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Evaluation of Internal Curing Impact on the Mechanical Properties and Durability of High-Performance Concretes

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Abstract
The durability and service life of concrete structures reduces considerably due to the induced cracks from the concrete volumetric changes. Therefore, adopting appropriate measures to overcome this drawback is crucial. In this respect, this research was conducted to investigate the effects of internal curing on high-performance concrete's autogenous shrinkage and mechanical properties. For this purpose, the curing capability of concrete specimens containing pre-saturated artificial aggregate (LECA), superabsorbent polymers (SAP), and recycled crushed bricks (RCB) as internal curing agents was investigated. The volumetric changes and mechanical properties tests of internal cured concrete specimens, including autogenous shrinkage, the compressive, tensile, bending strength, modulus of elasticity, and X-Ray diffractometer (XRD) tests, were performed to investigate the effect of internal curing on the micro-structures and hydration procedure. According to obtained results, the SAPs could omit the autogenous shrinkage of studied concrete specimens. The test results of specimens containing LECA also showed a reduction in the autogenous shrinkage value; however, using LECA caused a reduction in the mechanical properties. In comparison, recycled crushed bricks could reduce the concrete autogenous shrinkage and improve mechanical properties.

Keywords Internal curing, Autogenous shrinkage, lightweight aggregate, Superabsorbent polymers, High-performance concrete.

Introduction
Supplying suitable concrete curing is a critical factor in ensuring concrete structures' durability and sustainability. Hydration products and their penetration in the internal pores occur during curing, accompanied by sufficient water support. This process is associated with reduced porosity, concrete volume changes, and crack probability.

There are different ways to keep concrete internal humidity. External curing is a common and traditional method that performs poorly. In this technic, required moisture is provided by sprinkling water or using wet burlap, which primarily is not performed homogeneously. Some advanced methods for concrete curing have been proposed to overcome this problem in recent years.

Paul Klieger issued a report on internal concrete curing by LECA in 1957 [1,2]. In the mid-90s, some German and Dutch researchers introduced innovative methods for internal concrete curing by pre-wetted lightweight aggregates [2,3,4]. Water can penetrate some millimeters in the external curing of concrete with a low w/c ratio. In

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contrast, in the internal curing technique, humidity can be distributed uniformly in the whole parts of a concrete mass [5]. In the following, the use of other materials (e.g., superabsorbent polymers, cenospheres, and pre-wetted wood fibers) that were applied as internal water reservoirs was considered [6-10]. However, the production of hundreds of thousands of cubic meters of concrete with pre-wetted lightweight aggregate for internal curing in the US before 2007 [11] shows that this modern technology is efficient and economical.
One of the most significant purposes of internal curing is the reduction of autogenous shrinkage strains in higher-performance concrete (HPC) [5]. To this end, many studies have been carried out on the impact of internal curing on concrete shrinkage strains [12]. In addition, the measurement method of autogenous shrinkage [21] and reduction of autogenous shrinkage in hydrated cement paste are among the studied issues in this field. ASTM C1698 standard has introduced a method of autogenous shrinkage measurement based on the Jensen & Hansen method proposed in 1995 [15,16]. In the proposed method, a cement paste or mortar sample is put in a flexible polymer pipe, and the deflection is measured periodically. Giker et al. studied the autogenous shrinkage of mortar with water to cement ratio of 0.35, containing 8% Silica Fume (FSF), which was internally cured by pre-wetted lightweight aggregate (LWA) and (SAP) [17]. According to the Giker report, all specimens cured internally had more internal wet ratio and less shrinkage strain [17]. Henkensiefken et al. placed the prismatic specimens of the mortar after one-day curing under a moisture isolation situation to observe shrinkage as a function of lightweight aggregate replacement [17]. The results showed a considerable reduction in self-shrinkage strains.
Comparison between plastic shrinkage and the cracking tendency of concrete with and without internal curing was the subject of several studies [18, 19]. The results demonstrated a reduction in plastic shrinkage caused by internal curing with the LWAs.
In summary, despite the valuable studies and considering the problems of using SAPs and LWAS, such as non-uniform distribution inside the concrete volume, further investigation is needed. Also, introducing internal curing agents with a density closer to concrete can significantly increase the efficiency of internal curing, especially in concretes with a low water-to-cement ratio. In this study, in addition to a more detailed examination of the issue, crushed brick particles with a density close to concrete aggregates have been used as an internal curing agent, along with SAP and LWAS particles. In addition to internal curing, using crushed brick particles can play a significant role in reducing the accumulation of construction debris in nature.
In the literature, different methods were proposed to calculate the required LWA for internal curing of a concrete mixture with low water content (e.g., Eq. 1). Equation 1 determines the required mass of dry lightweight aggregate used as micro-water reservoirs [16].

