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ARTICLE

INTERNAL CURING EFFECT ON PROPERTIES OF SELF-COMPACTING CONCRETE

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ABSTRACT

One of the most common problems after concrete casting is shrinkage due to water loss from the hydrated cement paste. This phenomenon causes crack creation and increases the permeability of concrete where causes concrete durability reduction. In this research, the effect of internal curing on the mechanical properties of self-compacting concrete, shrinkage strain, permeability and corrosion of rebar has been evaluated. According to the obtained results, the internal curing of self-compacting concrete containing lightweight aggregates reduced or even eliminated the shrinkage strain. As a result, concrete durability will be increased by controlling the concrete crack propagation. Also, the mechanical properties of concrete specimens and concrete resistance against corrosion were improved due to internal curing.

KEY WORDS
Shrinkage, diffusion, internal curing, fraction, durability

INTRODUCTION

Self-compacting concrete (*SCC*) is a type of concrete which can be compacted by its weight without any vibrations. According to *ACI 237R-07*, SCC is a high workable concrete without any segregation which can fill up the concrete molds and cover the rebar up without any mechanical compaction [1]. The necessity of this type of concrete was proposed by Okamura in 1986. Studies to develop self-compacting concrete, including a fundamental study on the workability of concrete, have been carried out by Ozawa and Makala at the University of Tokyo [2]. The prototype of self-compacting concrete was first completed in 1988 using materials already on the market. The prototype performed satisfactorily with regard to physical and mechanical properties [3].

Internal curing by compensating the consumed water by hydration development and surface evaporation can help to decrease shrinkage, crack creation and permeability of concrete structure; it can also increase the durability and the service life of concrete. Thus, with regard to some areas with high risk of volumetric changes, investigating a method which can decrease shrinkage strain probability seems necessary.

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Leemann et al., have figured out that the drying shrinkage strain value in *SCC*, is about 10-15% more than the corresponding value in normal concrete [Fig. 1]. This difference also rises up to 24% at the age of 90 days [4].

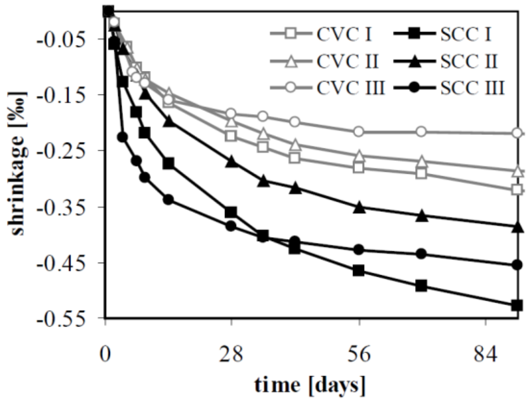

Fig. 1: Cson of shrinkage between *SCC* and normal concrete.

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In external curing in the concrete, water just can penetrate into the limited thickness of the members; while in internal curing, water molecules can be distributed in the whole body of the concrete members [5]. The possibility of using different additives that can be applied as internal water resources like *SAP* (Superabsorbent Polymers) [6,7], limestone aggregates [8], Cenospheres [9], Paraffin wax [10] and Pre-Wetted Wood Fibers [11] is studied recently.

The reasonable explanation for the effect of internal curing on decreasing or elimination of shrinkage has been presented by Weber and Reinhardt [12]. Based on the explanations, a set of capillary pores form in the cement paste during hydration. The diameters of the pores are less than the pores in lightweight aggregate. After the reduction of relative humidity in concrete the drying process develops due to hydration process and humidity gradient. The pores of hydrated cement paste, absorb the water in aggregates with capillary suction. Thus, anhydrous particles of the clinker will have more free moisture for hydration. The new products of hydration form in the pores of hydrated cement paste and make them smaller and more discrete. As the pores size and capillary networks get smaller, capillary tension, which is inversely related to the square of the pore diameters, is increased. Thus, water transfer from the saturated lightweight aggregate will continue until it is completely transferred from lightweight aggregate to hydrated cement paste [12].

When the concrete is internally cured, as the water in capillary pores of concrete is completely consumed by hydration process, water lack is compensated by internal water sources. So, less tensile stress is created in capillary pores and as a result, induced shrinkage strain is reduced. In this regard, volumetric dilatation of concrete is also possible in the first few days of concrete production [4]. The most important result of internal curing is the reduction of shrinkage which decreases the stresses during hardening process and also reduces cracking risk in low water to cement ratios.

