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RESEARCH ARTICLE-CIVIL ENGINEERING

Internal Curing Utilising Recycled Concrete Aggregate: A Sustainable Approach for Improving High-Strength Concrete's Performance

Mortada Sabeh Whwah[1] · **Laith Mohammed Ridha Mahmmod**[1] · **Huda Hafedh Abdoulhaleem**[1] · **Anmar Dulaimi**[1,2,3]

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Abstract

High-strength concrete (HSC) makes up the vast majority of materials used in the construction sector due to its exceptional mechanical characteristics and outstanding long-term behaviour. However, in cement-based materials with a low water-to-binder ratio (w/b), excessive autogenous shrinkage has become a prevalent issue. This work suggests the sustainable use of recycled concrete aggregate (RCA) to internally cure HSC in order to reduce autogenous shrinkage during the hydration and curing processes. RCA was employed with various volumetric replacement percentages with natural coarse aggregate as a water storage agent (0%, 8%, 16%, 24%, 32%, 50%, 75%, and 100%) under sealed and unsealed conditions. The efficiency of the adopted materials for internal curing was investigated by determining the autogenous shrinkage in addition to unconfined compressive and flexural strength. The laboratory results reveal that the studied properties significantly improved by incorporating RCA into HSC, and the improvement depends on the substitution rate of the coarse aggregate. A better shrinkage behaviour can be obtained by raising the substitution percentage of coarse aggregate with RCA; in contrast, the strengths decrease with increased RCA. RCA can be utilised as an internal curing material for HSC to alleviate autogenous shrinkage with a percentage of around 40%, with the adopted ambient conditions in the early age of HSC with full replacement of virgin coarse aggregate. It is recommended to use 24% RCA as a substitution for natural coarse aggregate for internal curing to improve the characteristics of HSC and the sustainability advantages and reduce its negative environmental impacts.

Keywords Autogenous · Sustainability · High-strength concrete · Shrinkage · Internal curing · Recycled concrete aggregate

1 Introduction

High-strength concrete (HSC) has been broadly utilised as a crucial structural material in various infrastructures worldwide; it is inherently characterised by high strengths, high abrasion resistance, high stiffness, and toughness against impacts, with lower creep strain [1, 2]. HSC is increasingly employed in enormous construction sectors worldwide due to its excellent mechanical behaviour and exceptionally long-term outstanding durability, because of its highly dense internal microstructure [3, 4]. Compared to conventional concrete, HSC is distinguished by a high binder concentration and a low water-to-binders ratio (w/b). This could lead to early age volume changes from the cement's hydration process and a considerable amount of autogenous shrinkage [5, 6]. Moreover, the progression of cement hydration depletes water inside the concrete pores, and the mixing water may need to be increased to sustain hydration progression. In contrast, this decrement in internal relative humidity causes

✉ Anmar Dulaimi
anmar.f@uokerbala.edu.iq; a.f.dulaimi@uowa.edu.iq; a.f.dulaimi@ljmu.ac.uk

Mortada Sabeh Whwah
mortada.s@uokerbala.edu.iq

Laith Mohammed Ridha Mahmmod
laith.m@uokerbala.edu.iq

Huda Hafedh Abdoulhaleem
huda.hafodh@uokerbala.edu.iq

[1] College of Engineering, University of Kerbala, Karbala 56001, Iraq

[2] College of Engineering, University of Warith Al-Anbiyaa, Karbala 56001, Iraq

[3] School of Civil Engineering and Built Environment, Liverpool John Moores University, Liverpool L3 2ET, UK

self-desiccation of cement paste and autogenous shrinkage of concrete, which has a more negative impact than drying shrinkage [2, 7]. The result of decreasing relative humidity is the generation of capillary pressure in the delicate pores of cement paste, leading to internal stress in constrained concrete and forming internal and external cracks if the stresses are higher than the tensile strength of the concrete [2, 3]. The formation of cracks at an early stage of concrete age would decrease the carrying capacity of the building and shorten its service life due to the formation of channels for the ingression of aggressive solutions [8, 9]. Thus, it is crucial to lower the risks of early autogenous shrinkage cracks by sealing or employing different curing techniques to ensure adequate HSC performance.

Traditional moist curing procedures, like water spraying, wet covering, and fogging, have been used widely to maintain the moisture and temperature of concrete. However, the supplied additional water stays on the external surfaces of the placed concrete without significant penetration through the pores of the concrete due to low w/b and dense microstructure [2, 10, 11]. The membrane curing method may also be used by applying compound systems on newly placed concrete for full water retention in the concrete [12]. Hence, the problem of the internal relative humidity falling inside concrete microstructures still needs to be resolved. Reducing early age autogenous shrinkage of HSC and self-desiccation concerns using internal curing approaches has received much global interest recently.

Internal curing is a technique that incorporates water reservoirs into the hydrated cement paste to maintain the internal relative humidity. Internal curing is conducted by incorporating small water reservoirs into concrete, which can supply additional water into the hydrated cement paste's structure, filling the voids fabricated during shrinkage through the hydrated cement paste. It keeps them saturated, delaying the decrease of critical pore size [13]. As cement hydration progresses, a humidity variation occurs between cement pores and incorporated water reservoirs, generating capillary pressure and releasing internally curing water and sustaining the hydration process [14, 15].

High absorption capacity is the main characteristic of materials utilised for internal curing purposes. Various materials have been well documented in previous studies as having a positive impact on the internal curing potential of HSC, like lightweight aggregate (LWA) [16], super absorbent polymer (SAP) [17], wood ash, expanded clay aggregate [18], cellulose fibres [19], polyethylene glycol[20], and cold-bonded aggregate produced from coal bottom ash [21]. Ashes with high absorption capacity can also be used as internal curing materials, like rice husk ash (RHA) [22], stoker, and circulating fluidised bottom ash produced from industrial boilers [23, 24]. Cenosphere fly ash can be used as an internal curing agent if the particles are chemically treated to remove the glass-crystalline film around them [25].

Despite internal curing materials creating additional pores that may reduce the compressive strength of concrete, the potential impact of lowering autogenous shrinkage and micro-crack formation at an early stage is overwhelming [13]. SAP shows high efficiency in increasing internal relative humidity and mitigating autogenous shrinkage of ultra-high-performance concrete (UHPC). During the same period, the SAP cavities can be filled partially with Portlandite, i.e. calcium hydroxide ($CaOH_2$) during hydration [26]. RHA increases the compressive strength of UHPC and prevents autogenous shrinkage by delaying the decrease in internal relative humidity because of its mesoporous structure and high water absorption capacity [22]. Internal curing can be used on its own or associated with another curing method; it can be used to sustain cement hydration, which can be decreased by heat curing and enhance long-term compressive strength. Internal curing with fine LWA as partial sand replacement significantly enhances the later age strength and degree of hydration for heatedly cured concrete, as well as improving the homogeneity of the interfacial transition zone [27].