$$C_f . C_s . \alpha_{mas} = S . \Phi_{LWA} . M_{LWA} \qquad (1)$$

Where C_f is the concrete mixture cement factor, C_s is the chemical shrinkage of cement in a complete reaction, and α_{max} is the maximum hydration rate with a value between zero and one. Also, S is the saturation ratio of the LWAs to the whole saturated level, Φ_{LWA} is the absorption capacity calculated from the internal reservoirs in pre-wetted conditions, and M_{LWA} is the value of internal reservoirs required for the internal curing. It should be noted that, on the right side of the equation, the LWA dis-absorption capacity should be considered [16].

2. Research Significance

The primary goal of this research is to assess the ability of pre-saturated artificial aggregate, LECA, SAPs, and recycled crushed bricks for internal concrete curing. In this regard, it has tried to study the absorption properties and determine the efficiency and performance of these internal curing agents. To this end, the absorption capacities of cited internal curing agents were primarily measured as the water reservoirs. The volumetric changes and mechanical properties tests of internal cured concrete specimens, including autogenous shrinkage, the compressive, tensile, bending strength, modulus of elasticity, and X-Ray diffractometer (XRD) tests, were performed to investigate the effect of internal curing on the micro-structures and hydration procedure.

3. Material and methods

The cement for the concrete specimens was ordinary Portland cement (Type I), and the cement content was 350 kg/m^3. The fine aggregate was river sand. The fine and coarse aggregates were crushed, and the maximum size of the coarse aggregate was 0.39 mm. In all studied mixes, 10% of cement weight was replaced by silica fume as an additive. In order to reach suitable workability, also reducing w/c, poly-carboxylic, as a high-range water-reducing admixture, is added to the mix designs (Table 1).
As mentioned, several different materials, including LECA, superabsorbent and crushed brick, were used for the internal curing of concrete specimens. The LECA (with an actual specific gravity of 970 kg/m3) was fine-grained with a maximum size of 4 mm. The 24- and 48-hour water absorption of LECA was 37.8% and 40.28%,

respectively. Using crushed brick (with 2050 kg/m3 actual specific gravity) is a new idea for internal curing, considering these particles' environmental obligations and noticeable porosity. This material's 24- and 48-hour water absorption was 51.2% and 53%, respectively. One of this research's main goals is to assess using brick as an internal curing agent in concrete to achieve knowledge of its performance. The used bricks were some recycled compressive ones crushed by the crusher machine. The maximum nominal diameter for the crushed bricks was 4.75 mm. The SAP used in this research was synthetic A200. The superabsorbent sizes and diameters were homogenous and between 2 and 3 mm. Also, the A200 water absorption in 5 and 115 minutes equals 14.5 and 105 times its weight, respectively.

The studied mix designs for the experimental program are presented in Table 1. Letters L, S, B, and C represent LECA, SAP, crushed bricks, and specimen. For example, in "35L33+10", "35" means the total water-to-cement ratio, "L" indicates the material for internal curing, "33" means the effective water-to-cement ratio, and "10" means the additional material replacement percentage.

Table 1. Mix designs of concrete specimens

Mixtures	$(w/c)_t$	$(w/c)_e$	W_e[1]	Agreegate[2]	LECA[3]	CB[4]	SAP
35S33+.14	0.4	0.033	115.5	1900	0	0	0.48
35S30+.34	0.4	0.3	105	1900	0	0	1.2
40S35+.34	0.4	0.35	122.5	1900	0	0	1.2
40S33+.49	0.4	0.33	115.5	1900	0	0	1.7
40S30+.68	0.4	0.3	105	1900	0	0	2.4
35L33+10	0.4	0.33	115.5	1805	49.6	0	0
38L30+20	0.4	0.3	105	1710	99.2	0	0
43L35+20	0.4	0.35	122.5	1710	99.2	0	0
45L33+30	0.5	0.33	115.5	1615	148.9	0	0
35L27+20	0.4	0.27	94.5	1710	197	0	0
35B30+4.5	0.4	0.3	105	1857	0	53.2	0
40B30+9	0.4	0.3	105	1814	0	106.3	0
C30	0.3	0.3	105	1900	0	0	0
C33	0.3	0.33	115.5	1900	0	0	0
C35	0.4	0.35	122.5	1900	0	0	0
C40	0.4	0.4	140	1900	0	0	0

1. Effective Water, 2. In saturation conditions with a dry surface, 3. Wetted for 48 hours, 4. Crushed Bricks: Weight ratio to cement (%)

Figure 1a compares the 72-hour water absorption curves for LECA and crushed brick. This figure shows that the water absorption rate in both materials is primarily high and reduces over time; Also, the 72-hour water absorption for crushed brick is more than LECA.

