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EFFECT OF PRE-SOAKED LIGHT EXPANDED CLAY AGGREGATE ON STRENGTH, DURABILITY AND FLEXURAL BEHAVIOUR OF HIGH-PERFORMANCE CONCRETE

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Abstract

The strength and durability requirements of high-performance concrete cannot be satisfied without proper curing. Relatively low permeability achieved through the presence of highly reactive pozzolanic additives along with low water-cement ratio can reduce the effectiveness of external curing and this has a negative effect on the strength and durability of high-performance concrete. In the construction industry, the normal field practice in most cases is providing external water curing for seven days, which is insufficient for effective hydration. Internal curing is an effective solution, which can enhance the hydration process and improve the concrete properties. Internal curing can be achieved using porous lightweight aggregates as an internal curing agent. This study investigates the effect of pre-soaked light expanded clay aggregate on strength, durability and flexural behaviour of high-performance concrete. Pre-soaked light expanded clay aggregate was added by replacing 10, 15, 20 and 25 percentages of coarse aggregate volume. The 15% replacement gave a maximum increase in strength of 17.5% at 28 days and this percentage was taken as the optimum based on which, further studies were carried out. Split tensile strength showed a slight decrease whereas flexural strength increased with the incorporation of LECA. Durability studies such as chloride penetration test, water permeability test and water absorption test were conducted, which showed better performance compared to mix without aggregate replacement. Flexural behaviour of RCC beams also improved with aggregate replacement. The 9.2% weight reduction was attained for 20% volume replacement maintaining the strength requirement.

Keywords: Durability, Flexural behaviour, High-performance concrete, Internal curing, Light expanded clay aggregate, Lightweight aggregates, Strength.

1. Introduction

High-Performance Concrete (HPC) is preferred than conventional concrete in situations where both strength and durability requirements need to be satisfied. HPC mixture is composed of low water-cement ratio, high cement content, highly reactive pozzolanic materials like silica fume and superplasticizers to achieve the desired workability. The major characteristic of such type of concrete is its dense structure of hydrated cement paste with discontinuous capillary pore system [1]. Since HPC follows a low water-cement ratio ranging from 0.2 to 0.38 [2], the mixing water is inadequate to hydrate all cementitious materials. Neville [1] mentioned that effective hydration on the surface of the concrete by readily available moisture makes it become impermeable and leaving unhydrated cementitious grains in the inside. The hydration of these unhydrated grains can impart higher strength to concrete.

The disconnected capillary pore network in HPC causes a reduction in water permeability even in 2-3 days. It prevents the water from entering the interior of concrete, which leads to self-desiccation and causes early age cracking due to autogenous shrinkage [2]. In HPC, internal curing is an effective solution and can be achieved through the distribution of adequate moisture content inside the concrete. In this method, extra water content other than the mixing water is retained inside the concrete using certain curing agents or Light Weight Aggregates (LWAs). LWAs have a porous structure and can effectively be used in internally curing the concrete [3]. These LWAs are pre-soaked to ensure the desired degree of water absorption and are added to the concrete. The presence of non-evaporable water retained in the LWAs contributes to a higher degree of hydration [4]. The water retained in the relatively larger pores of LWAs is naturally drawn into the smaller pores of the cement paste, which enhances the hydration process [5]. In addition, pre-saturated LWAs delays the relative humidity drop-in concrete and hence mitigate the formation of early cracking due to autogenous shrinkage [6, 7]. The nature of LWA itself has a contribution to the strength development of concrete. Cement paste surrounding the LWA infiltrate into the surface pores and bonds tightly. According to Lo and Cui [8], these well-bonded interfacial zones of LWAs also constitute high strength development.

Light Expanded Clay Aggregate (LECA) is one of the easily available LWA, which can be used for producing structural lightweight concrete. Manufactured LECA is also used for hydroponics. It has a porous structure and relatively lower density among the various artificial LWAs. This study investigates the application of pre-soaked LECA as an internal curing agent and its effect on strength, durability and flexural behaviour of HPC. This aggregate is added to the concrete by replacing an equal volume of coarse aggregate.

