustness of the concrete with increasing RBA amounts, which was observed at 7 and 28 days of passage.

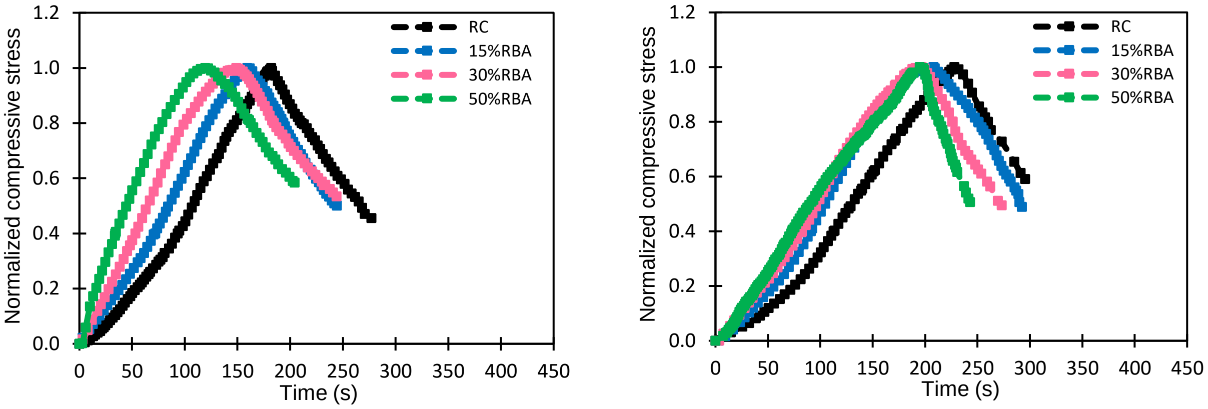
3. 5. Peak Phases According to Figures 9 and 10, it can be quantitatively determined that the difference in response time between the RC and RBA concrete after 28 days of passage was less than 17%. Such a finding is due to the fact that all concrete mixtures contain cement paste and mortar in the same amount. The response time did not differ significantly at this stage, indicating that the effort to sustain the inelastic phase owing to the current compressive load was controlled more by the mortar or cement paste, which bound the coarse aggregate to maintain the overall robustness of the concrete. These findings are corroborated by earlier scientific investigations. In accordance with the relevant scientific literature, when subjected to compressive stresses, the specimen underwent lateral and vertical deformations, with the lateral deformation retained by the mortar and ITZ bonding the coarse aggregate. Consequently, the quantity and quality of the mortar and paste used control the ability of the concrete to endure a load in the inelastic phase up to the peak stress (27).

3. 6. Ultimate Phases According to the experimental results acquired after 28 days, as depicted in Figures 9 and 10, the difference in response time between the RC and RBA concrete did not exceed 20%. This result indicates that efforts to maintain the ultimate phase (i.e., post-peak stress) were more controlled by the mortar or cement paste, which bound the coarse aggregate to maintain the overall strength of the concrete.

3. 7. Toughness Index According to the calculation of the toughness index depicted in Figure 11, 15%RBA disclosed a better energy capability of the concrete to resolve the failure of the material, which is 7.20% and 0.93% for w/c 0.52 and w/c 0.49, respectively, compared to RC values. Meanwhile, 30% and 50% RBA exhibited insignificant decreases in the toughness index values of 0.73% and 8.91% for w/c 0.52, and 0.12% and 3.64% for w/c 0.49, respectively, compared with RC. In accordance with the acquired toughness index values, 15%RBA exhibited comparable ductile behaviour to that of RC.