On the other hand, internal curing can also be achieved by using various recycled waste materials and has been broadly studied in recent decades to investigate the ability of recycled materials to achieve internal curing demands and show the impact on properties of traditional and special types of concrete [28–32]. In light of the growing environmental concerns around landfills, recycling the massive amounts of waste materials produced by many industrial sectors and eliminating solid trash have gained greater attention in lieu of disposing of them. One of the effective ways of utilising recycled materials is to employ them in the fabrication of sustainable concrete. Sustainable or green concrete is chiefly fabricated by the incorporation of waste and recycled end-of-life materials with the original raw ingredients used in traditional concrete [33]. Based on previous studies, recycled materials can act as porous media with significant water absorption capacity and release ability. The efficiency of recycled materials in internal curing is closely related to that of virgin materials and is cost-effective [28, 29, 31, 34, 35], and is strongly correlated with the particle size distribution, water absorption and release ability, and the percentage of replacement [36, 37].

Various previous studies have examined clay brick waste as an internal curing material. A recent study [35] investigated the effect of recycled fine clay brick aggregate on the properties of mortar; the result revealed that drying shrinkage of the mortar decreased and the percentage of replacement increased up to 100%. In contrast, the opposite trend was obtained for compressive strength. This waste also improves the flexural behaviour of reinforced concrete beams when incorporated as internal curing material [38]. Ceramic waste can also be used for internal curing [20, 39]. Xu et al. replaced coarse aggregate with three types of recycled ceramic material as a volumetric substitute with the percentage of 10%, 20%, and 30% as an effort to enhance the behaviour of high-performance concrete. The finding revealed that the strength decreased with the increase in the replacement percentage, while shrinkage performance improved with the increase in recycled ceramic content, which was significantly affected by the porosity of the wastes [29]. The performance and durability of concrete can be increased by using demolished concrete as an interior curing material [28, 40]. Yang et al. replaced natural coarse aggregate with pre-wetted RCA with four percentages (25%, 50%, 75%, and 100) as an internal curing agent inside the concrete. The output revealed that the progress of shrinkage at an early stage of concrete age was inhibited as a result of increasing the internal relative humidity; the durability of the produced concrete was also enhanced concerning the chloride ions' penetration due to the densification of the microstructure of the cement matrix [41].

Vast amounts of demolished concrete have been generated annually due to the demolishing of old buildings as a result of urbanisation [42]; 3.0 billion tons of demolished waste were generated worldwide each year until 2012, and the rate has risen constantly [43]; additionally, earthquakes dramatically contribute to the generation of huge quantities of demolished concrete [44]. The management of concrete debris is a critical environmental issue regarding disposal into landfills and pollution of the environment. Therefore, there is an urgent need for extensive research and efforts to find significant and applicable solutions for this international threat. There are various suggestions for how to deal with this situation; one of the most effective suggestions for how to manage concrete debris is recycling it to fabricate new concrete with either a better or just an acceptable performance to be utilised in various construction sectors [45–51]. This sustainable approach is cost-effective and diminishes the consumption of natural resources [52, 53].

The solution of reusing recycled concrete for eco-friendly concrete fabrication would particularly minimise economic and environmental problems relating to the generation of demolished concrete debris. Moreover, the inclusion of recycled concrete in concrete production can be considered a sustainable procedure to maintain the resources of concrete ingredients for as long as possible; in addition, the produced concrete's performance could be acceptable and may even be enhanced. Shaaban et al. employed RCA in producing green HSC with various percentages of replacement with natural aggregate up to 35%; the obtained results demonstrated that sustainable HSC could be fabricated utilising RCA with acceptable mechanical behaviour relative to that produced with virgin aggregate [54]. Similarly, El-Hawary and Al-Sulily [28] utilised RCA to replace 50% of fine and coarse aggregate individually and simultaneously. The outcomes prove that the performance of internally cured concrete with RCA was enhanced by up to 50% in terms of cracking delay, resistance to freezing and thawing, and shrinkage, with a slight negative impact on mechanical performance.

Building material waste from construction and demolition is being converted into porous materials for internal curing in greater quantities due to growing concerns about the high autogenous shrinkage of concrete with a low water-to-binder ratio. RCA is a promising end-life material which is suitable for use as an interior curing agent. Nevertheless, there has not been much focus on using RCA as an internal curing material in HSC. Furthermore, there is room to investigate the use of RCA for internal curing in HSC because it is widely known that the HSC matrix contains a significantly higher amount of unhydrated cement than traditional concrete as a result of low porosity eliminating the ingression of external curing water. The viability of reusing RCA for internal curing in HSC was examined in this study. Experimental research was conducted on the unconfined compressive strength, flexural strength, and autogenous shrinkage.

1.1 Significance of the Study

Recently, studies have been conducted to illustrate the impact of RCA if it is used as an internal curing material on the performance and characteristics of different cement-based materials [34, 36, 55]. However, the impact of the properties of recycled concrete on internal curing efficiency has scarcely been studied.

Thus, the main objective of the current study is to make concrete with a specific quality and then recycle it after 28 days of curing in water to reach a maximum degree of hydration, and after that use it inside HSC as an internal curing medium. RCA was employed as a substitution for natural coarse aggregate with various volumetric percentages. This procedure is a novel and significant attempt to fill the gap in investigating the effect of properties of recycled concrete when employed as an internal curing agent on the performance of HSC and the efficiency of internal curing due to the lack of studies in this field. Additionally, the study aimed to try to improve the behaviour of HSC, and find the optimal percentage of recycled concrete aggregate (RCA) to replace the virgin aggregate. To achieve this goal, extensive laboratory work was conducted to examine the effect of several RCA volumetric percentages of replacement on the mechanical properties and shrinkage behaviour of HSC and asses the results and response of the prepared specimens during laboratory tests. It is expected from the experimental works that partially replacing natural aggregate with specific percentages of RCA as the curing material will improve the behaviour of HSC, as the RCA acts as an additional water reservoir inside concrete structures.

2 Research Methodology

This study argues that the characteristics of recycled concrete before demolition significantly affect the efficiency of internal curing if it is employed as an internal curing material. Therefore, this research was conducted with an experimental methodology to find scientific responses to the primary research hypothesis. The worst scenario of the substitution approach for incorporation of an internal curing agent was adopted in the current study, where natural coarse aggregate was replaced with various percentages of RCA up to 100%. The main differences between the recent and previous studies are that coarse aggregate was replaced with internal curing material, instead of fine aggregate, which is usually substituted with internal curing materials, utilising different percentages of volumetric replacement up to full removal of natural coarse aggregate. Moreover, the intended concrete to be recycled was prepared firstly with specific characteristics and then recycled, to illustrate the impact of the properties of RCA on the effectiveness of the internal curing process.

3 Materials and Methods

3.1 Materials

Through the laboratory investigation, ordinary Portland cement (OPC), ASTM type (I), complying with Iraqi standard specification (I.Q.S-No.5) [56], with a 3.15 specific gravity, was used for the preparation of both concrete, which had to be recycled, and HSC specimens for various tests. Table 1 contains the used cement's physical properties as well as chemical composition.

