Research on Engineering Structures & Materials
www.jresm.org
MIM Research Group

Research Article

Mechanical properties and fracture behavior of concrete made with sintered fly ash lightweight coarse aggregate and electric arc furnace slag as fine aggregate

Brijesh Singh[1,*,a], Shamsher Bahadur Singh[2,b], Sudhirkumar V. Barai[2,c], P N Ojha[3,d], Rohit Kumar[3,e]

[1]*Birla Institute of Technology & Sciences Pilani, Pilani & Group Manager at National Council for Cement and Building Materials, Ballabgarh, India*
[2]*Department of Civil Engineering, Birla Institute of Technology and Sciences Pilani, Pilani, India*
[3]*National Council for Cement and Building Materials, Ballabgarh, India*

Article Info

Article history:

Received 14 Aug 2024
Accepted 29 Sep 2024

Keywords:

Sintered fly ash lightweight coarse aggregate;
Electric arc furnace slag;
Lightweight concrete;
Modulus of elasticity;
Stress-strain;
Fracture behavior

Abstract

The present work evaluates mechanical properties and fracture behaviour of concrete made with combination of sintered flyash lightweight coarse aggregate (SFA) and electric arc furnace (EAF) slag as fine aggregate. The mechanical properties and fracture performance of concrete has been evaluated at w/b of 0.6 and 0.4 for three concrete mix combinations namely (a) lightweight concrete with SFA and natural fine aggregate (b) lightweight concrete with SFA and electric arc furnace slag as fine aggregate (c) normal concrete with granite aggregate and electric arc furnace slag. The concrete mixes prepared are evaluated for compressive, flexural strength, split tensile strength, elastic modulus and stress strain curve behaviour. Fracture behaviour has been investigated on notched beams of size 100*100*500 mm under three-point bend test as per RILEM procedure for both normal weight and lightweight concrete. The plot of Load vs CMOD (Crack Mouth Opening Displacement) and Load vs displacement were used for evaluating the fracture behaviour of both types of concrete using various standards and RILEM recommendations. Fracture performance has been compared in terms of parameters such as modulus of elasticity, fracture energy, initial load compliance, stress-intensity factor, energy release rate, and characteristic length.

1. Introduction

The natural aggregates use in conventional reinforced concrete construction creates environmental problems and are energy intensive, which is crucial to consider for sustainable building and a circular economy. There has been need of huge number of aggregates by construction industry and natural sources are getting depleted over period of time. Fly ash and electric arc furnace slag are among major industrial bi-product generated in India. In last one and half decade, there is a serious focus towards adoption of industrial wastes in suitable ways thereby achieving sustainability and circular economy. Increase in use of renewable sources and other alternatives from industrial bi-products is a need of an hour to counter huge requirement of concrete as material in construction. Sintered fly ash lightweight concrete day by day is getting attention in construction industry because of its lower dead load, superior durability performance, enhanced thermal and sound insulation along with better fire resistance [1-2]. The structural grade

*Corresponding author: brijeshsehwagiitr96@gmail.com
[a] orcid.org/0000-0002-6512-1968; [b]orcid.org/0000-0001-6847-0701; [c]orcid.org/0000-0001-5100-0607; [d]0000-0003-1754-4488; [e]orcid.org/0009-0000-6167-375X
DOI: http://dx.doi.org/10.17515/resm2024.396me0814rs

lightweight concrete density generally varies from 1100 to 1900 kg/m^3 with minimum compressive strength of 17 MPa [3]. The sintered fly ash lightweight coarse aggregate (SFA) is mainly produced from fly ash as raw material through sintering process [1-2]. Lightweight concrete has been known to be better in mechanical, durability and thermal properties but one set back or limitation of lightweight concrete is its brittle behavior and lower resistance to crack formation under load. This brittle property of concrete limits its flexural capacity and can be hazardous in earthquakes [3-7]. Due to the brittle behavior, concrete structures undergo cracking under flexural loads and has possibility to fail suddenly without showing signs of distress. The mechanical performance and fracture behavior of normal weight concrete has been examined and researched deeply in the recent decades resulting in in-depth understanding of its fracture phenomenon [3-7]. Fracture performance of normal and ultra-high-performance concrete at different strain rate has been examined in past. The aggregate in concrete system is about 65-70% of the total volume and plays a critical role in deciding the physical properties and mechanical behavior of concrete both in its fresh and hardened state. The interactions among the aggregate and the cement paste impacts many of the concrete properties in hardened state such as strength, stiffness and fracture toughness. The study indicated that fracture parameters are sensitive to strain rates and not much effect of strain rate has been evident on softening fracture energy. The fracture behavior of lightweight concrete is reported to be comparable to normal concrete however in normal concrete, dense and strong aggregates resist the crack propagation, whereas crack propagation path can be different in lightweight concrete depending upon quality of interfacial transition zone [5-7]. The type of aggregate and its shape as well as surface texture has been highlighted to be having little impact on the facture energy of normal strength concrete compared to high strength concrete [7]. The fracture resistance of normal concrete depends on factors such as compressive strength; water/binder ratio; size, shape and content of the aggregate. In case of normal strength concrete both the toughness and the fracture energy of concrete have been reported to increase with the increase in compressive strength, size of aggregate size and quantity of aggregate.