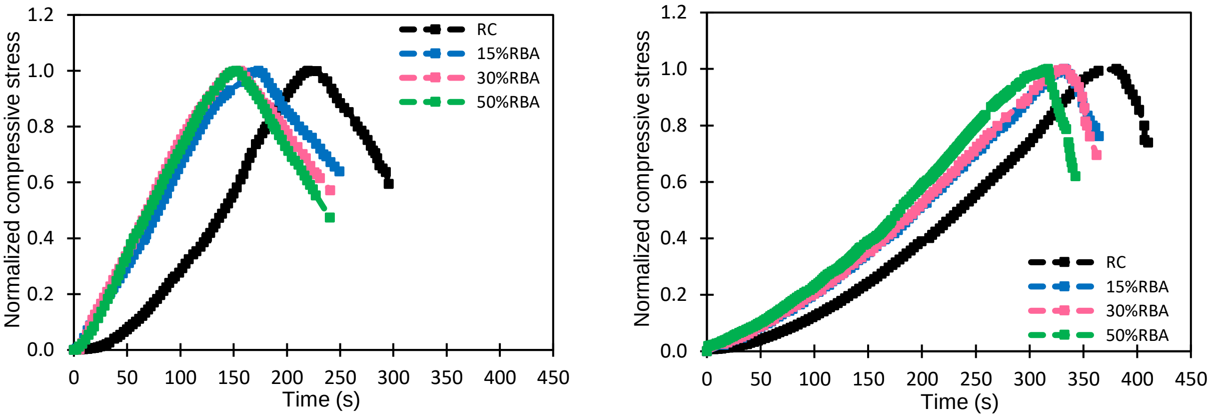
3. 8. Performance Criteria It is important to develop performance criteria for concrete containing RBA to ensure that they can be applied in actual construction work. This study proposes the acceptance of the RBA criteria as a coarse aggregate for concrete mixtures based on the performance of the relationship between compressive stress and response time. Such performance acceptance criteria are designed by adopting the principle used to accept pozzolanic waste as a partial replacement for cement. The strength activity index (SAI) was obtained from the results of the compressive strength test on the concrete after 28 days, with an adequate requirement of 75%, as established in ASTM C618 (28). The experimental findings in Table 3 demonstrate that all RBA mixtures for w/c 0.49 and 15% RBA for w/c 0.52 meet the minimum requirements for SAI. This indicates that for both water-cement ratios, the replacement of OCS with 15% RBA can be utilized in a concrete mixture.

3. 9. Cost Comparison Analysis In addition to considering the mechanical properties aspect of the compressive stress-time assessment of the use of RBA, the comparison of the finished cost of new concrete with reference concrete is also evaluated. The findings presented in Table 4 compare the costs of handling, processing, and transportation for RBA and natural coarse aggregate in the form of crushed stone (OCS). As can be seen, the acquisition costs for RBA processing are 29.34 \$/m^3, which is 51.84% less expensive than the necessary expenditures when using OCS. These results show that the use of RBA as a partial replacement for coarse aggregate in concrete mixes results in more economical concrete production costs compared to reference concrete (RC), as stated in Tables 5 and 6. The findings in Tables 5 and 6 demonstrate that the use of



(a) Experimental at 7 days passaged (b) Experimental at 28 days passaged

Figure 9. Compressive stress and response time with w/c 0.52 for different percentages of RBA in concrete



(a) Experimental at 7 days passaged (b) Experimental at 28 days passaged

Figure 10. Compressive stress and response time with w/c 0.49 for different percentages of RBA in concrete

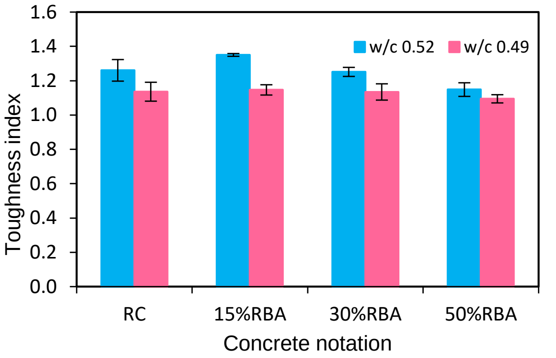


Figure 11. Toughness index for different percentages of RBA in concrete

TABLE 3. SAI of concrete mixture

Notation	RC	15%RBA	30%RBA	50%RBA
OCS, (%)	100	85	70	50
RBA, (%)	0	15	30	50
f'c for w/c 0.52, (MPa)	21.59	17.49	15.32	14.37
f'c for w/c 0.49, (MPa)	25.37	24.81	20.32	19.45
SAI for w/c 0.52, (%)	-	81.02	70.97	66.57
SAI for w/c 0.49, (%)	-	97.80	80.08	76.65