Natural coarse aggregate, fine aggregate, and coarse RCA aggregate were the three categories of aggregates that were chosen. Coarse aggregate with a maximum size of 20 mm and river fine sand with a maximum size of 4.75 mm were used in casting both concrete, which had to be recycled, and HSC specimens. Both types of aggregate were compliant with the Iraqi standard specification (I.Q.S-No.45) [57]. The physical and chemical properties of fine and coarse aggregate are tabulated in Table 2. The particle size distribution curves for all categories of aggregates used are illustrated in Fig. 1.

Table 1 Physical and chemical characteristics of OPC

Ingredients	%	Physical properties	
CaO	62.79	2-days compressive strength, MPa	16.4
SiO_2	20.58	28-day compressive strength, MPa	34.1
Al_2O_3	5.6	Initial setting period, Min	122
Fe_2O_3	3.28	Final setting period, Hr	3.13
Free CaO	0.9	Blaine fineness, m^2/kg	314
MgO	2.79		
SO_3	2.35		
LOI	1.94		
IR	0.86		
LSF	0.9		

Table 2 The aggregate's chemical and physical characteristics

The property	Aggregate type	
	Natural coarse aggregate	Fine aggregate
Specific gravity	2.61	2.6
Bulk density, kg/m^3	1620	1680
Water absorption, %	0.21	0.80
Clay and other fine materials, %	0.67	2.4
SO_3, %	0.08	0.21

3.1.1 Fabrication of Internal Curing Material

The preparation of the internal curing material (i.e. RCA) consisted of two main steps: preparing and recycling. Firstly, the concrete mixture was fabricated with a high water content (W/C of 0.61) to increase the capillary pores through the microstructure of the hydrated cement matrix and raise the water absorption capacity of the produced concrete [2]. Hence, this increases internal curing efficiency by providing adequate water reservoirs inside the concrete. Table 3 shows the mixture design of the prepared concrete utilised for internal curing according to ACI 211.1 [58]. The calculated rheological and hardened characteristics of RCA are also tabulated in the table after the crushing and sieving procedure.

Secondly, preparation of RCA began with sledgehammers to convert hardened concrete to fragments after 28 days of concrete casting, with gradation approximately near to the used natural coarse aggregate with particles with an upper limit of 20 mm to obtain comparable particle size distributions of both types of coarse aggregate, as plotted in Fig. 1. Figure 2 also shows the recycled concrete aggregate after gradation.

Fig. 1 Particle size distributions of all categories of utilised aggregate

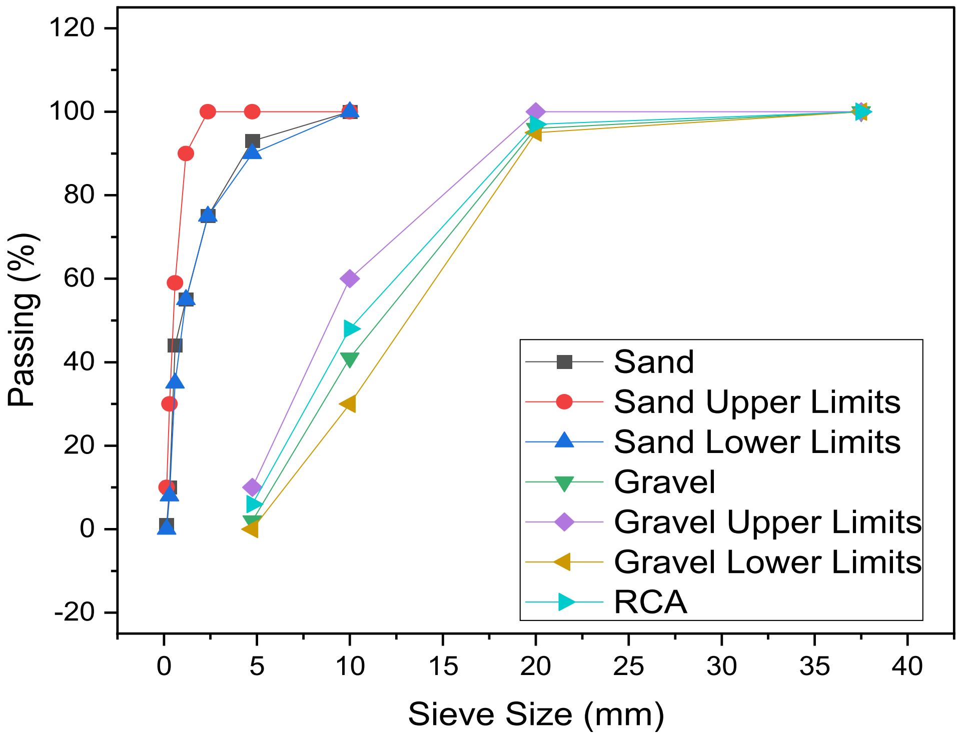


Table 3 Mixture proportion and characteristics of RCA

Cement*	Water *	Fine aggregate*	Coarse aggregate*
341	208	834	925
Fresh properties		Hardened properties	
Slump value, mm	96	28-day compressive strength, MPa	22
		RCA bulk density, Kg/m^3	2318
		RCA specific gravity	2.3
		RCA water absorption, %	7.5
		RCA SO_3 content, %	0.23