2. Research Significance

External curing practices are sometimes inadequate under field conditions. The unsatisfactory curing practices can badly affect the strength and durability of concrete. For high-performance concrete having a low water-cement ratio and containing reactive pozzolanic materials, the low permeability of the concrete does not allow external water to percolate inside. In addition, due to the low water content present in the concrete, there is a sudden decrease in the internal humidity as hydration progress. This causes the formation of shrinkage cracks. In the case of such concrete with low water-cement ratio and pozzolanic materials, the external curing may not give an expected performance. Internal curing using lightweight aggregate along with external curing for a shorter period can be easily practised, which gives better strength and durability to concrete. In addition, substituting the coarser fraction of aggregates with lightweight aggregates reduces the weight of concrete.

3. Experimental Methods

3.1. Materials and mix proportion

The cementitious materials for this study include Ordinary Portland Cement of 53 grade conforming to IS 12269 [9] (having specific gravity of 3.15, fineness of 7.33%, initial setting time of 145 minutes and final setting time of 350 minutes) and silica fume (with specific gravity of 2.63) in which, more than 95% of silica is in non-crystalline state. Locally available manufactured sand (with specific gravity of 2.67, fineness modulus of 2.69, bulk density of 1847 kg/m^3 and 24 hour water absorption of 1.6 %) as fine aggregate and crushed stone (with specific gravity of 2.71, fineness modulus 6.99 and bulk density 1564 kg/m^3 and 24 hour water absorption of 0.45 %) as coarse aggregate were used. The superplasticizer used was CONPLAST SP430 of sulphated naphthalene formaldehyde condensate type having a specific gravity of 1.2.

Coarse sized Light Expanded Clay Aggregate (LECA) (6-16 mm size, a specific gravity of 0.685, fineness modulus 6.64 and bulk density 368 kg/m^3) was used as lightweight aggregates for this study. This lightweight aggregate is made by heating clay pellets in a rotary kiln at a temperature of 1200 ^{0}C where it expands and converts into ceramic nature and does not undergo any volume change when soaked in water. The product obtained consists of a harder outer layer and spongy inner structure. The multi-separated air spaces existing inside the aggregate makes it lightweight and water absorbent. Figure 1 shows the LECA used for this study.

The total cementitious content adopted for all the mixes was 400 kg/m^3 including 3% silica fume. Water cement ratio adopted was 0.38 and dosage of superplasticizer was adjusted to 1.2% of the weight of cement to obtain workability of 80 mm slump. Mix design was based on IS 10262 [10]. Five concrete mixes were prepared for this study. The various mixture proportions adopted for this study are tabulated in Table 1. M0 is the control mix and M1, M2, M3, M4 are the mixes having equivalent volume replacement of coarse aggregate with pre-soaked LECA at 10, 15, 20 and 25 percentages respectively.

Table 1. Mixture compositions (kg/m^3) used for the study.

Mix no.	Cement	Silica fume	Water	Fine aggregate	Coarse aggregate	LECA	Superplasticizer
M0	388	12	150	702	1230	-	4.8
M1	388	12	150	702	1107	28.94	4.8
M2	388	12	150	702	1045.5	43.41	4.8
M3	388	12	150	702	984	57.88	4.8
M4	388	12	150	702	922.5	72.35	4.8

Fig. 1. Light expanded clay aggregate (LECA).

3.2. Curing

Internal curing can improve the inner structure of concrete. However, without proper external curing, the durability of the concrete surface may get affected. The less hardened and dusty outer surface of concrete may become prone to abrasive or erosive action. The practice of both external and internal curing can improve the strength and durability of concrete. Therefore, in order to satisfy the performance requirements, all the five mixes were given 7 days of external water curing followed by air curing until the day of testing to simulate actual field during practice. The efficiency of internal curing can be tested if external water curing is withdrawn after 7 days, which is the practice in actual construction.

3.3. Testing procedure

3.3.1. Aggregate crushing value

Other than being inert filler, the resistance of the aggregates to crushing load contributes to the overall strength of concrete. It is necessary to determine the crushing value of lightweight aggregates used and its various combinations with coarse aggregate to know the behaviour under gradually applied compressive load. Aggregate crushing value tests were conducted as per IS: 2386 - Part 4 [11] on representative samples of coarse aggregate and LECA corresponding to each replacement percentages of LECA from 0 to 100 % at 10% increment.