On the other hand, as it's necessary to externally vibrate the normal concrete for a better compaction, bleeding and segregation phenomena are observed in concrete. While these phenomena do not occur in *SCC* because there is no vibration process. Less porosity in transition area and the physical presence of mineral fillers are the main reasons of a more compressibility of the material in *SCC*. *SCC* mixes without any additive powder material which gain their stability and workability from plasticizers, usually have much permeability in compared to other *SCC* mixes [13]. Containing materials of hydrated cement paste, especially fillers, can have an important role on the behavior of *SCC* in the aggressive environments [14].

RESEARCH SIGNIFICANCE

In this study, the effect of using Light Expanded Clay Aggregate which is named *LECA* on the properties and characteristics of fresh and hardened concrete has been investigated. In order to reach this purpose, the water absorption characteristics of lightweight aggregates were measured and the final mix design of the self-compacting concrete has been obtained after performing several primary experiment at the trial and error procedure.

Fresh concrete tests include Slump-Flow test, *V*-Funnel test, *L*-Box test and *J*-Ring test; have been performed to assure the self-compacting characteristics of the mixes according to *EFNARC* [15]. Also, the mechanical properties, dimension stability, permeability of concrete and corrosion potential of rebar are measured to study the effect of internal curing on the solid properties and cracking potential of the concrete.

MATERIALS AND METHODS

Portland cement type I was used in this study. Crushed gravel with the maximum size of 20*mm* and river sand were respectively used as coarse and fine aggregates which were both graded according to [16]. Fine *LECA* with the dimensions of 0-4mm with the special gravity of 510 kg/m^3 was used as lightweight aggregate. The variations of water absorption related to the *LECA* during 72 hours is shown in [Fig. 2]. In the concrete mixes a superplasticizer was also used to maintain suitable workability.
In the mix design name, the first number represents "water to cement ratio" and the following number indicates the "the percentage of *LECA* replacement instead of fine aggregate". The specimens mix designs of Self-compacting concrete (*SCC*) and ordinary Portland cement concrete (*OPC*) are summarized in [Table 1].

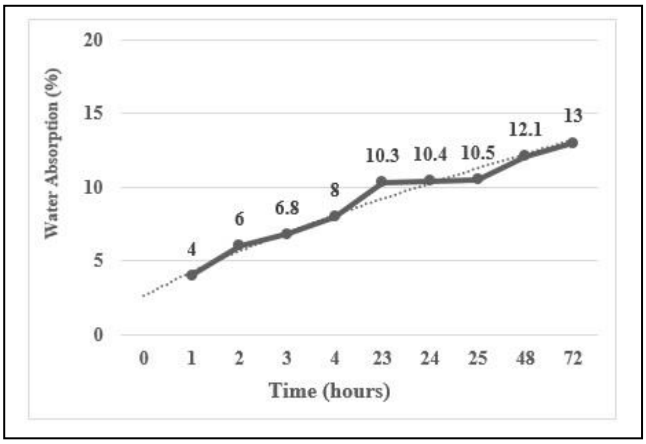

Fig. 2: Water absorption of Lightweight aggregates (*LECA*).

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Table 1: Mix designs of concrete specimens

Mixture	*w/c*	Cement Content (kg/m^3)	Silica Fume (kg/m^3)	Gravel (kg/m^3)	Sand[1] (kg/m^3)	*LECA*[2] (kg/m^3)
0.3 SCC+10	0.3	450	50	850	630	70
0.3 SCC+20	0.3	450	50	850	560	140
0.3 SCC+30	0.3	450	50	850	490	210
0.35 SCC+10	0.35	450	50	850	630	70
0.35 SCC+20	0.35	450	50	850	560	140
0.35 SCC+30	0.35	450	50	850	490	210
0.4 SCC+10	0.4	450	50	850	630	70
0.4 SCC+20	0.4	450	50	850	560	140
0.4 SCC+30	0.4	450	50	850	490	210
0.4 OPC+10	0.4	360	40	900	720	80
0.4 OPC+20	0.4	360	40	900	640	160
0.4 OPC+30	0.4	360	40	900	560	240
0.3 SCC	0.3	450	50	850	700	0
0.35 SCC	0.35	450	50	850	700	0
0.4 SCC	0.4	450	50	850	700	0
0.4OPC	0.4	360	40	900	800	0

1-In Saturated with dry surface condition, 2-In 48hr saturated with dry surface condition

All specimens were kept in laboratory condition and without any external curing. According to *BS EN 12350-9* [17], the plastic viscosity and filling ability of the self-compacting concrete has been evaluated with *V*-Funnel test which *EFNARC* [15] declares it as a criterion of passing ability and detachment strength evaluation. In this study, *L*-Box test has been carried out to evaluate (passing and filling ability and blockage possibility of the fresh concrete while encountering rebar. *J*-Ring test has also been utilized to investigate rheological characteristics of the studied mix designs [15].