*The quantity with Kg for each 1 m^3

Fig. 2 Recycled concrete aggregate

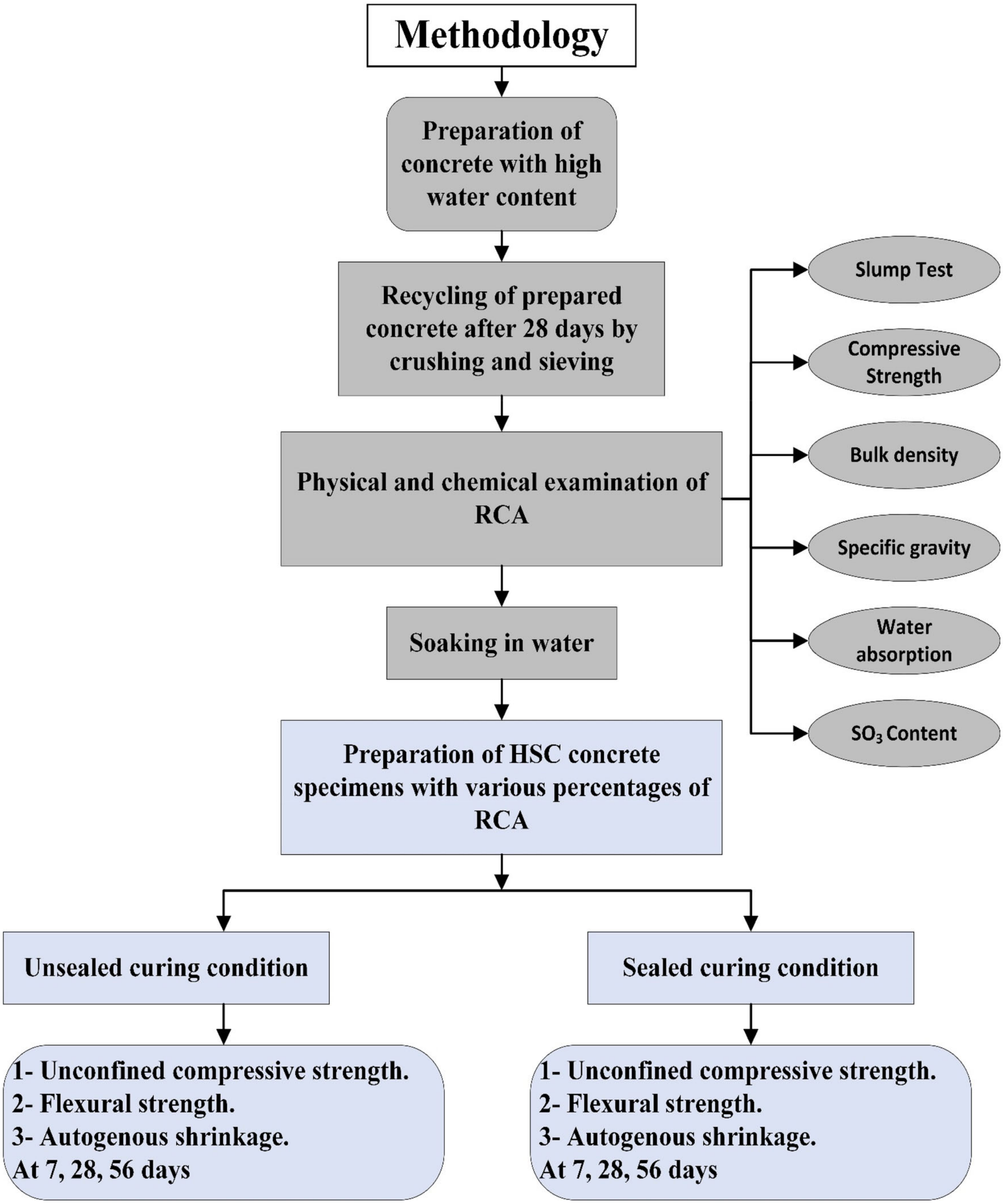


Fig. 3 Methodology summarising experimental works

3.2 Specimens and Investigated Concrete Properties

In the current work, various concrete specimens were fabricated to assess the efficiency of RCA in the internal curing technique under two other external curing conditions (i.e. sealed curing and unsealed curing); the experimental programme is summarised in Fig. 3.

To evaluate the capability of RCA as an internal curing agent, it was saturated with water before incorporation within the concrete; after that, the ingredients were mixed traditionally with a laboratory mixer to produce fresh concrete. Finally, three categories of moulds were utilised to assess the performance of hardened concrete at certain ages (i.e. 7, 28, 56, and 90 days). Two conditions were adopted to cure the specimens until the testing date (i.e. sealed and unsealed); the sealed condition refers to keeping specimens in polyethylene sheets until the testing age, whereas the unsealed condition

Table 4 Mixtures' codes and proportions

Mix code	Cement (Kg)*	Fine aggregate (Kg)*	Natural coarse aggregate (Kg)*	RCA (Kg)*	Water (Kg)*	Superplasticiser (Lit.)*
IC-0	673	499	972	–	202	4.8
IC-8	673	499	894	66	202	4.8
IC-16	673	499	816	132	202	4.8
IC-24	673	499	739	198	202	4.8
IC-32	673	499	661	264	202	4.8
IC-50	673	499	486	413	202	4.8
IC-75	673	499	243	619	202	4.8
IC-100	673	499	–	825	202	4.8

*The quantity with Kg for each 1 m^3

refers to curing specimens externally with water to the specified testing age, as shown in Fig. 3. Sixteen mixtures were produced to study the behaviour of HSC internally cured with various percentages; the prepared RCA was used as coarse aggregate with volumetric replacement with percentages of 8, 16, 24, 32, 50, 75, and 100%, for the study of the suitability of using RCA as an internal curing material and its effect on the performance of HSC when it fully replaced the course aggregate, as tabulated in Table 4, which illustrates the codes of each mixture and the quantities required to produce 1 m^3.

The behaviour of internally cured hardened HSC in addition to reference mixture (i.e. without internal curing) was assessed by unconfined compressive strength, splitting tensile strength, and autogenous shrinkage tests under sealed and unsealed conditions at different ages. The unconfined compressive strength was determined by testing three 100 mm cubes and calculating the average at each testing age according to BS EN 12390–4 [59]. Simple beam specimens (100 × 100 × 400 mm) were utilised for third-point flexural strength evaluation based on ASTM C-78 [60]. The effect of RCA as an internal curing agent on the autogenous shrinkage of HSC was measured at early and later ages from 1 to 90 days by testing prismatic specimens (75 × 75 × 285 mm) according to ASTM C-490 [61].

4 Experimental Results and Discussion

4.1 Unconfined Compressive Strength Test

Three cubes for each proposed mixture at each testing age were crushed in a compression machine to determine the unconfined compressive strength of HSC specimens, as displayed in Fig. 4. The obtained laboratory results at the ages of 7, 28, and 90 days are plotted in Figs. 5 and 6 for sealed and unsealed conditions, respectively, as a mean value, as summarised in Table 5.

As expected, the compressive strength revealed continued to gain as the testing period was increased for all mixtures. The plotted results in Fig. 5 illustrate a significant improvement in the behaviour of mixtures internally cured with RCA with different percentages relative to control mixture. Moreover, the efficiency of internal curing at later ages is higher than at early ages. The highest value shown is by mixture IC-24 (i.e. RCA is replacing 24% of coarse aggregate); the increasing percentages are 19.4%, 21.5%, and 18.2% at ages 7, 28, and 90 days, respectively, relative to the corresponding values for control mixture; the same trend was found by Yang et al. [41]. The activation of internal curing inside the cement matrix and the increased water provided by RCA, which maintains cement hydration, are responsible for this increase in compressive strength [3, 44]. On the other hand, additional examination of these data shows that compressive strength continuously decreases as the percentage of RCA substitution rises until 100%. However, the reduction in compressive strength can be considered marginal up to full use of RCA instead of coarse aggregate; the recorded percentages of decrement are 0.7% and 0.2% at ages of 28 and 90 days, respectively, compared with the reference mixture (i.e. without internal curing) under the sealed condition.

