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COMPARATIVE STUDY ON THE EFFECT OF LIGHTWEIGHT AGGREGATES ON THE PROPERTIES OF HIGH PERFORMANCE CONCRETE

PRADEEP P.[1,*], BEENA MOL[2]

[1]Department of Civil Engineering, Noorul Islam University,
Thukkulai, Kanyakumari, Tamil Nadu, India
[2]Department of Civil Engineering, LBS College of Engineering
(Government of Kerala Undertaking), Kasargode, Kerala, India
*Corresponding author: ppradeepadr@gmail.com

Abstract

Present curing practice in the construction industry is to provide external water curing for concrete up to 7 days followed by air curing at ambient temperature, which is insufficient for the attainment of high performance for concrete. Internal curing using pre-wetted lightweight aggregates can improve the properties of concrete and at the same time reduce its self-weight leading to the economy in construction. This paper presents a comparative study on the strength, durability, flexural behaviour and weight reduction of high-performance concrete incorporated with two types of Lightweight Aggregates (LWA) as internal curing agents. Type I concrete used Sintered Fly Ash Aggregate (SINTAG) and type II concrete used Light Expanded Clay Aggregate (LECA) as internal curing agents. In both types of concretes, the normal coarse aggregate was replaced with 10, 15, 20 and 25 percentages of lightweight aggregates by volume. The maximum increase in compressive strength of 29.5% compared to normal concrete was observed at 20% replacement for concrete incorporated with SINTAG, whereas maximum increment in compressive strength of 17.5% was observed at 15% replacement for concrete incorporated with LECA at 28 days. Tensile strength showed an increment of 2.6% for concrete having SINTAG whereas 2.4% decrease was observed for concrete having LECA. Flexural strengths for both types of concrete showed an increment with respect to normal aggregate concrete. Durability studies included Rapid Chloride Penetration Test (RCPT) and water permeability test. Resistance to chloride penetration was slightly less for SINTAG concrete whereas that for LECA concrete was slightly more compared to normal concrete. Results of water permeability for both types of concrete showed an improvement compared to normal concrete. Flexural behaviour of RCC beams for both types of concrete showed a slightly better performance compared to normal concrete. While maintaining the strength requirements of concrete, a weight reduction of 7.1% was attained for SINTAG concrete whereas, that for LECA concrete was 9.2% compared to normal concrete.

Keywords: Concrete durability, Flexural behaviour, High performance concrete, Internal curing, Lightweight aggregates, Lightweight concrete, Light expanded clay aggregate, Sintered fly ash aggregate.

1. Introduction

In the actual construction field, the normal curing practice is to provide external water for about one week followed by air curing at ambient temperature. This curing practice is insufficient for total hydration of all the cement particles in the concrete leading to low strength and durability characteristics. In High-Performance Concrete (HPC), external curing becomes ineffective due to its low permeability property because of the disconnected capillary pore system [1, 2]. External curing in the case of HPC makes the outer layer of the concrete hard and resistant to abrasive forces whereas, the internal portion is deprived of water. In addition, due to very low water-cement ratio used for HPC (0.2 to 0.38) [3], as hydration proceeds, the internal humidity of concrete gets reduced leading to self-desiccation and autogenous shrinkage, which negatively affects the performance of concrete [3].

Providing internal curing water through pre-wetted lightweight aggregates (LWAs) is an effective method of improving the properties of HPC. The water present in the pores of pre-wetted LWAs is absorbed by the un-hydrated cement particles in HPC for its complete hydration as well as the internal humidity of the concrete is retained for a much longer period [4, 5]. Kong et al. [6] studied the chemical reactivity of LECA and SINTAG in cement paste and observed that pozzolanic activity is higher in the case of SINTAG. The porous surfaces of these lightweight aggregates contribute to well bond interfacial zones [7].

Other than natural origin, certain aggregates are artificially manufacturing in the industry utilizing natural raw materials and industrial byproducts foreseeing the growing requirement in lightweight construction. The raw material for LECA is clay whereas that for SINTAG is fly ash. The raw materials are pelletized and sintered in a rotary kiln at about 1200° C. At this temperature these artificial aggregates become lightweight by the formation of a porous structure inside and a harder outer shell. The aggregate becomes ceramic in nature and is unaffected by the presence of water thereafter.