The concrete volume changes, shrinkage, was measured 24 hours after removing the molds according to *ASTM C157* [18]. Modulus of elasticity has been measured in 28-day age of concrete according to *ASTM C215* [19].

To measure the permeability as an important criterion for concrete durability, 24h water absorption of the specimens in the 28-day age of concrete has been measured. Also, chloride penetration depth has been specified by spraying silver-nitrate ($AgNO_3$) on the internal surface of specimens were kept in water with 3 percent of *NaCl* solution for 28 days [20]. In order to investigate rebar corrosion potential, electrical resistance of the specimens in the age of 7, 28 and 60 days was measured and the corrosion potential against the reference saturated calomel electrode was recorded within 8 weeks after applying corrosion condition.

RESULTS AND DISCUSSION

The rheological properties of fresh concrete for the mentioned mixtures are shown in the [Table 2]. According to this [Table 2], as the water to cement ratio increases, Slump Flow and J-ring diameter increase accordingly.

Table 2: Rheological behavior of the studied mixes design

Test	Slump flow (*cm*)	*T50cm* (*s*)	*V*-Funnel (*s*)	*L*-box (*h ratio*)	*J*-ring (*mm*)
0.3SCC+10	70	4.5	9.5	0.9	7
0.3SCC+20	69	4	10.7	0.92	8
0.3SCC+30	68	5	11.5	0.85	9
0.35SCC+10	70	4.4	8.2	0.9	7
0.35SCC+20	71	5.1	8	0.85	8
0.35SCC+30	69	3.8	7.7	0.8	8
0.4SC C+10	73	4.1	10.2	0.93	3
0.4SCC+20	72	4.3	9.6	0.9	3
0.4SCC+30	70	4.8	9.1	0.85	4
0.3SCC	70	4.2	9	0.92	7
0.35SCC	72	4.5	8.5	0.88	5
0.4SCC	75	4	10.7	0.8	2

In order to evaluate the effect of internal curing on the compressive strength of the specimens, compressive strength test results at 7 and 28 days are displayed below [Fig. 3].

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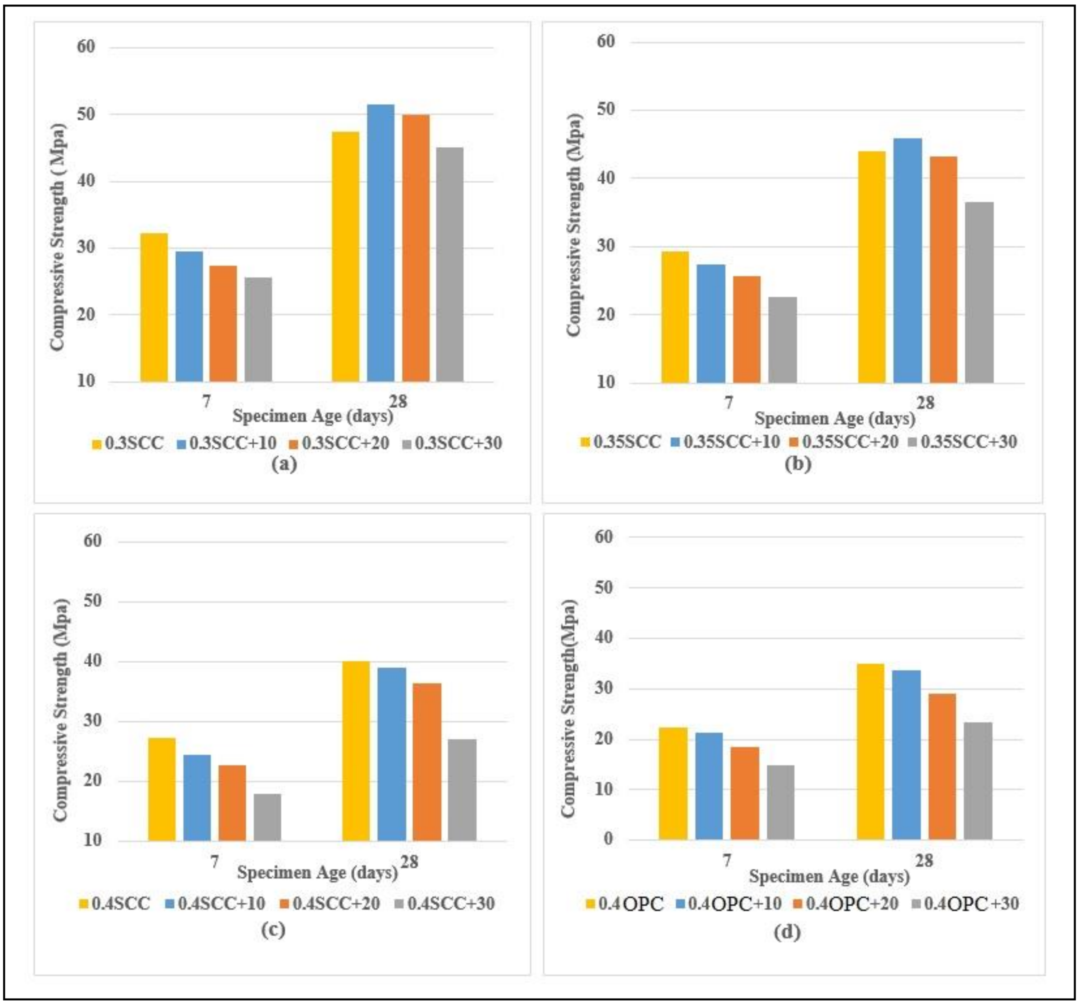