The compressive strength results under unsealed conditions are provided in Fig. 6. Specimens under the sealed conditions behaved similarly to those under the unsealed conditions, as strength increased with the progression of the curing age. In general, the strength obtained under unsealed conditions is higher than that calculated under sealed conditions due to the additional water absorbed by the cement matrix, which improves the cement hydration process. In a similar way, the percentage of 24% of RCA revealed higher compressive strength compared with other mixtures, increasing by 18.1% and 5.3% for IC-24 at ages of 28 and 90 days,

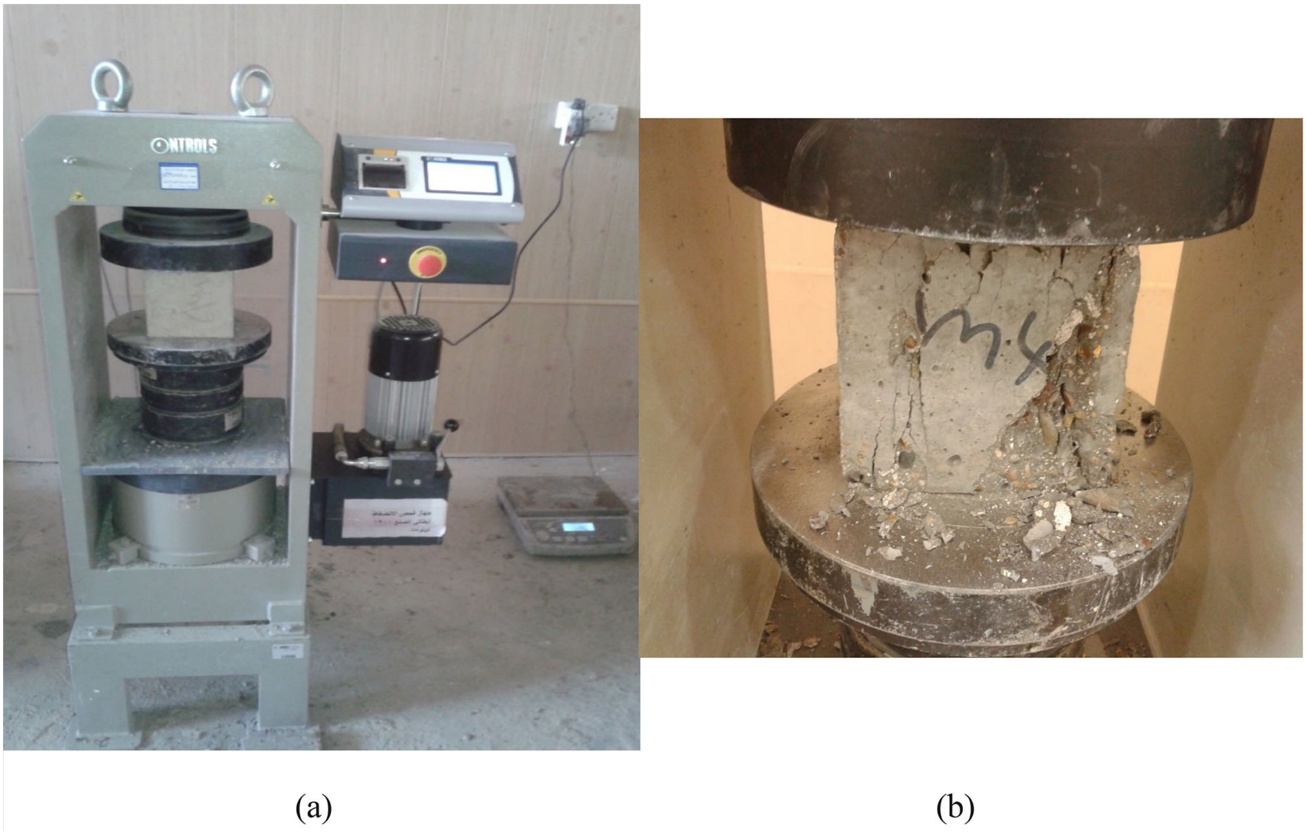


Fig. 4 **a** Compressive strength test with hydraulic testing compression machine, **b** Failure configuration after compression test

respectively, relative to the control mixture. As the content of RCA rises, the compressive strength decreases marginally up to full substitution of natural coarse aggregate.

Thus, it can be concluded that using RCA as an internal curing material as a volumetric replacement of coarse aggregate enhances the compression behaviour of HSC under an unconfined compressive strength test without adverse effects when increasing the RCA content. This behaviour distinguishes the beneficial impact of RCA for the internal curing technique from other substances utilised for this purpose, which adversely affect compressive strength by raising the percentage of replacement [15, 37].

In addition to the impact of internal curing on the strength of HSC, external conditions have also affected the development of specimen strength: those externally cured with unsealed conditions exhibited higher compressive strength than those externally cured under sealed conditions. This improvement can be attributed to additionally supplied water that provides the most appropriate environment to sustain cement hydration and enhance the characteristics of HSC. Figure 7 clarifies the impact of the external curing environment on 28-day compressive strength for all mixtures.

4.2 Flexural Strength Test

A recent study has shown that internal curing utilising various percentages of RCA does not positively impact the flexural strength of HSC at early and later stages under sealed conditions. However, there is no significant reduction in flexural strength with increased RCA content in HSC mixtures. In addition, as the content of RCA increases, the flexural strength of HSC will gradually decrease. In contrast, internal curing with 16% RCA showed improvement in the behaviour of HSC during flexure tests at the age of 28 and 90 days under unsealed conditions. Similar to the sealed condition, internal curing with other percentages of RCA exhibited a marginal reduction in the flexural strength of HSC at all testing ages. The obtained laboratory results revealed that the flexural behaviour of internally cured HSC was also affected by the external environmental conditions and the amount of internal curing agent.

Figure 8 illustrates the one point flexural strength test of prism specimens. Table 6 summarises the average flexural strength of HSC with various RCA replacement percentages after curing in sealed and unsealed conditions at all testing ages.

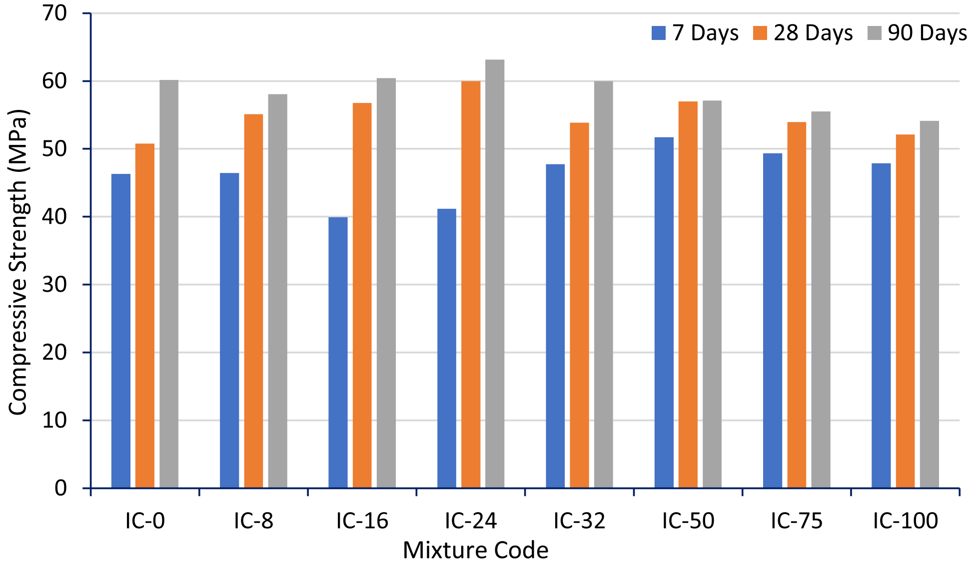


Fig. 5 Compressive strength of internally cured specimens under sealed conditions