Introduction of LWAs in structural concrete by replacing normal coarse aggregate up to a certain percentage without compromising on its strength and durability is an effective method for reducing the weight of concrete thus, economizing the design of structural members leading to a reduction in an overall cost of construction.

This study is intended to assess the changes in strength, durability and flexural characteristics and reduction in self-weight of concrete when two types of pre-wetted lightweight aggregates (SINTAG and LECA) are incorporated in concrete separately by replacing equal volumes of normal coarse aggregate and compare these properties with that of properties of control concrete. In addition, the comparison is made between the properties obtained for concretes incorporated with SINTAG and LECA for getting an idea about, which one performs better to other in different aspects so that it can provide guidance for the use of these concretes in actual construction industry appropriately.

2. Experimental Programme

2.1. Materials and mixture proportion

Ordinary Portland cement of 53 grade conforming to IS 12269 [8] (with specific gravity 3.15, fineness 7.33%, initial setting time 145 minutes and final setting time

350 minutes) along with silica fume (having specific gravity 2.63) were used as cementitious materials. Manufactured sand (having specific gravity 2.67, fineness modulus 2.69, bulk density 1847 kg/m^3 and 24-hour water absorption 1.6%) was used as fine aggregate. The coarse aggregate used was crushed rock (having specific gravity 2.71, fineness modulus 6.99, bulk density 1564 kg/m^3 and 24-hour water absorption 0.45%). Sulphonated naphthalene formaldehyde-based superplasticizer 'CONPLAST SP430' with specific gravity 1.2 was used as water reducing admixture.

Artificial porous lightweight aggregates used were SINTAG (8-16 mm size, fineness modulus 5.01 and bulk density 848 kg/m^3) and LECA (6-16 mm size, fineness modulus 6.64 and bulk density 368 kg/m^3). Figures 1(a) and (b) shows lightweight aggregates used for the study.

(a) Sintered fly ash aggregate (SINTAG).

(b) Light expanded clay aggregate (LECA).

Fig. 1. Light weight aggregates used in the study.

For all the mixes, total cementitious content was kept at 400 kg/m^3 including 3% silica fume. Water cement ratio was kept at 0.38 and for obtaining a slump value of 80 mm, the superplasticizer dosage was adjusted to 1.2% of the weight of cementitious materials. Mix design was based on IS 10262 [9]. M0 is the normal mix for which, no replacement of aggregate was done. SFAC10, SFAC15, SFAC20 and SFAC25 represents Sintered Fly ash Aggregate Concretes having 10, 15, 20 and 25 percentage normal coarse aggregate replaced with equal volumes of SINTAG respectively. ECAC10, ECAC15, ECAC20 and ECAC25 represents Expanded Clay Aggregate Concrete having 10, 15, 20 and 25 percentage normal coarse aggregate replaced with equal volumes of LECA respectively. Tables 1 and 2 shows mixture compositions of SFAC and ECAC respectively with the following characteristics: Cement 388, Silicafume 12, Water 150, Fine aggregate 150, and Superplasticizer 4.8.

Table 1. Mixture compositions (kg/m^3) for the study: For sintered fly ash concrete (SFAC).

Mix	Coarse aggregate	LECA	Density kg/m^3
M 0	1230	-	2489
ECAC 10	1107	28.94	2393
ECAC 15	1045.5	43.41	2345
ECAC 20	984	57.88	2299
ECAC 25	922.5	72.35	2251

Table 2. Mixture compositions (kg/m^3) for the study:
For expanded clay aggregate concrete (ECAC).

Mix	Coarse aggregate	SINTAG	Density kg/m^3
M 0	1230	-	2489
SFAC 10	1107	66.65	2430
SFAC 15	1045.5	100.06	2402
SFAC 20	984	133.38	2374
SFAC 25	922.5	166.63	2346

2.2. Curing

In high-performance concrete, external water curing can improve the hardness of outer-layer, which is necessary for resisting the abrasive forces, whereas, it is not effective for total hydration of all the cement particles inside the concrete due to its low permeability. Internal curing is effective in HPC as it can contribute to the total hydration of all the cement particles as well as retain the internal humidity, which is needed to resist autogenous shrinkage. This study was conducted by providing 7 days of external water curing followed by air curing at ambient temperature to simulate the actual field practice in the construction industry. The withdrawal of external curing after one week also helps in testing the efficiency of internal curing.