Fig. 3: Compressive Strength at 7 and 28 days of the specimens with different *w/c* ratio.

As shown in the [Fig. 3], in *w/c=0.3*, the maximum 7-day compressive strength belongs to the specimen without *LECA* and after that, there are specimens with 10%, 20% and 30% *LECA* content. Whereas in 28-day compressive strength, specimens with 10% *LECA* content had the highest compressive strength with about 8% of increase compared to the control specimen. After that, there are "*0.3SCC+20* and" and "*0.3SCC*". Meanwhile, the specimen with 30% *LECA* content has the minimum compressive strength. Thus, it can be stated that in *w/c=0.3* [Fig. 3(a)], internal curing can affect the compressive strength positively and can improve mechanical properties of concrete specimens in 28-day tests. While in 7-day tests, the effect of *LECA* usage is totally negative. The considering increase in compressive strength can be related to cement paste hydration and the improvements of the transition zone. As the lightweight content increases in concrete specimens, the decrease in the compressive strength seems to be overcoming the strength increasing due to cement phase hydration and the improvement of transition zone. This results repeated in the 30% *LECA* content specimen.

In *w/c=0.35* [Fig. 3(b)], *LECA* had a negative impact on compressive strength at the age of 7 days. However, 10% replaced *LECA*, increased compressive strength compared to control specimens at 28 days. But unlike *w/c=0.3*, in *w/c=0.35* replacing 20% of *LECA* with sand, had a negative effect on 28-day compressive strength.

According to the [Fig. 3(c)] for *w/c=0.4* ratio, internal curing of concrete has a reduction effect on compressive strength at 7 and 28 days. It seems that in *w/c=0.4* ratio, as the water content is increased compared to the previous specimens, less shrinkage strains is created and as a result, internal curing seems less necessary. By increasing *LECA* replacement with sand, not only the aggregate strength decreases, but also the result is like increasing water to cement ratio. Studying normal concrete with *w/c=0.4* has shown the same trend [Fig. 3(d)].

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The [Fig. 4] show tensile strength changes at 7 and 28 days.