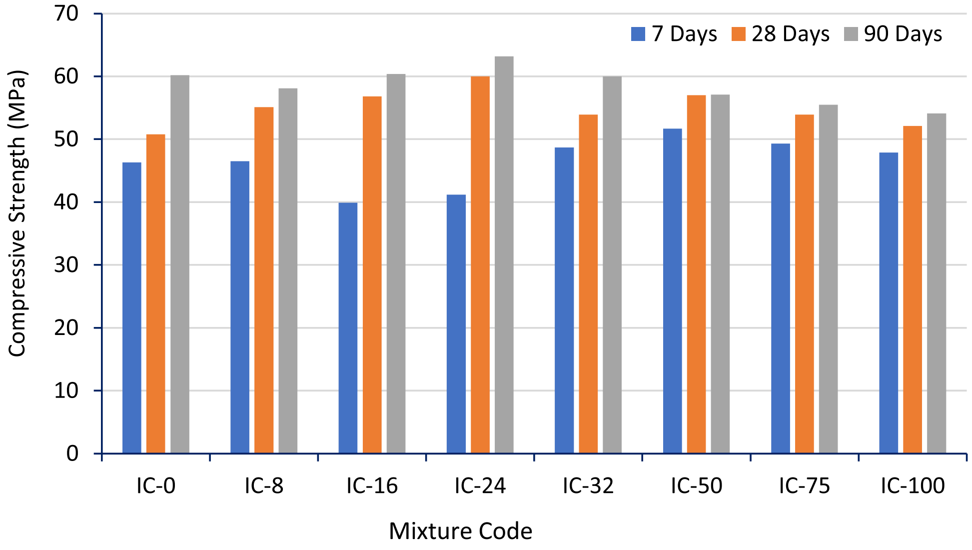


Fig. 6 Compressive strength of internally cured specimens under unsealed conditions

Table 5 Findings for compressive strength for sealed and unsealed specimens, MPa

Mix code	Sealed specimens			Unsealed specimens		
	7 (days)	28 (days)	90 (days)	7 (days)	28 (days)	90 (Days)
IC-0	40.3	45.1	47.6	46.3	50.8	60.2
IC-8	45.8	47.8	49.9	46.5	55.1	58.1
IC-16	37.9	49.7	52.4	39.9	56.8	60.4
IC-24	48.1	54.9	56.3	41.2	60.0	63.2
IC-32	44.4	51.1	52.4	48.7	53.9	60.0
IC-50	43.2	48.8	50.2	51.7	57.0	57.1
IC-75	41.9	45.2	48.2	49.3	53.9	55.5
IC-100	40.7	44.8	47.7	47.9	52.1	54.1

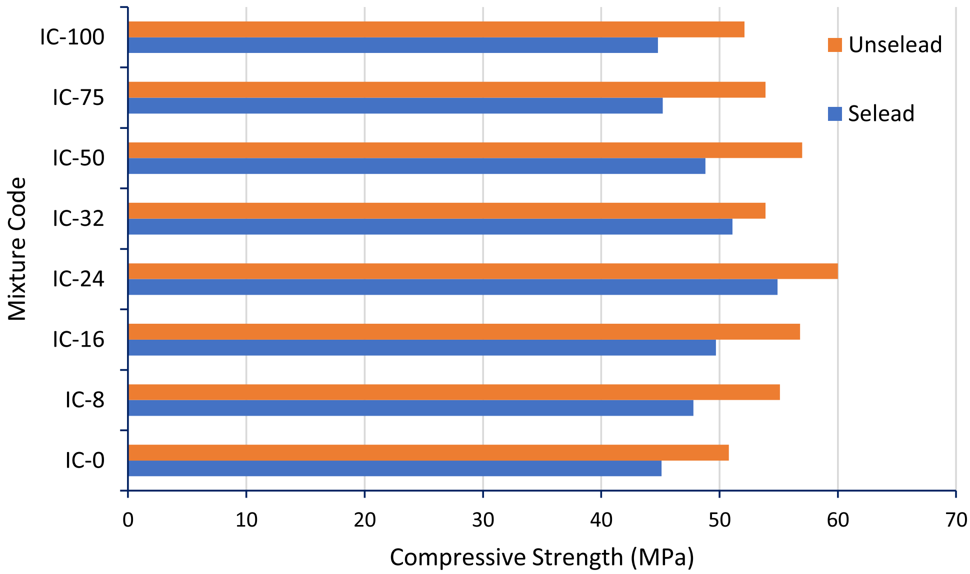


Fig. 7 Impact of external curing condition on compressive strength of internally cured HSC

Fig. 8 Flexural strength test with hydraulic testing compression machine

Table 6 Findings for flexural strength for sealed and unsealed specimens, MPa

Mix code	Sealed specimens			Unsealed specimens		
	7 (Days)	28 (Days)	90 (Days)	7 (Days)	28 (Days)	90 (Days)
IC-0	4.47	5.45	5.94	4.57	5.62	6.15
IC-8	4.10	4.71	4.85	3.46	4.24	5.51
IC-16	4.88	5.11	5.79	4.36	6.03	6.41
IC-24	4.47	4.59	5.61	3.62	4.51	5.73
IC-32	4.30	5.33	5.62	3.32	4.62	5.22
IC-50	4.42	5.09	5.68	3.45	4.87	5.71
IC-75	4.27	4.65	5.24	4.02	5.23	5.69
IC-100	4.41	4.78	5.11	4.12	5.04	5.57