2.3. Tests carried out

2.3.1. Aggregate crushing value

Based on IS: 2386-Part IV [10], tests were conducted to determine aggregate crushing value for different combinations of normal coarse aggregate and lightweight aggregates at different replacement levels from 0 to 100% at 10% increments. This test is to find out how much percentage of normal coarse aggregate can be replaced with lightweight aggregates so that the combination can be safely used for structural purposes.

2.3.2. Strength tests

Compressive strength tests were performed on concrete cubes of size 150 mm × 150 mm ×150 mm as per IS: 516 [11] for M0 concrete as well as for SFACs and ECACs. Compressive strengths for M0 mix and the two types of LWA mixes with 10, 15, 20 and 25% replacements were determined. The replacement percentages, which gave maximum compressive strengths for the two types of LWA mixes were taken as the optimum replacement levels for the respective LWA mixes.

Split tensile strength tests were carried out as per IS 5816 [12] on the cylindrical specimen of size 300 mm length and 150 mm diameter for M0 concrete as well as for SCAC and ECAC at their optimum replacement levels. Flexural strength tests were performed as per IS: 516 [11] on PCC beam specimen of size 100 mm × 100 mm × 500 mm under two-point loading on M0 concrete and SINTAG concrete and LECA concrete at their optimum replacement levels. As per IS: 2770-Part 1 [13], test for determining bond strengths were conducted. 16 mm diameter reinforcement bar embedded in the concrete cube of size 150 mm × 150 mm × 150 mm was pulled out using a universal testing machine. The resistance offered by the bonding force between the bar and cube gives the bond strength. The test setup for bond strength determination in a universal testing machine is shown in Fig. 2.

Fig. 2. Test setup for bond strength.

2.3.3. Durability test

Rapid Chloride Penetration Tests (RCPT) and Water permeability tests were performed on specimens for determining the durability of mixes. The resistance of concrete to the passage of chloride ions was measured using RCPT as per ASTM C 1202 [14] on concrete disc specimen of size 100 mm diameter and 50 mm length. Test setup for RCPT is shown in Fig. 3.

Cube specimens of size 150 mm × 150 mm × 150 mm were used to perform water permeability tests. The tests were performed based on DIN 1048 part 5 [15]. For 3 continuous days, 5 bar pressure was applied on cube surface and maximum and the average depth of water were noted. Figure 4 shows the test setup for determining water permeability.

Fig. 3. Rapid chloride penetration test.

Fig. 4. Water permeability test.

2.3.4. Flexural behaviour of RCC beams

Referring to IS 456 [16], RCC beam of cross-section 150 mm × 200 mm and length 1200 mm was designed as under reinforced section under simply supported condition. Fe 415 MS ribbed bars were used as reinforcement. Figure 5 shows the reinforcement details. Beams were tested under simply supported conditions at an effective span of 1000 mm under two-point loading. Deflection of beams at mid-span and quarter span were recorded at 10 kN increments of load. Initial cracking loads and ultimate loads were also noted. The experimental setup is shown in Fig. 6.

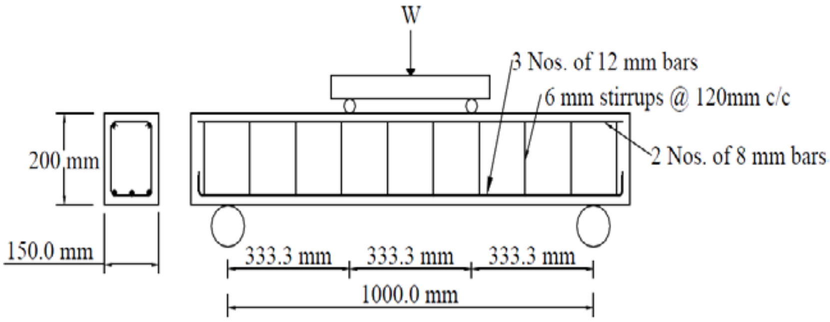


Fig. 5. Reinforcement details of RCC beam.