3.3.2. Strength tests

Compressive strength test at the age of 7, 28, 56 and 90 days were performed on concrete cubes (size 150 × 150 × 150 mm) as per IS: 516 [12]. From compressive strength test results obtained from all mixes, the optimum mix was chosen based on the maximum strength obtained corresponding to 28 days.

Split tensile strength, flexural strength and bond strength of mix M0 with no LECA and the optimum mix were determined at the age of 28 days. Split tensile strength tests were conducted on cylindrical specimens (size 150 mm diameter and 300 mm length) as per IS: 5816 [13]. Flexural strength tests were conducted on PCC and RCC beam specimens (size 100 × 100 × 500 mm) under two-point loading as per IS: 516 [12].

Bond strength test was conducted as per IS: 2770 - Part I [14]. Bond strength was determined as the resistance offered by the bonding force between concrete cubes (size 150×150×150 mm) and embedded ribbed bar of 16 mm diameter when the bar was pulled out from the cube using the universal testing machine. Figure 2 shows the bond strength test conducted using Universal Testing Machine.

Fig. 2. Bond strength test.

3.3.3. Durability tests

Durability testing includes rapid chloride permeability, water permeability and water absorption test. Rapid Chloride Penetration Test (RCPT) was done to measure the resistance of concrete to chloride ion penetration. Concrete disc specimens (size 100 mm diameter and 50 mm length) were subjected to RCPT as per ASTM C 1202 [15] at the age of 56 days (as shown in Fig. 3).

Water permeability and water absorption of concrete were tested on cube specimens (size 150 × 150 × 150 mm). Water permeability test was done as per DIN 1048 - Part 5 [16]. After 56 days of hardening, 5 bar water pressure was applied on the cube surface other than the cast face for a period of 3 days and average and a maximum depth of penetration were measured. Figure 4 shows the water permeability test done on concrete cubes.

Water absorption test was done on concrete cubes after 28 days as per ASTM C 642 [17]. The percentage of water absorption was measured after oven drying and subsequent immersion in water for 48 hours.

Fig. 3. Rapid chloride penetration test.

Fig. 4. Water permeability test.

3.3.4. Flexural behaviour of RCC beam

Simply supported RCC beams (of cross-section 150 mm × 200 mm and 1200 mm length) were designed as under reinforced section according to IS: 456 [18] and subjected to flexural failure. The reinforcement details are shown in Fig. 5. Expected maximum load as per calculation was 105 kN. Beams were tested as simply supported under two-point loading over an effective span of 1000 mm. Load was applied uniformly and deflection recorded at mid-span and quarter span corresponding to 10 kN increment. In addition, initial cracking load and ultimate load of specimens were noted for comparison. The experimental setup for determining the flexural behaviour of RCC beams is shown in Fig. 6.

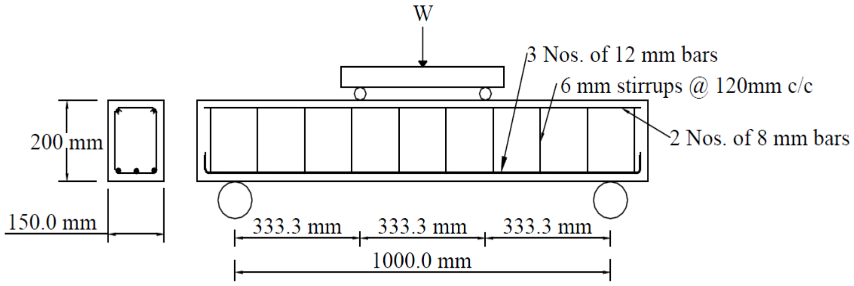


Fig. 5. Reinforcement details of beam.

Fig. 6. Experimental setup for determining flexural behaviour of RCC beams.

3.3.5. Weight reduction

Weights of concrete cubes were measured at 28 days, keeping the specimens under room condition after 7 days of water curing. Any significant reduction in weight of concrete by the addition of LECA can be verified by comparing the weight of normal mix M0 with mixes having various percentages of LECA.