Fig. 9 Flexure strength of internally cured specimens under sealed conditions

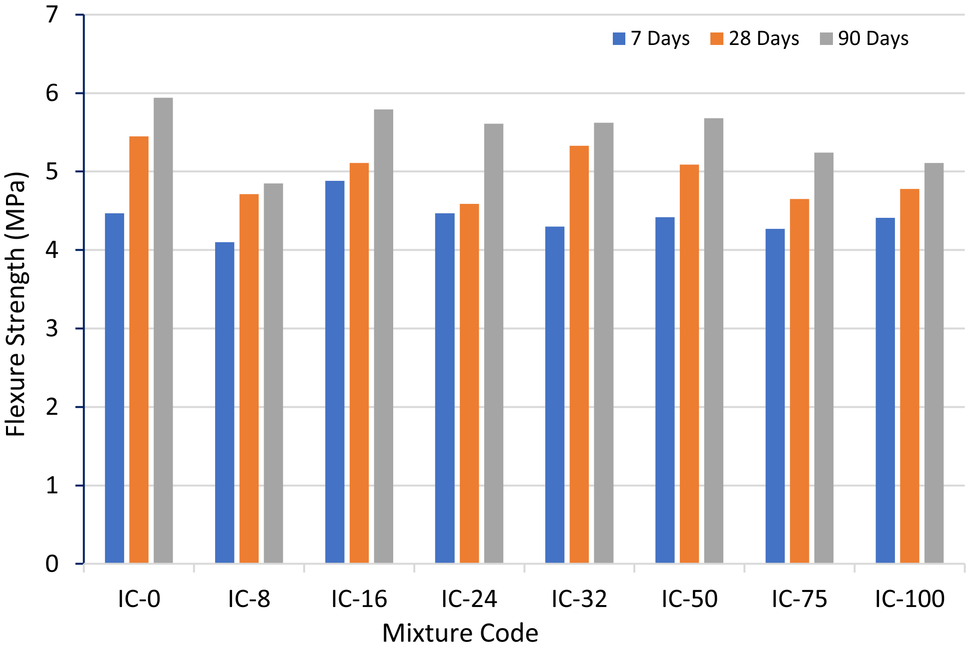
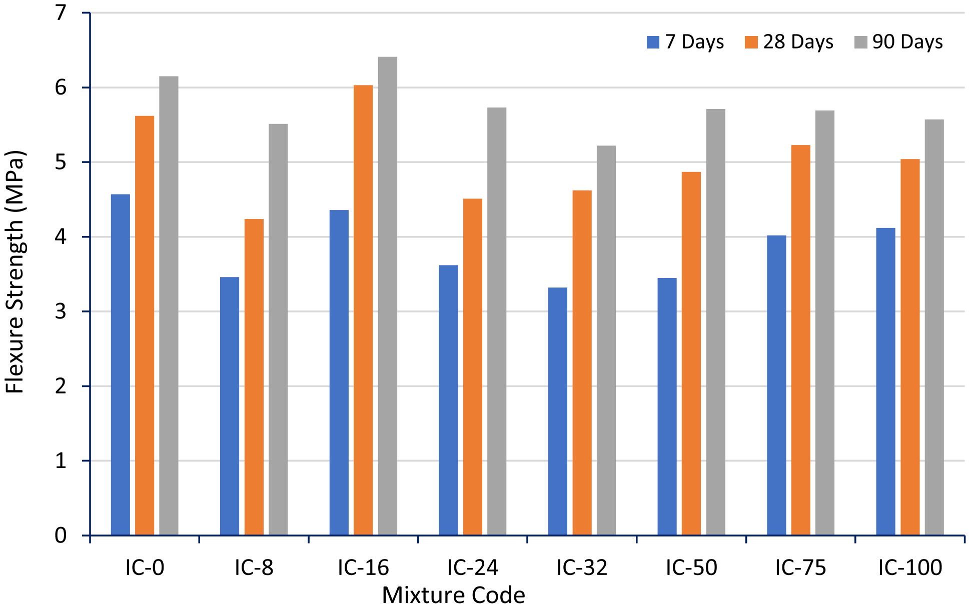


Fig. 10 Flexure strength of internally cured specimens under unsealed conditions



Similar to the unconfined compressive strength, flexural strength also developed with the progression of the age of HSC, and the values obtained at later ages were higher than those obtained at early ages. The highest 28-day flexural strength of HSC was recorded when the RCA replacement ratio was 32%, and the percentage of decrement relative to the control mixture was 2.2% under sealed external curing.

Figures 9 and 10 illustrate the flexural strength of HSC internally cured with various contents of RCA and externally treated with sealed and unsealed conditions, respectively. As can be noticed, the flexural strength of HSC marginally decreases with continuously increasing RCA content, with a proportional relationship under both treatment conditions; a similar trend was also found in [28].

The reduction in flexural strength with an increase in the content of RCA may be attributed to the poor interface bonding between the cement matrix and RCA surfaces, which significantly affects the flexural behaviour of cementitious composites. Another important finding that should be recorded is that using a large amount of RCA (i.e. 100% replacement) does not cause a significant reduction in the flexural strength of concrete like in the case of utilising other materials for internal curing, for instance, ceramic waste [29].

Fig. 11 Shrinkage test of prismatic specimens

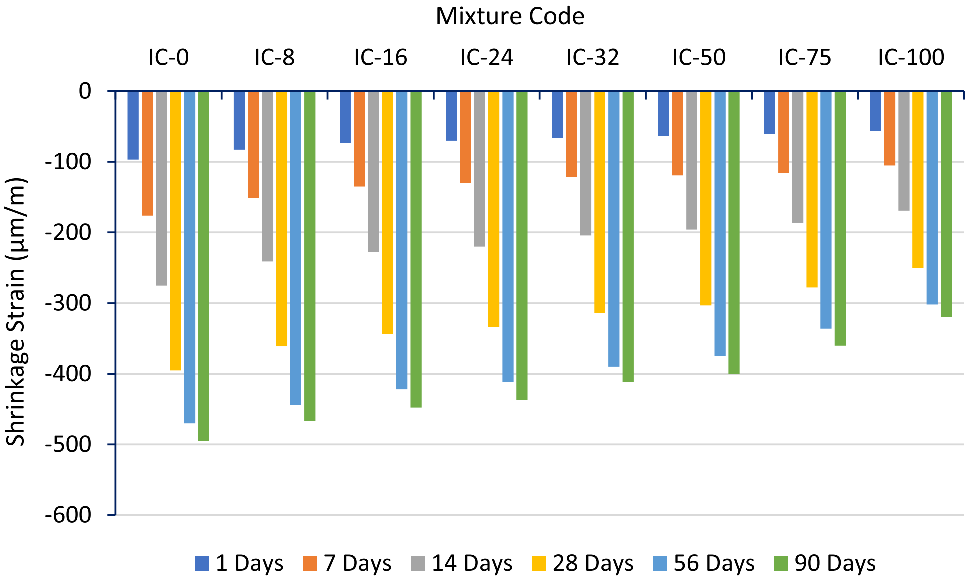
4.3 Autogenous Shrinkage Test

One of the significant problems of HSC is autogenous shrinkage due to high cementitious content and low (W/B) [1, 3] in HSC. Internal curing technique is one of the proposed methods to reduce the autogenous shrinkage of HSC [37, 44] due to providing additional internal water continuously and maintaining appropriate internal relative humidity within the matrix with the progression of the hydration process, hence reducing autogenous shrinkage [62, 63].

In general, the autogenous shrinkage appears on the first day after casting of HSC, and so the initial length of the prepared specimens was recorded. Afterwards, the change in the size was observed both at early and later stages of hydration (i.e. 1, 7, 14, 28, 56, and 90 days after curing) in both sealed and unsealed conditions; the specimen setup is displayed in Fig. 11. The autogenous shrinkage of specimens was determined depending on the average length observed at a specified testing age. The recorded value compensates for the average of three readings at all testing ages. Figure 12 illustrates the variation in the results of autogenous shrinkage of HSC specimens under sealed conditions with all testing ages. It can be noticed that the shrinkage strain increases with increase in concrete age for all mixtures.