Fig. 6. Test setup for testing flexural behaviour of RCC beam.

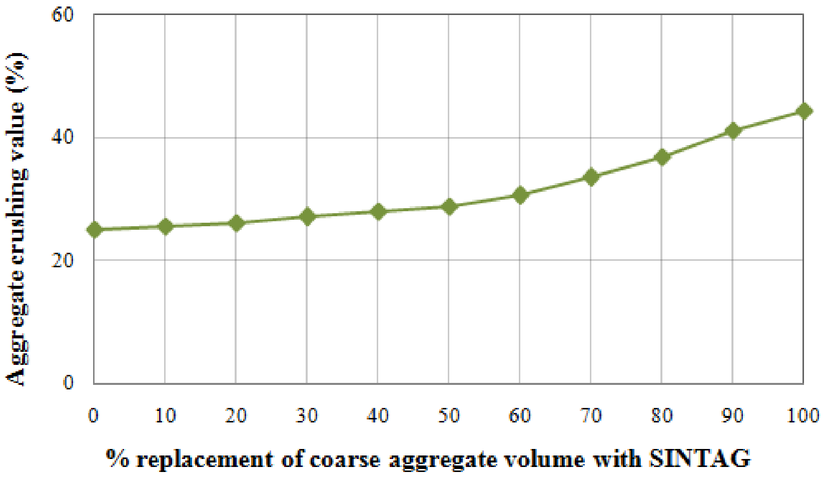
2.3.5. Weight reduction

Weights of concrete cubes of size 150 mm × 150 mm × 150 mm for SINTAG concrete and LECA concrete were measured and compared with that of M0 concrete for obtaining the respective weight differences. The percentage of weight reductions of the two types of concrete were calculated with reference to M0 concrete.

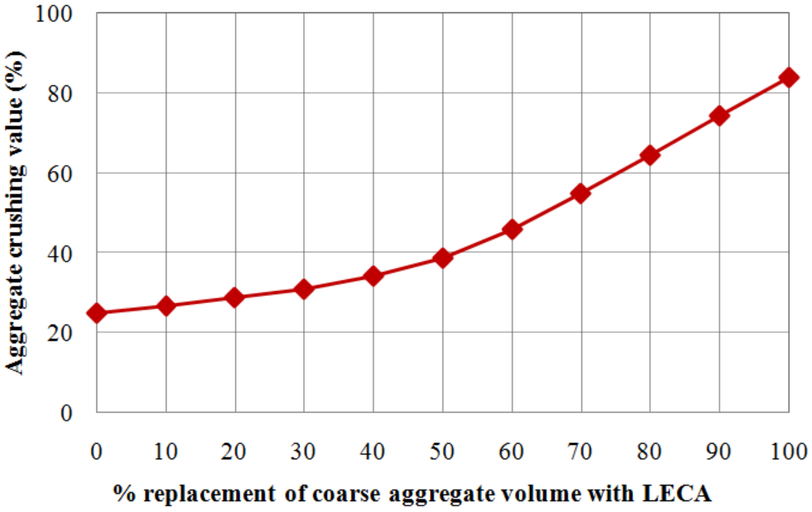
3. Results and discussions

3.1. Aggregate crushing value

According to IS 383 [17], aggregate crushing value is restricted to 30% for use in wearing surfaces and to 40% for use in structural purposes. Results of aggregate crushing value tests for different combinations of normal coarse aggregate and SINTAG as well as for normal coarse aggregate and LECA are shown in Figs. 7(a) and (b) respectively. From the graph, it is observed that safe replacement of up to 80% is possible in the case of SINTAG and 50% is possible in the case of LECA for use in structural purposes.



(a) Coarse aggregate- SINTAG combinations.



(b) Coarse aggregate- LECA combinations.

Fig. 7. Aggregate crushing value test results.

3.2. Strength tests

3.2.1. Compressive strengths

Figures 8(a) and (b) represents the compressive strength test results obtained for SFACs and ECACs respectively with reference to M0 concrete at different ages for 10, 15, 20 and 25% replacements of coarse aggregate. For SFACs all the four replacement levels showed an increase in compressive strength compared to M0 mix and maximum increment of 29.5% in compressive strength with respect to M0 mix was obtained for 20% replacement of coarse aggregate with SINTAG.