4. Results and Discussions

4.1. Aggregate crushing value

Aggregate crushing value test results obtained for various combinations of coarse aggregate and LECA are presented in Fig. 7. The crushing value obtained for coarse aggregate is 25% and LECA is 84%. From the curve, it is clear that the variation of slope remains slightly changed up to 50% replacement. Increased percentage of LECA decreases the crushing resistance of coarse aggregates due to its high crushing value. As per IS 383 [19], aggregate having a crushing value up to 40% can be used for structural purposes and that up to 30% can be used for wearing surfaces. From the figure, it is clear that safe replacement is possible up to 50% of coarse aggregate volume for use in structural purposes.

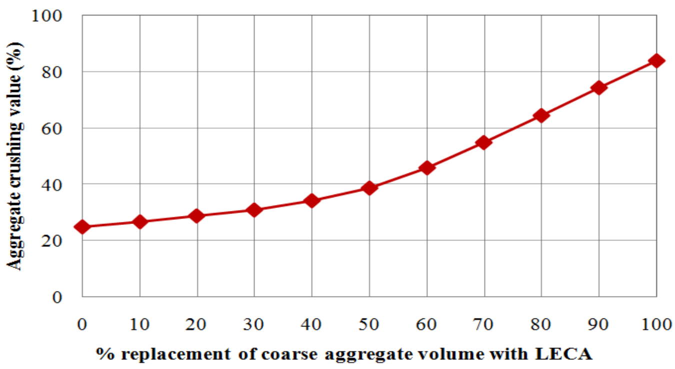


Fig. 7. Aggregate crushing value test results.

4.2. Strength tests

4.2.1. Compressive strength

Compressive strength obtained for various mixes are represented in Fig. 8. M1, M2, M3 mixes with 10, 15 and 20% LECA obtained an increased compressive strength than control mix M0. M4 mix with 25% LECA is less efficient to meet the required strength. Twenty-eight days compressive strength of M1, M2 and M3 mix showed an increment of 7.5%, 17.5% and 9.4% respectively as compared to M0. This type of improvement agrees with the findings of Dayalan and Buella [20]. Therefore, M2 mix with 15% LECA, which obtained maximum compressive strength, was selected as optimum. For the case of M1, M2 and M3 mix the internal moisture availability through pre-soaked LECA resulted in enhanced curing, which increased the strength of concrete. In M4 mix with an increased percentage of LECA, the effect of low crushing strength of LECA decreased the strength of concrete by crushing through the aggregate phase. Up to 20% LECA, the internal curing ability attained through pre-soaking counteracts the effect of porous and crushing aggregates while internal curing through an increased percentage of LECA cannot compensate the strength loss due to excessive crushing of aggregates. Table 2 shows the strengths obtained at different ages.

Figures 9(a) to (c) shows the failure surface of concrete cubes representing M0, M2, and M4 mixes respectively. By observing the colour of failure surfaces, it can be understood that more hydration has occurred in mixes containing lightweight aggregates.

Table 2. Compressive strengths obtained for different ages (N/mm^2).

Mix	7 days strength	28 days strength	56 days strength	90 days strength
M0 (0% LECA)	36.66	47.55	49.77	52
M1 (10% LECA)	37.62	51.11	54.07	60.44
M2 (15% LECA)	39.55	55.85	61.77	64
M3 (20% LECA)	37	48.59	52	55.11
M4 (25% LECA)	32.88	39.85	45.03	47.55

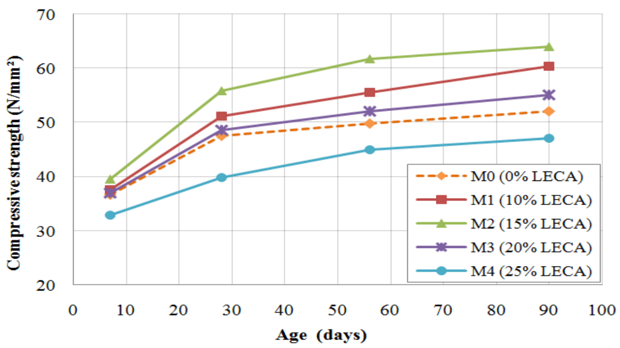
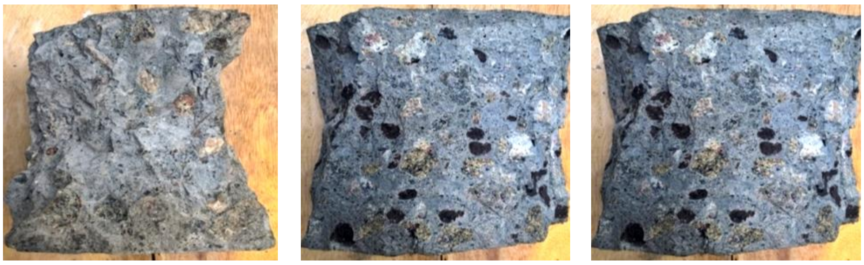


Fig. 8. Compressive strength of mixes measured at different ages of concrete.