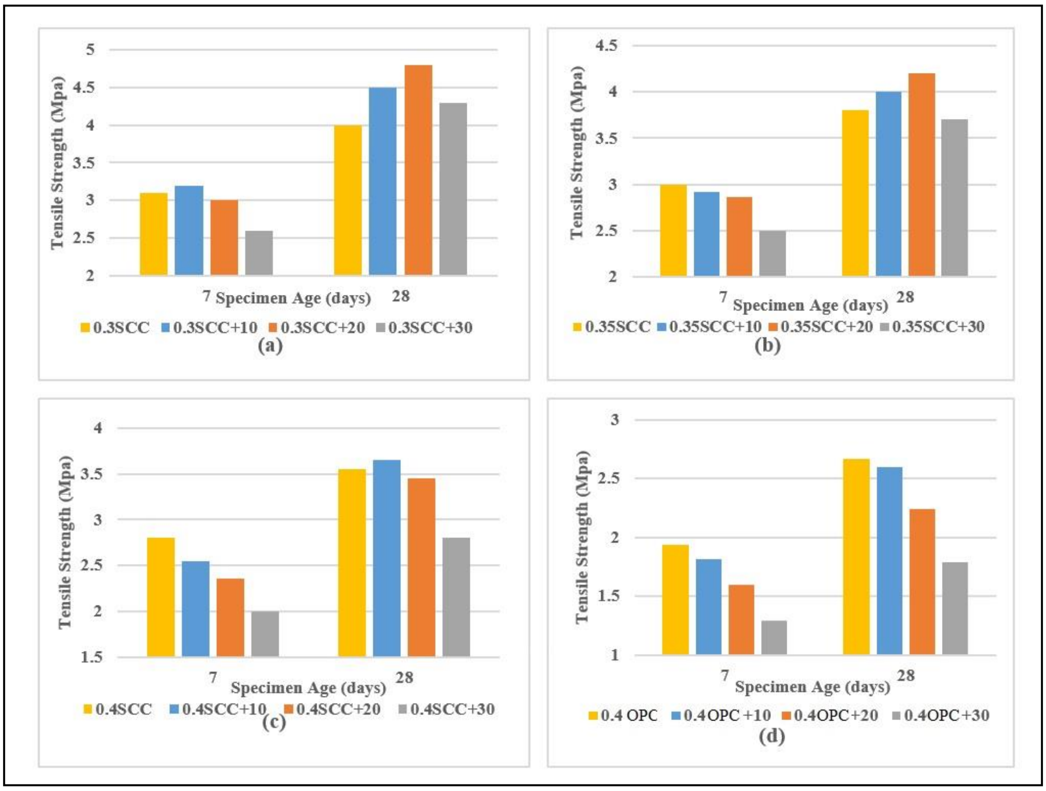

Fig. 4: Tensile strength at 7 and 28 days for of the specimens with different *w/c* ratio.

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In *w/c=0.3* [Fig. 4(a)], 10% *LECA* content specimen has the maximum tensile strength at the age of 7 days. Whereas the maximum tensile strength at 28 day is related to 20% *LECA* content specimen. The 30% *LECA* content shows the minimum tensile strength at 7 days and the control specimen shows the lowest tensile strength at the age of 28 days. The most important reason for such increase in tensile strength as a result of internal curing is the decrease of the micro cracks creation in cement paste due to the decrease of shrinkage strains. The maximum tensile strength in *w/c=0.35* ratio [Fig. 4(b)] and at the age of 7 days is related to the control specimen. Totally, *LECA* has a negative impact on the concrete at 7 days. But with comparing the tensile strength results at 28 days, positive effect of internal curing is obvious in 10% and 20% *LECA* replacement. Also, 30% *LECA* content has a tensile strength similar to the control specimen. In the mixes with 10% and 20% *LECA* content, within 5% and 10% increase of tensile strength can be seen respectively.

In *w/c=0.4* [Fig. 4(c)], tensile strength results have a decreasing trend at 7 days, same as the results in *w/c=0.35*. Also, in this water to cement ratio, internal curing effect seems to be less efficient in 28- days tensile. Therefore, it can be stated that generally, internal curing has a positive impact on tensile strength but the actual appreciable increase occurs in the water to cement ratios less than 0.4. No efficient effect of internal curing on tensile strength was observed in Normal Concrete specimen with *w/c=0.4* [Fig. 4(d)]. Measured dynamic modulus of elasticity are shown in [Fig. 5]. It can be understood from the result that, in the specimens with *w/c=0.35* ratio the maximum amount of E_c is gained in the 10% *LECA* content specimen and after that stands the specimen with 20% *LECA* content. Whereas the 30% *LECA* content specimen has the least amount of E_c. It can be seen from the figures that the modulus of elasticity and compressive strength changes follow the same trend. According to this, improvements in internal hydration and the decrease of micro-cracks creation in cement paste (especially in transition zone) can be stated as the main reason for this changing trend.