For ECACs, 10, 15 and 20% replacement showed an increment in compressive strength whereas, 25% replacement showed a decrease compared to

M0 mix and the maximum increment of 17.5% were observed for 15% replacement with LECA. Similar types of observations were reported by Dayalan and Buella [18]. In their study, the compressive strength obtained for internally cured concrete was about 20% higher compared to plain concrete for a replacement level of 20% when expanded shale was used as lightweight aggregate. Based on maximum increment in compressive strengths compared to M0 concrete, SFAC20 and ECAC15 were selected as optimum replacement levels for SINTAG concrete and LECA concrete respectively.

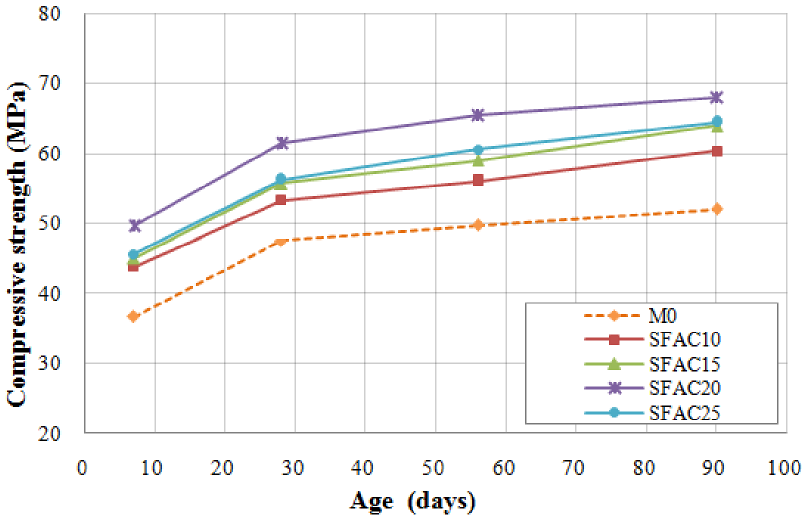
In the case of all the four replacement levels for SFAC and 10, 15 and 20% replacements for ECAC, internal moisture available within the presoaked lightweight aggregates enhanced the curing increasing the strengths of concretes. In the case of ECAC25, the increased percentage of LECA, which has a low crushing strength reduced the crushing strength by crushing through the aggregate phase. Tables 3 and 4 give the compressive strength values obtained for SFACs and ECACs respectively.

Table 3. Compressive strength of concretes at different ages (N/mm^2): Sintered fly ash aggregate concretes (SFACs).

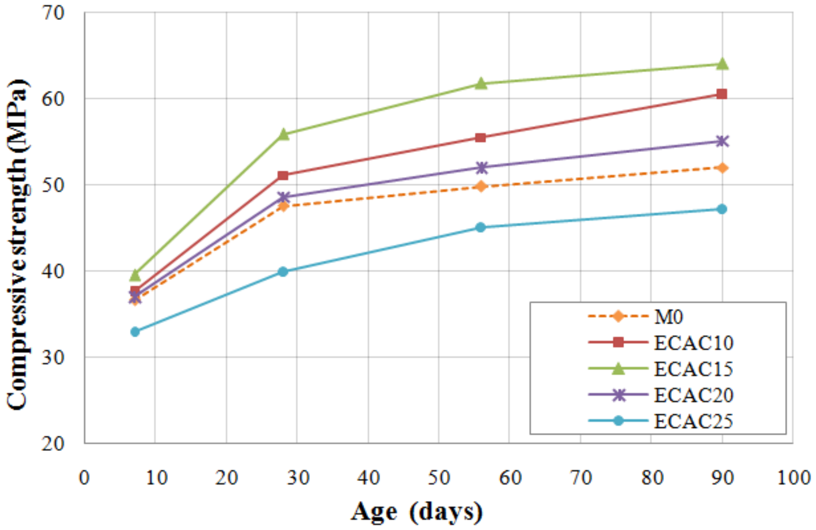
Mix	7 days strength	28 days strength	56 days strength	90 days strength
M0 (0% SINTAG)	36.66	47.55	49.77	52
SFAC10 (10% SINTAG)	43.85	53.3	56.01	60.4
SFAC15 (15% SINTAG)	45.03	55.7	59	63.9
SFAC20 (20% SINTAG)	49.67	61.57	65.5	68.01
SFAC25 (25% SINTAG)	45.6	56.21	60.55	64.42

Table 4. Compressive strength of concretes at different ages (N/mm^2): Expanded clay aggregate concretes (ECACs).