(a) (b) (c)

Fig. 9. Failure surface of concrete cubes: (a) M0 mix, (b) M2 mix, (c) M4 mix.

4.2.2. Split tensile strength and flexural strength

Comparing the 28 days split tensile strength of control mix M0 and optimum mix M2, the tensile strength of M2 mix with 15% LECA decreased by 2.4%. Unlike the compressive strength of the mix, the tensile behaviour of concrete was reduced. This can be due to the porous nature of LECA, which permits the propagation of a split plane through the aggregate. Table 3 gives the split tensile strengths obtained at 28 days. Tables 4 and 5 shows the flexural strengths obtained for PCC and RCC beams respectively.

Variations in 28 days flexural strength were found out in the case of both PCC and RCC specimens of M2 mix from M0 mix. Flexural strength of M2 mix showed an increment of 3.5% for PCC specimens and 4.2% for RCC specimens.

Table 3. 28 days split tensile strength (N/mm^2).

Mix	Strength	% decrease
Normal	4.385	-
15% LECA	4.279	2.4

Table 4. 28 days flexural strength on PCC beam (N/mm^2).

Mix	Strength	% increase
Normal	6.2	-
15% LECA	6.42	3.5

Table 5. 28 day flexural strength on RCC beam (N/mm^2).

Mix	Strength	% increase
Normal	21.6	-
15% LECA	22.5	4.2

4.2.3. Bond strength

From the test conducted on M0 and M2 concrete, bond strength increased by 7.26% for M2 concrete with 15% LECA. This rise in bond strength developed can be attributed to hardening of cement paste surrounding the reinforcement bar. Thus, the distribution of internal moisture through LECA is effective in developing bond strength in structural members. Table 6 shows the bond strengths for mixes.

Table 6. 28-days bond strength (N/mm^2).

Mix	Strength	% increase
Normal	3.99	-
15% LECA	4.28	7.26

4.3. Durability tests

4.3.1. Rapid chloride permeability

The chloride ion penetration is obtained by measuring the current passed through the concrete at various time intervals. Figure 10 presents the plot of current passed (in milliampere) at various time intervals for M0 and M2 concrete. M2 concrete obtained reduced chloride ion conductivity than M0. The total charge passed for 6 hour period was 1446.3 coulombs for M0 concrete and 1287.9 coulombs for M2 concrete. As per ASTM specifications, concrete having charge passage between 1000 and 2000 coulomb falls under low chloride ion penetration category. The reduced chloride ion permeability of M2 concrete can be attributed to the formation of strong inter transition zone around lightweight aggregate due to improved hydration, which resisted the passage of chloride ions through the otherwise weak zone. Zhutovsky and Kovler [21] reported that reduction in chloride penetration for concrete having lightweight aggregate.

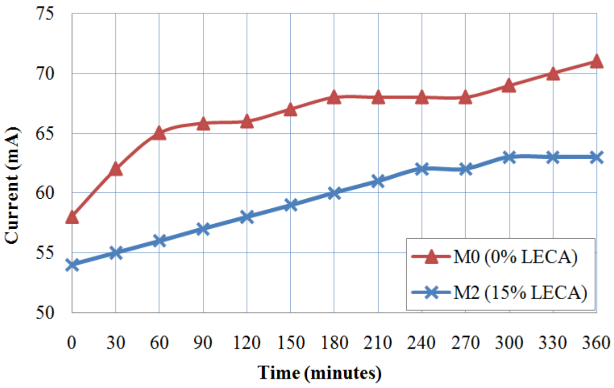


Fig. 10. Current passed through concrete at various time intervals.