Also, in *SCC* specimen with *w/c=0.35* and *w/c=0.4* ratios, the control specimen has the maximum amount of E_c and replacing lightweight aggregate with sand, results in modulus of elasticity decrease. Finally, the 30% *LECA* content mixture has the minimum E_c in all water to cement ratios.

Shrinkage strain changes of insulated specimen from a day after concrete production until the age of 28 days are shown in [Fig. 6]. According to [Fig. 6(a)], internal curing has a considerable effect on shrinkage decrease of *SCC* concrete with *w/c* equals to 0.3. As the maximum shrinkage is recorded for the control specimen with 700 micro-strains. Shrinkage has decrease as the more lightweight is replaced with the sand in a way that, in 10% *LECA* content mixes, 400 micro-strains and in 20% *LECA* content, around 300 micro-strains were observed in the first few days. The shrinkage in these specimens has decreased to the amount of 150 micro-strains at 28 days which has totally decreased 550 micro-strains compared to the control specimen.

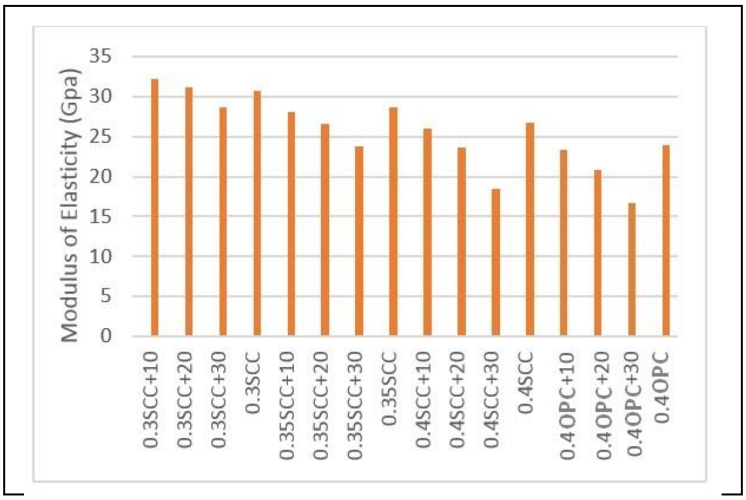

Fig. 5: Modulus of Elasticity of the concrete specimens at the age of 28 days.

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In [Fig. 6(b)] it can be seen that the maximum amount of shrinkage is about 560 micro strains and it's for the control specimen with *w/c=0.35* and similar to the previous statements, the more lightweight aggregate is added to the mixes, the more shrinkage decreases. The 30% *LECA* content specimen had a longitudinal increase of 150 micro-strains, during the first 4 days and in the end, not only shrinkage has been completely eliminated as at the age of 28 days, but also 50 micro-strains of longitudinal increase has been observed.

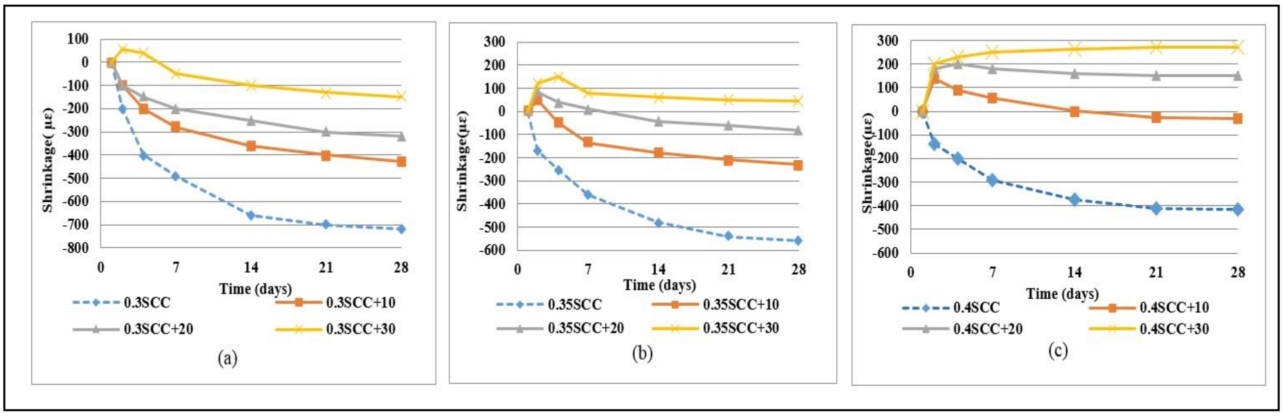

Fig. 6: Shrinkage strain variation for specimens with different ratio of w/c.