TABLE 4. Cost analysis of ordinary crushed stone (OCS) and RBA materials

No	Item	Quantity	Unit	Rate per unit ($)*		Cost ($)	
				OCS	RBA	OCS	RBA
A.	Materials						
	- Raw materials	1	m^3	18.99	0	18.99	0
	- Transportation (max. distance 20 km)	1	m^3	2.83	2.83	2.83	2.83
	- Wash water	2	m^3	1.86	1.86	3.72	3.72
B.	Labor						
	- Non-skilled labor	1	man/d	7.13	7.13	7.13	7.13
	- Skilled labor	1	man/d	11.64	11.64	11.64	11.64
C.	Tools and equipment						
	- Processing tools (2% of material cost)					0.51	0.13
	- Electricity (1% of material cost)					0.26	0.07
D.	Total cost (A+B+C)					45.08	25.52
E.	Overheads and profit (15% x D)					6.76	3.83
Cost per m^3 of materials (D+E)						51.84	29.34

**Prices according to the Makassar, Indonesia, local market as of May 2023*

TABLE 5. Cost analysis of conrete w/c 0.52 with different RBA content

No	Item	Quantity (kg/m^3)				Rate per unit ($)*	Actual cost ($)			
		RC	15%RBA	30%RBA	50%RBA		RC	15%RBA	30%RBA	50%RBA
A.	Materials									
	- Water	238	238	238	238	0.0034	0.81	0.81	0.81	0.81
	- Cement	458	458	458	458	0.1668	76.39	76.39	76.39	76.39
	- RS	755	755	755	755	0.0134	10.12	10.12	10.12	10.12
	- OCS	1132	962	793	566	0.0168	19.02	16.16	13.32	9.51
	- RBA	0	159	318	531	0.0028	0.00	0.45	0.89	1.49
B.	Labor									
	- Non-skilled labor (man/d)						7.82	7.82	7.82	7.82
	- Skilled labor (man/d)						12.21	12.21	12.21	12.21
C.	Equipment and tools									
	- Tools and plants (2% of material cost)						2.13	2.08	2.03	1.97
	- Electricity (1% of material cost)						1.06	1.04	1.02	0.98
D.	Total cost (A+B+C)						129.56	127.08	124.61	121.30
E.	Overheads and profit (15% x D)						19.43	19.06	18.69	18.19
Cost per m^3 of concrete modified with RBA (D+E)							148.99	146.14	143.30	139.49

**Prices according to the Makassar, Indonesia, local market as of May 2023*

TABLE 6. Cost analysis of conrete w/c 0.49 with different RBA content

No	Item	Quantity (kg/m^3)				Rate per unit ($)*	Actual cost ($)			
		RC	**15%RBA**	**30%RBA**	**50%RBA**		**RC**	**15%RBA**	**30%RBA**	**50%RBA**
A.	Materials									
	- Water	236	236	236	236	0.0034	0.80	0.80	0.80	0.80
	- Cement	487	487	487	487	0.1668	81.23	81.23	81.23	81.23
	- RS	743	743	743	743	0.0134	9.96	9.96	9.96	9.96
	- OCS	1115	948	781	558	0.0168	18.73	15.93	13.12	9.37
	- RBA	0	157	314	523	0.0028	0.00	0.44	0.88	1.46
B.	Labor									
	- Non-skilled labor (man/d)						7.82	7.82	7.82	7.82
	- Skilled labor (man/d)						12.21	12.21	12.21	12.21
C.	Equipment and tools									
	- Tools and plants (2% of material cost)						2.21	2.17	2.12	2.06
	- Electricity (1% of material cost)						1.11	1.08	1.06	1.03
D.	Total cost (A+B+C)						134.07	131.64	129.20	125.94
E.	Overheads and profit (15% x D)						20.11	19.75	19.38	18.89
	Cost per m^3 of concrete modified with RBA (D+E)						154.18	151.38	148.58	144.84