4.3.2. Water permeability

From the water permeability, test on concrete cubes, the average water penetration measured was 17.6 mm for M0 and 10 mm for M2 concrete. In addition, the maximum penetration depth obtained was 26 mm for M0 and 20 mm for M2 concrete. The test result shows that the permeability of concrete was decreased in internally cured specimens. A similar type of performance was reported by Chia and Zhang [22]. From the result, it is understood that even though LECA has a porous structure, it does not contribute to water permeability of concrete incorporated with the lightweight aggregate. This can be attributed to the non-interconnectivity of pores of LECA as well as the formation of a strong inter transition zone. Table 7 shows the depth of water permeability obtained at 56 days.

Table 7. Water permeability at 56 days.

	Normal	15% LECA
Average depth of penetration (mm)	17.6	10
Maximum depth of penetration (mm)	26	20

4.3.3. Water absorption

Figure 11 shows the water absorption results for various mixes. Water absorption showed a decreasing trend up to M2 mix with 15% LECA. Up to 15% LECA, the water absorption decreased due to low permeability. From M2 to M4 mix, water absorption showed a linearly upward variation. At high percentage addition of LECA, the absorption characteristics of LECA become predominant.

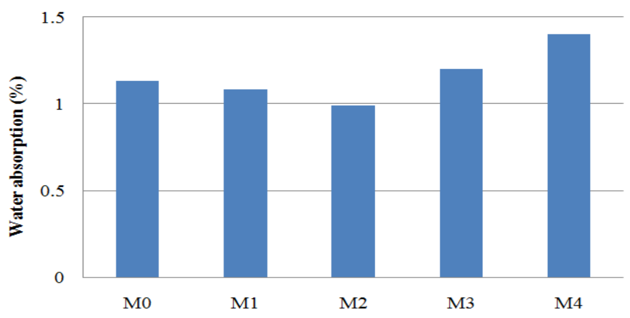


Fig. 11. Water absorption results obtained for various concrete mixes.

4.4. Flexural behaviour of RCC beams

Flexural tests were performed on beams with M0 and M2 mixes at the age of 28 days. The initial crack load and ultimate load obtained for both the beams is shown in Table 8. The initial cracking load and ultimate load of M2 beam increased by 6%.

Table 8. Initial cracking load and ultimate load of specimens.

Mix	Initial cracking load (kN)	Ultimate load (kN)
M0	33	140
M2	35	149

Figure 12 shows the load vs. average mid-span deflection of the beams tested. Beams of M2 mix obtained slightly lesser deflection compared to M0 mix.

Even though compressive strength increased considerably for concrete with LECA, there was only marginal improvement in tensile strength and flexural strength of small PCC and RCC beams. The same type of behaviour is observed in this case also. Figure 13 shows the crack pattern of beams tested.

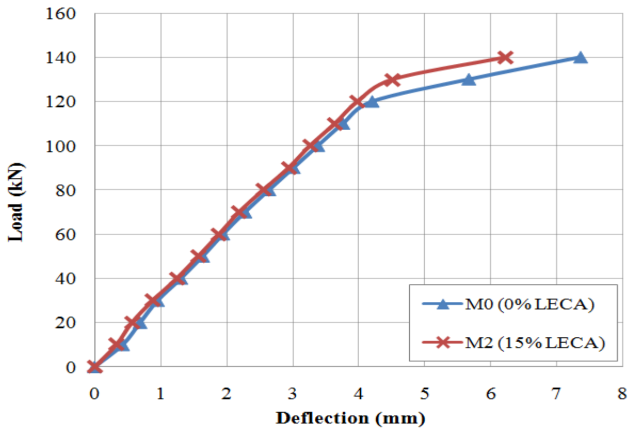


Fig. 12. Load vs average mid-span deflection of beams tested.

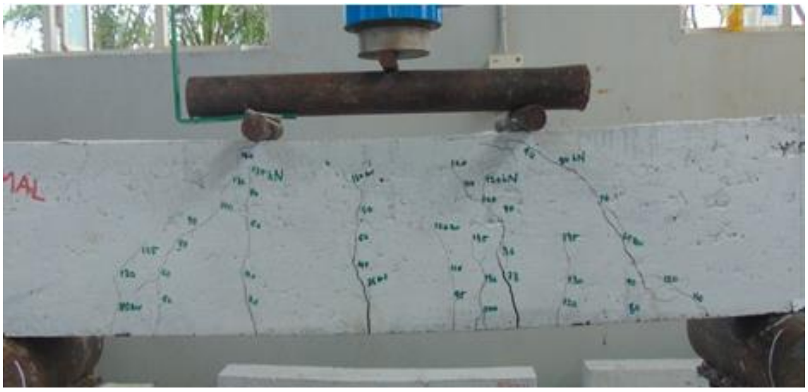


Fig. 13. Crack pattern of beam tested.