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Twenty-four hour water absorption results are shown in [Fig. 7]. According to this, water absorption in specimens with *w/c=0.3*, was less than the other specimens which is due to denser structure of hydrated cement paste in low water to cement ratios and less permeability of the specimens.

Also, replacing *LECA* in the specimens with the water to cement ratio of less than 0.4, has a more positive effect on water absorption decrease. In lower water to cement ratios, hardened cement paste faces lack of water and self-desiccation occur due to hydration reactions. Therefore, the lower the *w/c* ratio gets, the more internal curing seems to be necessary and its positive impacts on the concrete features take over its negative ones. Normal concrete specimens show more water absorption than the *SCC* in *w/c=0.4*. Actually, *SCC* shows less permeability due to its more compact micro structure. Also, in *w/c=0.4*, replacing 20% and 30% sand with *LECA* had a negative effect on concrete permeability. Normal concrete seems more sensitive to this because of its lower volume of cement paste.

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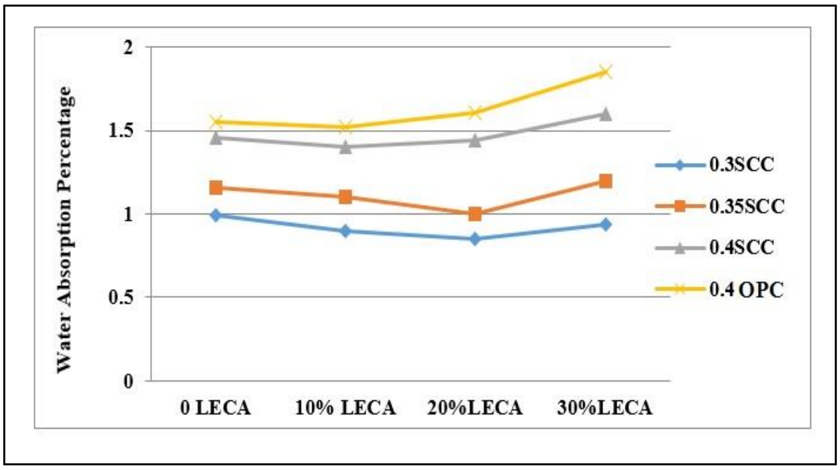

Fig. 7: The water absorption of concrete specimens.

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The depth of chloride ion penetration in all of the specimens after 28 days of being in *NaCl* water solution, has been measured and illustrated in [Fig. 8]. According to this figure, in lower ratios of water to cement, the depth of chloride ion penetration was also less which shows denser micro structure of hardened cement paste and its less permeability due to discrete internal pore network in concrete body.

Among all of the specimens with *w/c=0.3*, the 20% *LECA* content seems to have the minimum amount of penetration depth. Control specimen has the maximum amount of penetration depth with about 6mm of infiltration. The results represent the positive effect of internal curing on decreasing the permeability in this w/c ratio. In *w/c=0.35*, the specimen with 10% *LECA* content had the minimum amount of chloride penetration depth and the maximum amount goes to the specimen with 30% *LECA* content.

In *SCC* specimens with *w/c= 0.4*, 10% *LECA* content specimen has the minimum penetration depth of 8mm and the 30% *LECA* content has the maximum amount of 12*mm*. Although the general trend of the changes in normal concrete is similar to *SCC*, they have higher amounts of infiltration due to their more porous micro structure.

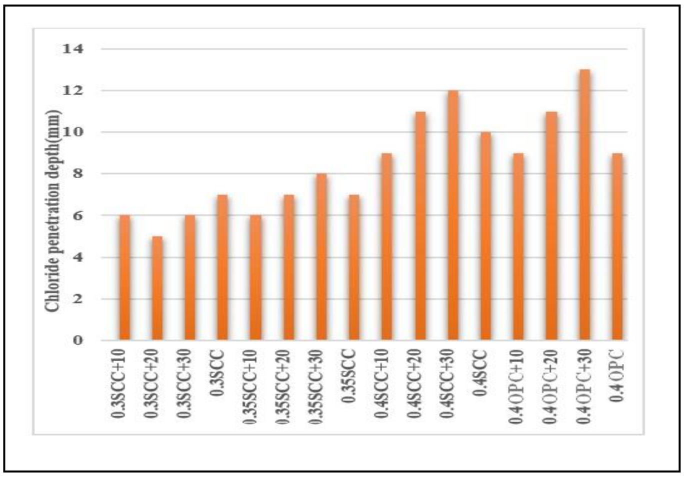

Fig. 8: Chloride penetration depth after 28 days.