Moreover, the experimental results prove that utilising RCA for internal curing effectively reduces the autogenous shrinkage of HSC at an early and later age, and the efficiency is more pronounced when replacing the natural aggregate with a higher percentage of RCA. Further analysis in Fig. 13 indicates that the autogenous shrinkage of the control mixture reaches − 97 µm/m in the first 24H, which is higher than that of IC-100, which exhibits a value of − 56 µm/m in the same period. Compared with the other fabricated mixtures, fully replacing natural coarse aggregate with RCA provides better behaviour concerning autogenous shrinkage of HSC. This trend of the laboratory results can be attributed to the additional water that is held in the pores of RCA, which is crucial to enhance the continuous hydration process of cement, particularly with low water content in HSC mixtures

Fig. 12 Autogenous shrinkage of internally cured specimens under sealed conditions



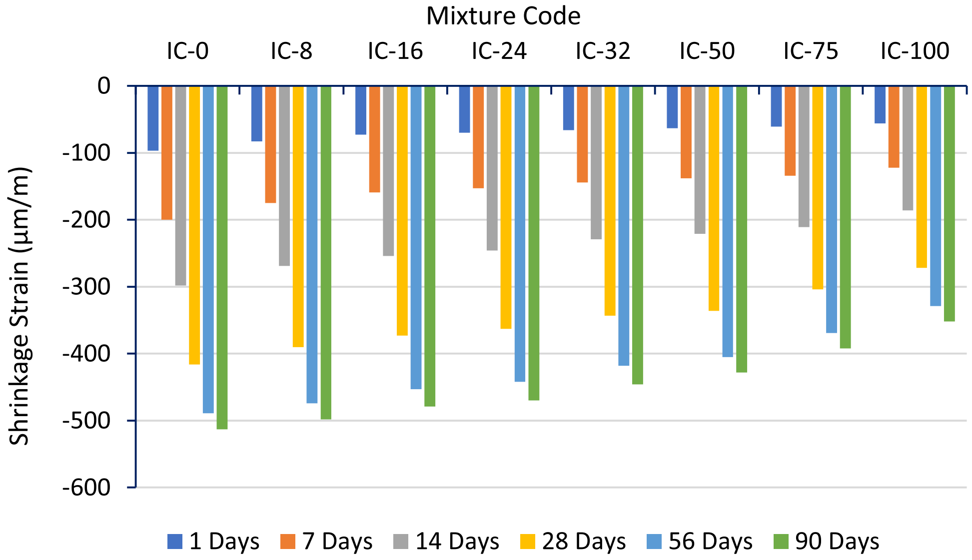


Fig. 13 Autogenous shrinkage of internally cured specimens under unsealed conditions

Table 7 Percentage of reduction in autogenous shrinkage for HSC relative to control mixture

Unsealed condition						
IC-0	–	–	–	–	–	–
IC-8	14.4	14.2	12.4	8.6	5.5	5.7
IC-16	24.7	23.3	17.1	12.9	10.2	9.5
IC-24	27.8	26.1	20.0	15.4	12.3	11.7
IC-32	32.0	30.7	25.8	20.5	17.1	16.8
IC-50	35.1	32.4	28.7	23.3	20.2	19.2
IC-75	37.1	34.1	32.4	29.6	28.5	27.3
IC-100	42.3	40.3	38.5	36.7	35.7	35.4
Sealed condition						
IC-0	–	–	–	–	–	–
IC-8	14.4	12.5	9.7	6.3	3.01	2.9
IC-16	24.7	20.5	14.8	10.3	7.4	6.6
IC-24	27.8	23.5	17.4	12.7	9.6	8.4
IC-32	32.0	28.0	23.2	17.5	14.5	10.1
IC-50	35.1	31.0	25.8	19.2	17.2	16.6
IC-75	37.1	33.0	29.2	26.9	24.5	23.6
IC-100	42.3	39.0	34.6	34.6	32.7	31.4

resulting in autogenous shrinkage because of rapid diminishment in the internal relative humidity within the cement matrix due to cement hydration [2, 3]. It is worth mentioning that utilising RCA as an internal curing agent cannot eliminate autogenous shrinkage but can only alleviate this phenomenon. Other previous related studies that adopted RCA for internal curing purposes also found a significant dropping of autogenous shrinkage when increasing the RCA content; in addition, there was a proportional relationship between the water absorption capacity of RCA and the dropping in the autogenous shrinkage [13, 36, 44].

Figure 12 shows the experimental data for autogenous shrinkage of HSC cured internally with RCA under unsealed conditions with different ages. The behaviour of HSC concerning autogenous shrinkage under unsealed conditions is similar to that under sealed conditions, i.e. the shrinkage strain decreases clearly with increased RCA content in the mixtures. It can be noticed from Figs. 12 and 13 that the progression of autogenous shrinkage of HSC is higher in the early stages than in the later stages.

The comparison between Figs. 12 and 13 explains the effect of external treatment conditions accompanied by internal curing on the autogenous shrinkage of HSC; the determined results indicate better shrinkage behaviour of internally curing HSC under unsealed conditions relative to HSC internally cured in combination with sealed conditions;

the obtained results are in line with the findings of Xu et al. [29] and Yildirim et al. [44]. Table 7 summarises the percentages of reduction in autogenous shrinkage for all mixtures prepared through the experimental programme. It introduces a clear comparison between the obtained results for specimens treated with sealed and unsealed conditions until the age of the test.

5 Conclusion

This study has been carried out to investigate the feasibility of utilising RCA as an internal curing agent in HSC, as a substrate for natural coarse aggregate as with partial and fully volumetric replacement, which considers the worst scenario for particle size distribution and percentage of replacement for internal curing agents utilised in the internal curing technique. The following main findings can be concluded:

- The efficiency of internal curing of HSC utilising RCA is dramatically affected by the replacement percentage in addition to the external treatment conditions. It is largely affected by the amount of additional water supplied by the incorporated internal curing agents.
- The calculated unconfined compressive strength of HSC can be enhanced by substituting natural coarse aggregate with up to 24% RCA by volume under sealed and unsealed conditions. The effect is more pronounced at 28 days and later. When the replacement percentage exceeds 24%, the unconfined compressive strength cannot be further increased.
- Full replacement of natural coarse aggregate with RCA in the fabrication of HSC can improve the unconfined compressive strength without negative impact compared with the reference mixture.
- The flexural tensile strength of HSC is reduced with increased percentages of replacement of natural coarse aggregate with RCA. So, HSC with full replacement of coarse aggregate exhibits flexural strength lower than the control mixture with percentages of 12.3% and 10.3% at 28 days for sealed and unsealed conditions, respectively.
- The utilisation of RCA to volumetrically partially replace natural coarse aggregate can significantly diminish the autogenous shrinkage of HSC, especially with high cement and low water content in the mixtures. When the replacement rate of RCA increases, the autogenous shrinkage reduces proportionally.
- The autogenous shrinkage of HSC is most significant in the early stages of cement hydration with the reduction in the internal relative humidity. The use of RCA can effectively reduce the autogenous shrinkage of HSC, particularly in early ages, and the reduction is greatly affected by the RCA amount.
- The external conditions for the treatment of specimens significantly impact the determined characteristics of HSC in addition to the internal curing. Hence, the efficiency of internal curing is dramatically influenced by the ambient conditions at which HSC is maintained. The determined laboratory data prove that the watery cured specimens exhibit better performance in comparison with the sealed conditions.
- The investigated approach in the current study for internal curing was a promising technique for improving the examined properties of HSC. However, there is a vital need for further investigations regarding microstructure analysis and assessment of the durability characteristics of fabricated HSC subjected to various aggressive circumstances.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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