**Prices according to the Makassar, Indonesia, local market as of May 2023*

RBA as a partial replacement for coarse aggregate is effective in reducing concrete production costs. With details for w/c 0.52 and 0.49, the cost savings achieved for mixture variations of 15%RBA, 30%RBA, and 50% RBA as compared to reference concrete (RC) are 1.5–2.0%, 3.5–4.0%, and 6.0–6.5%, respectively. This acquisition indicates that, in addition to providing economic benefits, the use of RBA helps minimize degradation of the environment. As a result, the inclusion of RBA in the concrete mix will support sustainable concrete movement.

4. CONCLUSIONS

This paper evaluates the basic engineering properties of waste refractory brick as a coarse aggregate through compressive stress-time relationship assessment. The following conclusions were drawn from the experimental results of this study.

1. The presence of RBA of 15%–50% at w/c 0.49 and 0.52 is able to interact well with natural aggregate and mortar so as to produce good workability.
2. The presence of 15% RBA provides comparable performance at both w/c 0.49 and 0.52 related to compressive strength and toughness index based on compressive stress and time relationship.
3. Referring to the SAI analysis, concrete with 15%–50% RBA at w/c 0.49 meets the minimum requirement, while at w/c 0.52, only concrete with 15% RBA meets the requirements.
4. The utilization of RBA as a partial replacement for coarse aggregate in concrete mixtures has a positive impact on reducing material costs and concrete production by approximately 51.84% and 1.5–6.5%, respectively.

5. ACKNOWLEDGMENT

All activities were carried out at Eco Materials Laboratory of the Civil Engineering Department, Universitas Hasanuddin, Indonesia.

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Persian Abstract

چکیده

هدف این مطالعه بررسی استفاده از محصولات جانبی آجر نسوز (RBA) به عنوان جایگزینی برای سنگدانه درشت در تولید بتن پایدار است. مخلوط‌های بتنی با دو نسبت آب به بایندر 0.52 (w//c) و ۰.٤۹ و حاوی ۰، ۱۵، ۳۰ و ۵۰ درصد RBA به عنوان جایگزینی جزئی برای سنگ‌های خرد شده معمولی (OCS) تولید شد. خواص زیر در این مطالعه مورد بررسی قرار گرفت: کارایی، مقاومت فشاری، رابطه تنش-زمان، شاخص چقرمگی، معیارهای عملکرد و تحلیل هزینه. نتایج آزمایش نشان داد که افزایش درصد RBAدر مخلوط‌های بتن به طور مثبتی به کارایی بتن کمک می‌کند. علاوه بر این، با افزایش درصد RBA در مخلوط بتن، مقاومت فشاری و تمام مراحل در تنش فشاری و رابطه زمانی کاهش یافت. با این حال، در ۱۵٪RBA ، مقدار شاخص چقرمگی با بتن مرجع قابل مقایسه بود، در حالی که بر اساس معیارهای عملکرد، جایگزینی OCS با ۱۵٪ RBA برای هر دو نسبت آب به سیمان حداقل الزامات را برآورده کرد. در همین حال، تجزیه و تحلیل مقایسه هزینه نشان می دهد که هزینه های مواد و تولید را می توان به ترتیب تقریباً ۵۱.۸٤٪ و ۱.۵-٦.۵٪ کاهش داد. بر اساس تجزیه و تحلیل تمام نتایج آزمایش، ۱۵ RBA %تفاوت های ناچیزی در ارزش در مقایسه با بتن مرجع نشان داد. بنابراین، استفاده از ۱۵ RBA %به عنوان جایگزین OCS یک گزینه قابل قبول و قابل قبول برای تولید بتن پایدار است.