Mix	7 days strength	28 days strength	56 days strength	90 days strength
M0 (0% LECA)	36.66	47.55	49.77	52
ECAC10 (10% LECA)	37.62	51.11	54.07	60.44
ECAC15 (15% LECA)	39.55	55.85	61.77	64
ECAC20 (20% LECA)	37	48.59	52	55.11
ECAC25 (25% LECA)	32.88	39.85	45.03	47.55



(a) Sintered fly ash aggregate concretes (SFACs).



(b) Expanded clay aggregate concretes (ECACs).

Fig. 8. Compressive strengths of concretes at different ages.

3.2.2. Split tensile strength and flexural strength

It is observed that 28 days split tensile strength for optimum replacement level mix SFAC20 showed an increase in tensile strength of 2.6% while ECAC15 showed a reduction of 2.4% compared to M0 mix. The decrease in tensile strength of ECAC can be attributed to its porous nature permitting the split plane propagation through the aggregate [19]. Flexural strengths at 28 days of PCC beams for SFAC20 and that for ECAC15 showed an increment of 6.2% and 3.5% respectively compared to M0 concrete.

3.2.3. Bond strength

It is observed from tests conducted that the bond strength of SFAC20 increased by 6.4% and that for ECAC15 increased by 5.2% compared to M0 concrete. The hardening of cement pastes surrounding steel bars due to internal curing could have improved the bond strengths for both types of concrete.

3.3. Durability tests

3.3.1. Rapid chloride penetration

In the rapid chloride penetration test, the measurement of current passing through concrete specimen at various time intervals give a direct measurement of chloride ion penetration through the specimen. Figure 9 presents the current passed through M0, SFAC20 and ECAC15 at various time intervals. SFAC20 showed a slightly increased chloride penetration compared to M0 whereas ECAC15 showed a decreased chloride ion penetration with respect to M0 concrete. For M0 concrete, the total current passed for a period of 6 hours was 1446.3 coulombs whereas, that for SFAC20 was 1476 coulomb and that for ECAC15 was 1287.9 coulomb. As per ASTM specification, concrete with the current passage between 1000 and 2000 coulomb is categorized under low chloride penetration type. Even though porous LWAs were incorporated in SFAC20 and ECAC15, the chloride ion permeability did not vary much due to the formation of strong interfacial zone formed around the LWAs because of improved hydration. Zhutovsky and Kovler [20] have reported a similar type of behaviour in RCPT when lightweight aggregates were used in concrete. They have observed a reduction of 500 coulombs for a w/c ratio of 0.33 when pumice was used as a lightweight aggregate.

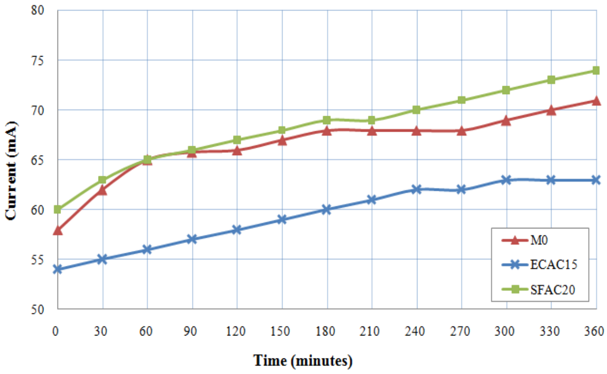


Fig. 9. Charge passed through concrete specimens at different time intervals.

3.3.2. Water permeability

Table 5 gives the water permeability results obtained for M0, SFAC20 and ECAC15. Water permeability of both LWA concretes showed a decrease compared to M0 concrete. Based on the results it can be inferred that even though porous aggregates were introduced into normal concrete, the water permeability reduced because of non-interconnectivity of the lightweight aggregates as well as the formation of hard inter transitional zone on the surface of the LWAs. Chia and Zhang [21] have reported that the depth of water penetration reduced by 30% when lightweight expanded clay aggregates were incorporated in concrete. As per DIN standards, concrete having water permeability less than 30 mm can be used in aggressive environments and that below 50 mm can be used for water retaining structures.