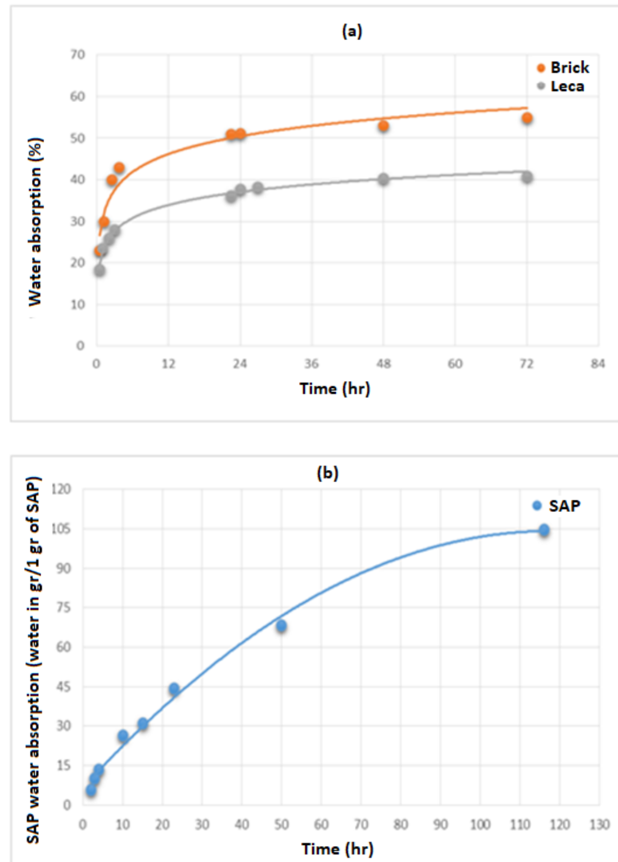

Fig 1. Water absorption capacity, a) A comparison between water absorption of LECA and crushed bricks, b) Superabsorbent water absorption

In this research, to calculate the required values of LECA and crushed brick, the 48-hour water absorption equivalent to 40 and 55% is considered. The teabag method is employed to calculate SAP's water absorption curve. In this method, 0.2 grams of A-200 superabsorbent were put in a teabag, and the water absorption changes were measured. Figure 1b shows the water absorption curve for superabsorbent.

The prismatic concrete specimens with 50×10×10 cm size were used to measure concrete volumetric changes. A waterproof polymer material was used to keep the existing water in the specimens and avoid moisture loss from the concrete surface. After isolation, concrete specimens were put under a strain gauge, and the length changes of the specimens were recorded in specific time intervals.

The XRD (X-Ray Diffractometer) test was performed to compare the specimen's reactivity degree by specifying the existing phases. This test is a practical method to evaluate the efficiency of the internal curing material and the hydration or reactivity degree. Moreover, the mechanical properties of the internally cured concretes and the control specimen were studied by performing the compressive, tensile, bending strengths, and modulus of elasticity tests in 7 and 28 days.

4. Results and discussion

This section presents the results relevant to the tests performed on concrete specimens to investigate concrete volume changes along with mechanical properties.

4.1. Internal curing effect on the autogenous shrinkage strains

Figure 2a shows the autogenous shrinkage of the control specimens and specimens containing LECA, with the effective water-to-cement ratio of 0.3 and 0.35. As seen in Figure 2a, in the specimen of 20% LECA with water to cement 0.3, the autogenous shrinkage has been omitted approximately, while the C30 control specimen in the first week after demolding had about 600 µm shrinkage, and its 28-day shrinkage reached 400 µm. Similar results can be observed for the specimen containing 20% LECA with a 0.35 water-to-cement ratio. According to the obtained results, in addition to autogenous shrinkage elimination after 28 days, the specimens containing LECA experienced an approximately 100 µm longitudinal expansion, while in the C35 control specimen, after 28 days, the shrinkage strain was 200 µm. As seen in Figure 2a in the uncured specimens, the autogenous shrinkage at 3 and 7 days' age is at its maximum value. This probably occurs because of the low relative internal moisture in these specimens' microstructure. In other words, eliminating autogenous shrinkage strain in the specimens containing LECA could happen because of a reduction in capillary stresses by the presence of water in the capillary pores. Also, the logged water from the LECA increased the separating force, leading to separation in the capillary layers and volume expansion. It is worth mentioning that similar results have been reported by other researchers [20].