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Electrical resistivity of the specimens has been measured at 7, 28 and 60 days in order to evaluate the quality of internal pore network of concrete and investigate of the internal curing effect. In w/c=0.3 ratio [Fig. 9(a)], specimens with LECA have been observed to have less amount of electrical resistivity at 7 days compared to the control specimen. This trend has changed at 28 days in a way that, the 20% LECA content specimen had the maximum amount of electrical resistivity while the control specimen was the least resistant of all. This trend kept on at 60 days but the amount got larger. While studying the electrical resistivity diagram, in w/c=0.35 [Fig. 9(b)], control specimen had the maximum amount of electrical resistivity at 7 days. At the age of 60 days, the specimen which contains 20% LECA showed 25% increase in electrical resistivity compared to the control specimen. After that, there are 10% and 30% LECA content specimens which had an increase of 14% and 4% respectively compared to the control specimen. As the water to cement ratio rises, electrical resistivity decreases gradually which is because of the porosity increase (as the saturated and semi- saturated internal pore network gets more and also more continuous and the electrons can move easier inside pore electrolyte liquid) and the permeability of cement paste

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increases as a result. Thus, less amount of electrical resistivity can be seen for the specimens with w/c=0.4 [Fig. 9(c)], than the ones with w/c=0.3 and w/c=0.35 ratios.

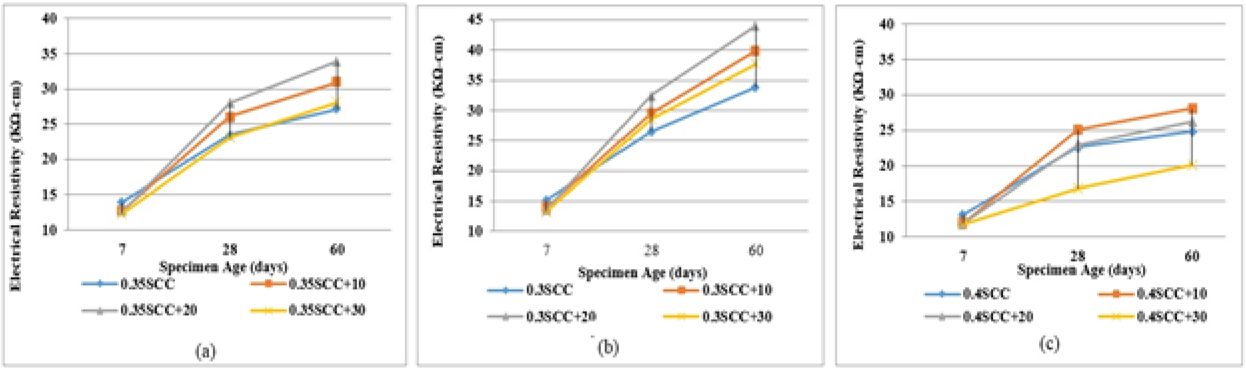

Fig. 9: Electrical resistivity of concrete specimens.

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CONCLUSION

In addition to decreasing shrinkage, internal curing of concrete by hydration of unhydrated cement particles can have a positive effect on the mechanical properties of concrete. On the other hand, replacing too much of lightweight aggregate with sand, can result in a reduction in mechanical properties. So, it is necessary to determine the optimal proportions of lightweight aggregate replacement in the mix design by measuring absorption features of the aggregates. The gained results represent positive impact of internal curing on decreasing permeability of concrete elements. Based on the obtained results, the following can be concluded:

-Internal curing had different effects on the mechanical properties, modulus of elasticity and permeability of the concrete depended on the amount of lightweight content and the water to cement ratio. These effects are depended on the curing duration as the short-term effect is negative but the long-term effect shows a total positive trend.

-Internal curing decreased the permeability of the concrete specimens.
-As the permeability of the specimens decrease, electrical resistivity of the specimens increase, especially in low water to cement ratios mixtures.
-Internal curing was more effective on *SCC* than *OPC* concrete in all aspects of concrete volume changes, permeability and mechanical properties.

CONFLICT OF INTEREST

Authors declare no conflict of interest.

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