Table 5. Water permeability of different mixes.

	M0	SFAC20	ECAC15
Average depth of penetration (mm)	17.6	12.5	10.2
Maximum depth of penetration (mm)	26.2	22.4	20.5

3.4. Flexural behaviour of RCC beams

Results of tests conducted for assessing the flexural behaviour of RCC beams with M0 concrete, SFAC20 and ECAC15 showed the almost similar type of performance. Initial cracking loads and ultimate loads the beams are shown in Table 6. The initial cracking load of SFAC20 and ECAC15 beams increased by 6% compared to M0 beam. Ultimate load increased by 6.4% for SFAC20 and 7.6% for ECAC15 compared to M0 beam.

Table 7 gives the values of average deflection for load increments at 10 KN intervals. Load vs. average mid-span deflection of beams M0, SFAC20 and ECAC15 are shown in Fig. 10. Beams incorporated with lightweight aggregates showed a slightly lesser deflection compared to beam with M0 concrete. Even though the compressive strengths of SFAC20 and ECAC15 showed a considerable increment compared to M0 concrete, their improvements in flexural properties were marginal. Figure 11 shows the crack pattern observed for the beam.

Table 6. Initial crack loads and ultimate loads for different mixes.

Mix	Initial cracking load (kN)	Ultimate load (kN)
M0	33	140
SFAC20	35	149
ECAC15	35	150.6

Table 7. Average deflection of RCC beams for different loads.

Load (KN)	Average deflection of tested beams(mm)		
	M0	SFAC20	ECAC15
0	0	0	0
10	0.425	0.48	0.33
20	0.69	0.78	0.57
30	0.955	1.05	0.88
40	1.31	1.39	1.25
50	1.64	1.69	1.57
60	1.945	2.01	1.89
70	2.28	2.32	2.19
80	2.645	2.64	2.56
90	3.015	3.01	2.94
100	3.385	3.34	3.27
110	3.765	3.72	3.64
120	4.21	4.19	3.99
130	5.675	5.02	4.52
140	7.37	6.01	6.24

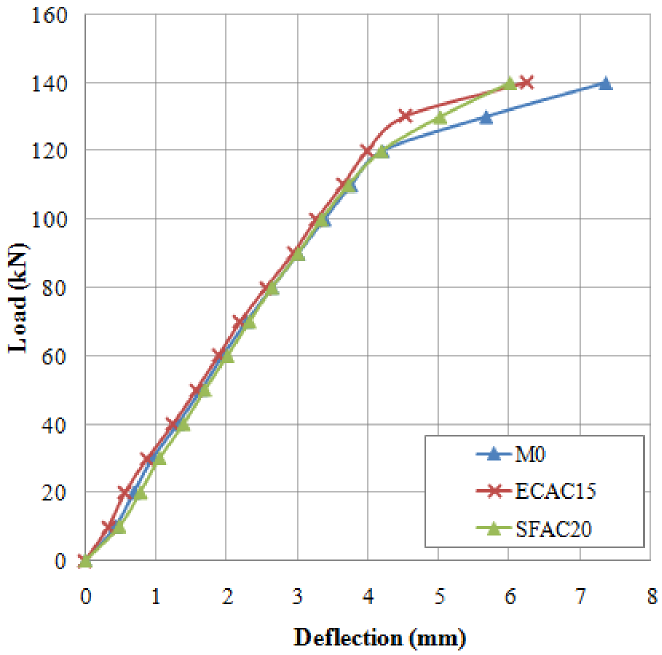


Fig. 10. Load vs. mid span deflection of beams.