For the specimens containing LECA with different effective water-to-cement ratios (0.27, 0.30, and 0.35) with identical amounts of LECA equal to 20% of sand volume, as predicted, the autogenous shrinkage reduces as the increase of the water-to-cement ratio. Comparing the concrete specimens with different LECA quantities, with a constant water-to-cement ratio, shows that the shrinkage is restricted or even omitted in the mix with 20% LECA. These results show that in the specimen with a constant

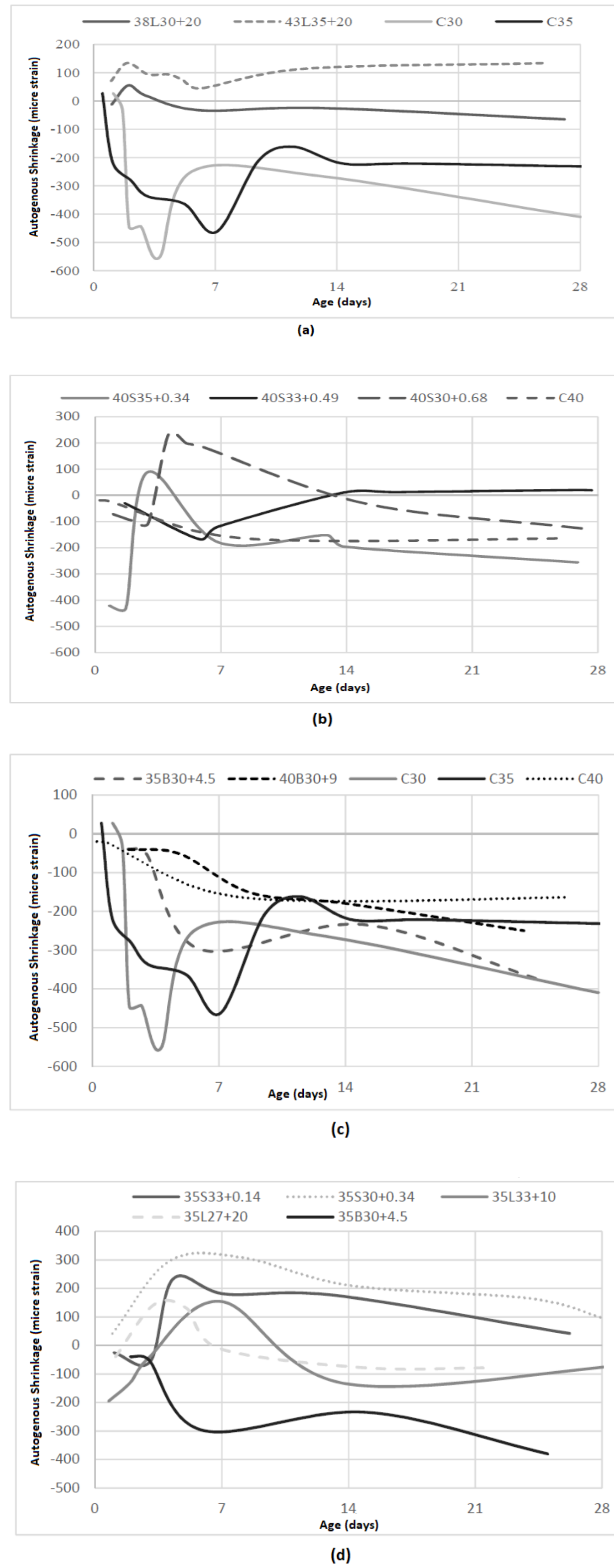

Fig 2. Autogenous shrinkage of the concrete specimen containing different quantities of internal curing agents vs. control mixes, a) LECA, b) SAP, c) Crushed bricks, d) Comparative results

total w/c, the effect of saturated LECA on the induced autogenous shrinkage strains is more than the effect of increasing effective w/c.

Figure 2b indicates the autogenous shrinkage in the mixes containing different quantities of SAP with equal (w/c) t=0.4. Accordingly, it could be detected that the autogenous shrinkage at the 28-day age does not necessarily decrease by increasing SAP values. For instance, the specimen with 0.68% SAP has more autogenous shrinkage than the specimen with 0.49% SAP. The results also proved that in w/c=0.4, there is an optimum value for SAP in the 34 to 49% range. The comparison was made among the specimens with w/c=0.35, containing different quantities of SAP, and an optimum amount of SAP was detected. Other specimens with (w/c)e between 0.3 and 0.33, containing different SAP, were studied. The observed outcomes indicate that both concrete specimens had less (or even zero) autogenous shrinkage than the counterpart control specimens.