4.5. Weight reduction

The bulk density of LECA is around 70% lesser as compared to crushed stone aggregate. By partially replacing the volume of coarse aggregate with LECA, it is possible to obtain a considerable reduction in the self-weight of concrete. Figure 14 shows the percentage weight reduction of concrete corresponding to various replacements of coarse aggregate with LECA. From the compressive strength results, the strength of concrete with LECA is greater than normal concrete up to 20% replacement. Considering the strength requirement of concrete, 20% volume of coarse aggregate can be safely replaced with pre-soaked LECA and it showed a weight reduction of 9.2%. 15% replacement showed a weight reduction of 7.3%.

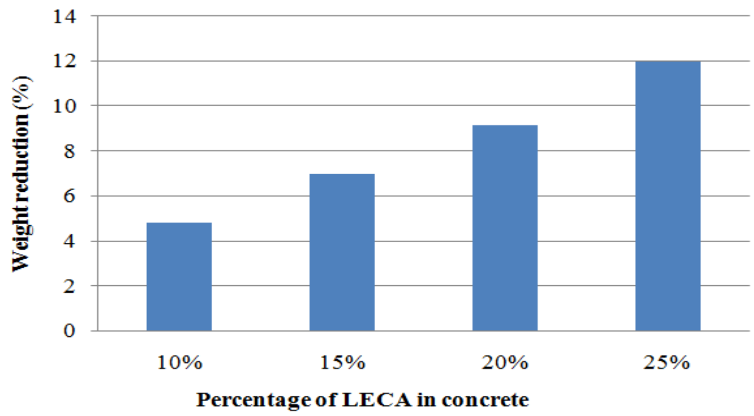


Fig. 14. Weight reduction of concrete obtained corresponding to various percentage replacements of coarse aggregate with LECA.

5. Conclusions

This experimental study leads to the following conclusions.

- Internal curing using pre-soaked LECA replacing coarse aggregate volume up to 20% is an effective method of curing concrete. At higher replacement levels, the lower crushing strength of LECA resulted in decreased strength of concrete.
- Considering the various replacement percentages (10, 15, 20 and 25%) of LECA, internal curing is most effective in a mix with 15% LECA. Concrete with 15% LECA obtained an increased 28-days compressive strength of 17.5% and also showed an increased variation at later ages when compared to normal.
- Unlike compressive strength, the split tensile strength of concrete with 15% LECA was slightly decreased. Concrete with 15% LECA obtained a small increase in the flexural strength. Even though the internal curing effect of LECA increases the strength, the brittleness of LECA can negatively affect the tensile properties of concrete. This may be the reason, which prevents the concrete from developing a higher tensile strength.
- In concrete with 15% pre-soaked LECA, better bonding has developed between the cement paste and reinforcement as a result of internal curing. Hence, the bond strength increased by 7.26%.
- Internal curing obtained through pre-soaked LECA slightly decreases the chloride ion permeability, water permeability and water absorption of concrete. The porous nature of LECA has no significant effect on the durability characteristics of concrete up to the optimum replacement level.
- RCC beams tested with pre-soaked LECA obtained a slight increase in load-carrying capacity along with lesser deflection. Therefore, application of LECA as an internal curing agent in structural members compensates the reduction in external curing period.
- 20% replacement of coarse aggregate volume with LECA gives a weight reduction of 9.2% along with satisfying the strength requirements of concrete.

- Future works can be carried out by adding fibre reinforcement in concrete containing LECA as tensile and flexural strengths have not shown considerable improvement compared to improvement in compressive strength.

Abbreviations	
ASTM	American Society for Testing and Materials
DIN	Deutsches Institut
HPC	High-Performance Concrete
IS	Indian Standards
LECA	Light Expanded Clay Aggregate
LWA	Light Weight Aggregate
PCC	Plain Cement Concrete
RCC	Reinforced Cement Concrete

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