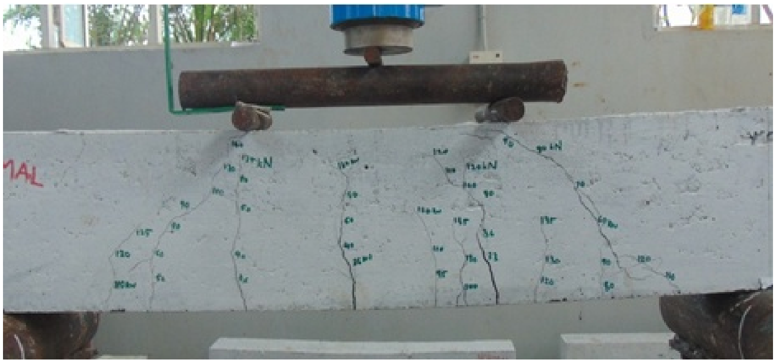


Fig. 11. Crack pattern of beam tested.

3.5. Weight reduction

The bulk density of SINTAG is 56% lesser and that of LECA is 73% lesser than the normal coarse aggregate. Partial replacement of normal coarse aggregate with an equal volume of LWAs reduces the self-weight of structural concrete. It is observed from the experiments that up to 25% of coarse aggregate can be replaced by SINTAG and up to 20% coarse aggregate can be replaced with LECA without a reduction in compressive strength than M0 concrete. The corresponding weight reductions achieved for SFAC is 7.1% and that for ECAC is 9.2% with respect to normal concrete. The self-weight reduction of structural members results in its' economic structural design reducing the overall weight of structure leading to considerable cost savings in construction.

4. Conclusions

The following conclusions can be made from the experimental study:

- Considerable improvement in compressive strength of high performance was obtained when normal coarse aggregate was replaced with both the types of lightweight aggregates. 20% replacement of coarse aggregate with SINTAG showed a maximum increment of 29.5% whereas, in the case of LECA, 15% replacement showed a maximum increment of 17.5% compared to normal concrete.
- Replacement levels of up to 25% with SINTAG as well as 20% with LECA showed an increase in compressive strength than normal concrete. Up to these levels, the enhanced and extended hydration of cement particles due to internal curing by water provided from within the lightweight aggregates counteracted the lower crushing strength of porous SINTAG and LECA.
- The split tensile strength of concrete with 20% SINTAG showed a slight increment whereas that with 15% LECA showed a slight decrease with respect to normal concrete. Both types of lightweight aggregate concrete showed a slight increment in flexural strength of PCC beams compared to concrete with normal aggregate.
- Chloride ion penetration of 20% SINTAG concrete showed a slight increment whereas that for 15% LECA concrete showed a slight decrease in comparison with a normal mix. Based on the current passed through the specimens, all the three types of concretes can be categorized under low chloride penetrability type.
- For both 20% SINTAG concrete and 15% LECA concrete, there was a decrease in water permeability compared to normal concrete. Based on DIN standards, all three types of concrete can be used for water retaining structures as well as in severe exposure conditions.
- The flexural performance of both SFAC20 and ECAC15 beams were almost similar to that of a concrete beam without replacement. The load-carrying capacity of both types of LWA beams increased slightly whereas, their deflections were almost similar compared to M0 beam.
- The maximum replacement levels possible for compressive strengths being greater than that for normal concrete are with 25% SINTAG and 20% LECA. For these levels of replacements, the corresponding weight reductions were 7.1% for SINTAG concrete and 9.2% for LECA concrete compared to normal concrete. These considerable reductions in self-weight of concrete lead to the economical design of structural elements thus, saving the overall cost of construction.
- It can be noted from the results of RCPT and water permeability tests that incorporation of LWAs at optimum levels did not negatively affect the durability of both types of concretes and can be categorized under high-performance type as that of M0 concrete. Compressive strengths of LWA concrete increased remarkably with respect to normal concrete however, a corresponding increment in tensile and flexural strengths were not attained. Future works in this area can be carried out by incorporating fibre reinforcements for improving the tensile and flexural properties of concretes.

Abbreviations

ASTM	American Society for Testing and Materials
DIN	Deutsches Institut fur Normung
ECAC	Expanded Clay Aggregate Concrete
HPC	High Performance Concrete
IS	Indian Standards
LECA	Light Expanded Clay Aggregate
PCC	Plain Cement Concrete
RCC	Reinforced Cement Concrete
SFAC	Sinered Flyash Aggregate Concrete
SINTAG	Sintered Flyash Aggregate

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