Figure 2c illustrates the autogenous shrinkage of specimens containing 4.5 and 9% crushed bricks vs. the C30 control specimen with the same (w/c)e. according to this figure, mixes containing crushed bricks can effectively reduce autogenous shrinkage strain. In the specimen with 4.5% crushed brick, the small amount of crushed brick and inappropriate spatial distribution decreased the autogenous shrinkage less than the expected value. In comparison, based on the (w/c)t instead (w/c)e, in the specimens with total w/c=0.35 and 0.40, the autogenous shrinkage for the third and fourth weeks is approximately equal to the counterpart control specimens.

Figure 2d compares the mixes containing LECA, SAP, and crushed brick as water reservoirs in concrete for a (w/c)t=0.35. According to this figure, the SAP performs more effectively as an internal curing material for reducing or omitting the autogenous shrinkage in concrete.

4.2. The effects of internal curing on the mechanical properties

Figure 3 indicates the compressive strength of the mixes with SAP vs. control specimens. Comparing the result of cured specimens shows an increase in the compressive strength of the specimens containing SAP (figure 3). All the specimens with SAP have greater 7-day compressive strengths compared to C40. Also, the 28-day compressive strength of the mixes with 0.34 and 0.49% SAP has more than the control mix. The results obtained show that the specimen with 0.49% SAP has the maximum strength, while the compressive strength of the specimen with 0.68% SAP was 4% less than the C40. Similar results were observed in the mixes with SAP in w/c=0.35.

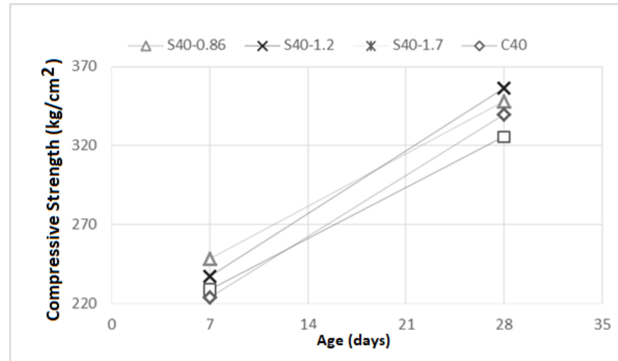

Fig 3. Compressive strength of the specimens having SAP with total w/c=0.40.

Figure 4 shows the specimens containing 10 and 20% LECA have more 7-day compressive strength than the C35. The 28-day compressive strength of the specimen with 20% LECA with a total w/c=0.35 is approximately 11% less than the control specimen. While for the specimen with 10% LECA and the same total w/c, approximately no changes were observed in the 28-day compressive strength. In the specimens with 20% saturated LECA, an increase in the compressive strength was observed by reducing the effective w/c and fixing the LECA substitution value.

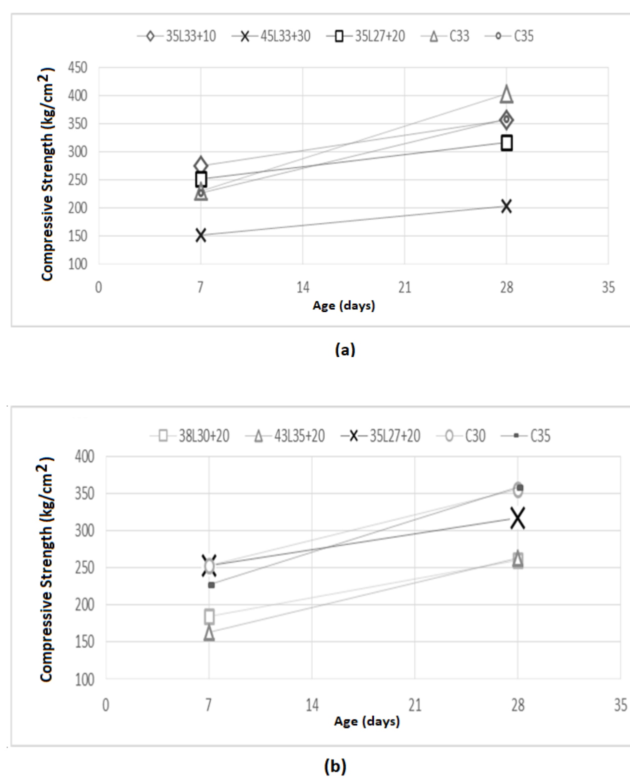

Fig 4. Compressive strength of the cured specimens with LECA and the control specimen.

The 7-day compressive strength of C33, 35L33+10, and 45L33+30 (constant effective w/c) were 235.5, 275.5, and 152 kg/cm2. For the specimen with 10% LECA, approximately 20% increase in the strength, and for the specimen containing 30% LECA, a 34% decrease in the 7-day strength was observed compared to the control mix. This means more strength decrease is observed with an increase in LECA substitution.

Figure 5 shows the 28-day compressive strength for the specimens having crushed bricks. For the specimens with 4.5% crushed brick, the compressive strength was 407 kg/cm2, and for the specimen with 9% crushed brick, the strength was 362 kg/cm2. Compared to the C30 control mix with the same effective w/c, a 14.5 and 2% increase in compressive strength was observed for the specimens containing 4.5 and 9% crushed brick. Therefore, the internal curing by crushed bricks improved the concrete compressive strength. According to Figure 5, the noticeable decrease in primary autogenous shrinkage in the specimens having crushed bricks and, consequently, the reduction in the micro-cracks caused by the volumetric changes can be considered the main reason for the strength increase.

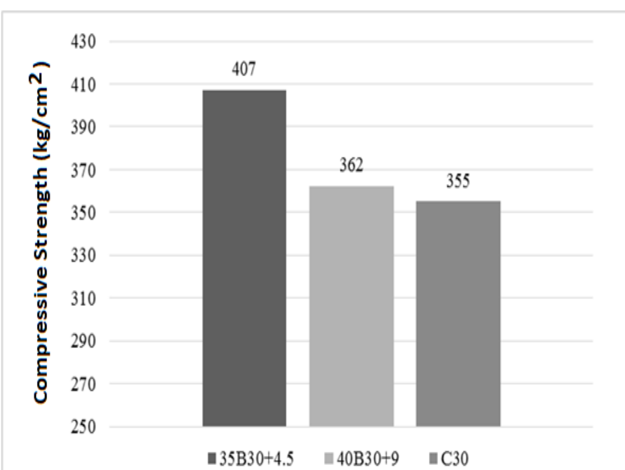

Fig 5. Compressive strength of the specimens internally cured by crushed brick (28 days).

Figure 6 shows the 7 and 28-day tensile strength for the specimens containing 0.34, 0.49, and 0.68% SAP with a total w/c=0.40. All specimens showed an increase in tensile strength for the 7 and 28-day ages compared to the C40 control specimen. At 7-day age, the maximum increase in compressive strength in comparison to tensile strength is for the specimens containing 0.68 and 0.49% SAP. Also, the specimen with the minimum SAP value reached the maximum tensile strength in 28 days (42.4 kg/cm2.

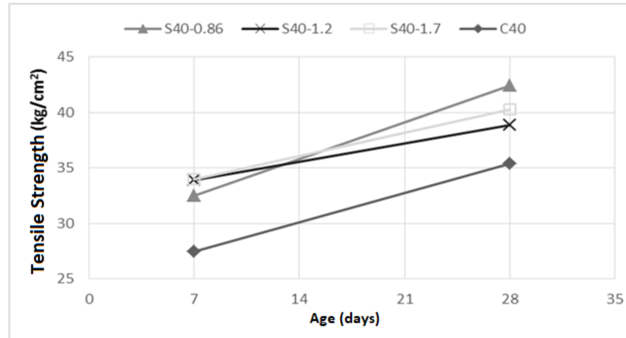

Fig 6. Tensile strength of the specimens containing SAP with total w/c=0.40

Conducted study on the specimens with w/c=0.35 containing SAP and the C35 control specimen showed similar results for the tensile strength.

The tensile strength for the specimens with LECA was measured, and its outcomes are given in Figure 7. For the specimens 35L33+10 and 35L27+20 with total w/c=0.35, internal curing reduced the concrete strength compared to the C35 control sample (7 and 5% in order). The tensile strength of the internally-cured specimens with crushed bricks was measured (figure 8). The 28-day tensile strengths for specimens containing 4.5 and 9% were 46.5 and 45 kg/cm2, which is greater than the control sample's tensile strength.

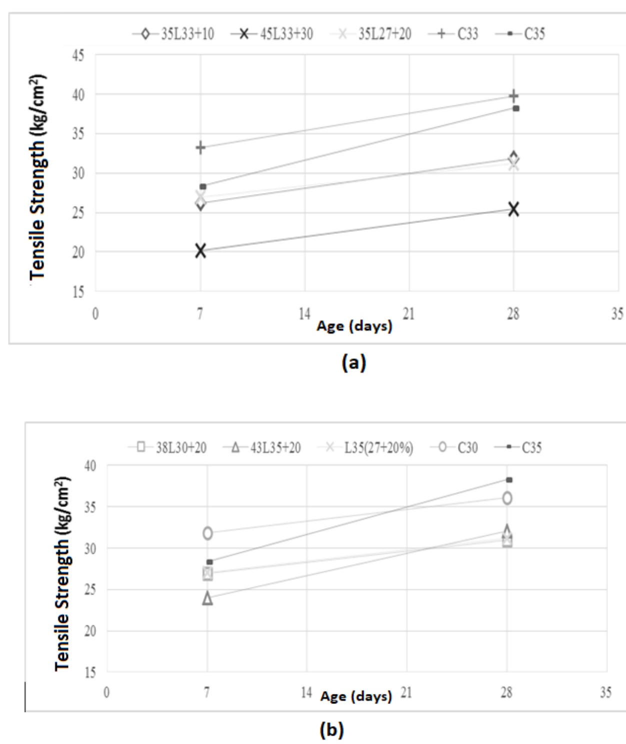

Fig 7. Tensile strength of the specimens internally cured by LECA and the control specimen

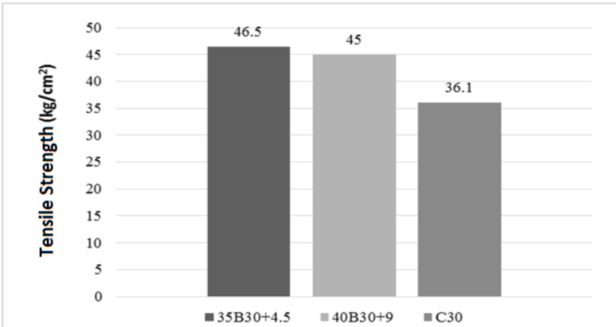

Fig 8. Tensile strength of specimens internally cured by crushed bricks (28 days)

Figure 9 shows the bending test results for cured and control specimens at 28 days.

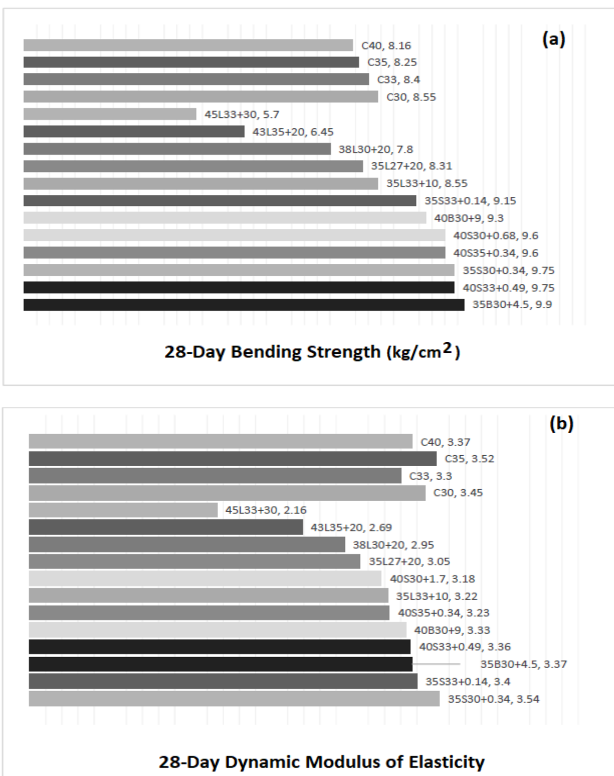

Fig 9. Bending strength and dynamic modulus of elasticity of the specimens, a) Bending strength, b) modulus of elasticity

According to Figure 9a, using SAP has an improving effect on bending strength. The specimens with total w/c=0.40 and containing 0.34, 0.49, and 0.68% SAP have bending strengths of 9.6, 9.75, and 9.6 kg/cm2, respectively. These results show an approximately 17% increase compared to the C40 control sample. The specimens with 10 and 20% LECA and total w/c=0.35 showed a negligible increase in 28-day bending strength compared to the C35 control sample. The presence of crushed bricks as water reservoirs for internal curing caused an increase in the bending strength of the specimens compared to their counterpart control specimen. The 28-day bending strength of the specimen containing 4.5% crushed bricks (35B30+4.5) is 9.9 kg/cm2, and the specimen containing 9% crushed bricks (40B30+9) is 9.3 kg/cm2 that shows 16 and 9% increase in comparison to the C30 specimen. The results of the dynamic modulus of elasticity test are given in Figure 9b.

As seen in Figure 9b, among the specimens with total w/c=0.40 and different amounts of SAP (0.34, 0.49, and 0.68%), the 40S33+0.49 mix design has the maximum modulus of elasticity, which is approximately equal to the C40 control sample. Considering this figure, substituting LECA with sand causes a decrease in the concrete modulus. Also, the internal curing of concrete by crushed bricks has no improving effects on the concrete dynamic modulus of elasticity.

4.3. Internal curing effects on hydration degree

The Calcium Hydroxide (CH) percentage in a complete reaction should be calculated to determine the hydration degree. Table 2 depicts the amounts of calcium hydroxide in the cement hydration reaction in the specimens with a total ratio of water to cement equal to 0.35.

According to obtained results, except for the specimen containing 4.5% crushed bricks, the rest of the specimens show an increase in CH compared to the C35 control sample. It could be because of the less available water to develop the hydration process. In the specimens with effective w/c=0.3, it is observed that the specimen containing crushed bricks could recover the hydration degree slightly. The specimen containing 20% LECA with effective w/c=0.27 could increase the hydration products well and has a greater degree of hydration than the control samples with w/c=0.35. Also, as observed, the hydration degree has increased by enriching the percentage of LECA substitution by sand from 10 to 30%. The specimen containing 0.14% SAP has an approximately similar hydration product to 30% LECA. Figure 10 shows the graph of the XRD test for the 35S33+0.14 mix design.

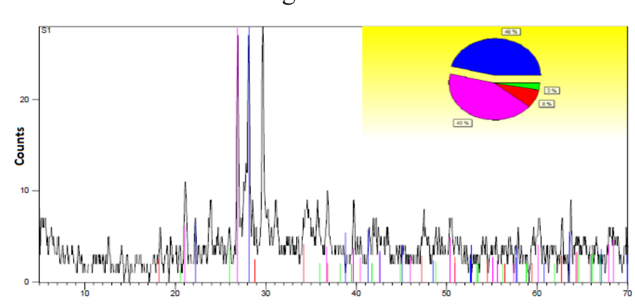

Fig 10. The XRD test results for 35S33+0.14 mix design

Table 2. The percentage of calcium hydroxide in the hydration reaction of cement ((w/c)t=0.35)

	35S33+0.14	35S30+0.34	35L33+10	35L27+30	35B30+4.5	C30	C35
$CA(OH)_2$	3	5	2.58	3	1	<1	2.38

5. Discussion

The comparison between the results obtained from the specimens containing the internal curing agents indicates that despite the effect of the internal curing on reducing or even eliminating the autogenous shrinkage of concrete, the internal curing has caused a decrease in the compressive strength and modulus of elasticity in some specimens. Internal curing by preparing and providing appropriate and sufficient moisture inside the concrete, in addition to eliminating capillary stresses, improves the strength of concrete by increasing the degree of hydration of un-hydrated cementitious materials. On the other hand, low specific weight and low resistance of light grains reduce the strength and modulus of elasticity in internally cured concrete. The superabsorbents inside the concrete, whether they contain water or not, by creating and increasing the porosity in the concrete, reduce concrete compressive strength and modulus of elasticity. Accordingly, improving hydration and microcracks on the one hand, reducing specific weight, and increasing porosity on the other, each of which has a more significant impact on concrete, will cause an increase or decrease effect in compressive strength, respectively. Based on the results obtained, it is evident that the specimens containing super absorbent have a higher strength and modulus of elasticity while also effectively reducing shrinkage strains. The specimens containing crushed brick reduced shrinkage strains by 20-50% and simultaneously increased the compressive strength of concrete compared to the control specimens.

The reason for the ineffectiveness of crushed brick compared to LECA in reducing shrinkage strains is its higher specific weight. In the mix designs, an attempt was made to use fine-grained aggregates to improve the spatial distribution of water reservoirs in concrete. However, due to the crushed brick's high absorption and specific weight, achieving proper spatial distribution in concrete was impossible compared to LECA and other agents.

6. Conclusion

Considering the significant effect of autogenous shrinkage in the low w/c ratio concretes, this study tried to reduce the negative impact of shrinkage strains on the strength and durability of concrete. To this end, it was tried to supply internal curing conditions for the studied mixes using SAP, LECA, and crushed bricks, as the internal water reservoirs. In the following, the most significant outcomes of the study are summarized:

- Internal curing by SAP, LECA, and crushed bricks has caused a reduction or even elimination of the autogenous shrinkage in the studied specimens. SAPs have more satisfactory results than LECA and crushed bricks. The specimens containing SAP and crushed bricks increased the tensile strength of the concrete by 3 to 35%. The maximum increase relates to the specimens containing SAP equal to 0.34% cement weight. The 28-day bending strengths of concrete showed an increase by using all internal curing agents compared to the counterpart control specimen.
- Specimens containing crushed bricks with 4.5 and 9% substitution could reduce the autogenous shrinkage from 20 to 50% in the low ages and increase the concrete strength specifications compared to control samples.
- The specimen with very low w/c=0.25 with 20% LECA has less autogenous shrinkage than the control specimen with w/c=0.4. In specimens that have water-to-cement ratios greater than 0.4, where the autogenous shrinkage potential is less, using SAP should be selected in its minimum value. In this study, the proper weight of SAP was obtained between 0.34 to 0.49% for the concrete mixes with w/c=0.4.

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Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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