There are several fracture models available for non-linear analysis of concrete structures such as the Hillerborg et al. model on fictitious crack theory [6], Jenq and Shah [7] model considering two parameter approach and Bazant et al. model on crack band [8]. The brittleness and ductility estimation of concrete can be quantified through its fracture properties [9-11]. To determine the concrete's fracture properties, RILEM [12-13] recommends testing of notched beams via a three-point bend tests. Among different fracture parameters, fracture energy is one important indicator for comparing or analyzing the concrete cracking resistance and toughness. RILEM definition of fracture energy is the quantum of energy needed to develop a crack with unit area. Apart from fracture energy, other indicators of fracture behavior are stress based intensity factor, rate of energy release, initial load compliance and characteristic length. Trivedi et al. [15] investigated three different approaches for fracture behavior study of concrete such as Bi-linear approximation, RILEM procedure and energy release rate and found similar results indicating that either of three approaches are suitable. Experimental investigation by Murthy et al. [16] on tension softening for nano engineered concrete and fracture energy highlighted that ratio of notch to depth significantly influence fracture energy determination under RILEM method. Gil et al. [17] examined the effects of addition of silica fume as supplement cementitious material in normal weight concrete and investigated how various aggregate sizes influence fracture parameters also an optimized dose of silica fume for fracture toughness and peak strength was determined. Study conducted by Siregar et al. [18] highlights that degree of brittleness of high strength concrete gets affected by w/b and aggregate size wherein aggregate strength mainly influences peak fracture energy. EAF slag is a co-product of metallurgical processes of steel manufacturing and produced from EAF of primary steel producers generating low carbon steel which does not have problem of heavy metals or free lime due to low basicity. This type of slags can be better suited for the construction industry as fine aggregate. EAF are responsible for over 40% production of steel globally [19]. The older plants have been using basic oxygen furnace (BOF) routes for making steel from recycled scrap metal in order to be more sustainable and economical. Steel production using electric arc furnaces in Europe generates slag over 10 million tons every year, and this amount will further increase in the future. Past studies with EAF slag as aggregates from steel making has shown improved mechanical characteristics and high specific density (generally more than 3.2) primarily because of its elevated levels of ferrous oxide. However, carbon steel slag production in past from basic oxygen furnace (BOF) has shown some dimensional instability because of hydration of magnesia and free lime [20-22]. EAF slag aggregates from steel making process has shown water absorption coefficient varies from 0.2% - 10 % [21]. In past decade [23-24], studies have focused on durability and mechanical properties of concrete containing EAF slag for normal concrete. The previous studies have reported feasibility of producing structural concrete utilizing EAF slag as coarse aggregate by fully replacing natural aggregates in normal concrete. Improvements in compressive strength, tensile strength, and elastic modulus have been reported with the use of EAF slag as coarse aggregate. [23-27]. The utilization of EAF slag is also environment friendly and has lower environmental emissions compared to natural aggregate [26-29]. However, the studies with SFA and EAF slag as fine aggregate for lightweight concrete production and subsequent evaluation of mechanical and fracture performance is not reported in literature.

1.1 Research Significance

The literature survey indicates that there are numerous studies conducted on total replacement of aggregate from natural origin with EAF slag as coarse aggregate in normal weight concrete. The comparison of fracture energy and related mechanical parameters of plain lightweight concrete with SFA in comparison to normal weight concrete with natural coarse aggregate is scanty. However, no study could be found in literature pertaining to concrete's fracture behavior and mechanical properties made with combination of SFA and EAF slag as fine aggregate. In the present study, concrete's mechanical characteristics and fracture behavior of concrete has been evaluated at water to binder ratio of 0.6 and 0.4 for three concrete mix combinations namely (a) lightweight concrete with SFA and natural fine aggregate (b) lightweight concrete with SFA and EAF slag as fine aggregate (c) normal concrete with natural granite aggregate and EAF slag.

2. Materials

This research explores the production of normal weight concrete, OPC cement (43 Grade) conforming to IS:269 [29], coarse (Figure-1b) and fine aggregates (Figure-1a), silica fume, superplasticizer and water are used. For production of lightweight concrete, OPC cement (43 Grade), natural fine aggregate and SFA, silica fume, superplasticizer and water are used. For production of lightweight concrete with EAF slag as fine aggregate, OPC cement (43 Grade), SFA and EAF slag as fine aggregate, silica fume, superplasticizer and water are used. In the study, crushed fine aggregate and EAF as fine aggregate conforms with Zone II of IS 383:2016 [30] and coarse aggregate having 20 mm as maximum nominal size also conforms with IS 383:2016. Table 1 displays the physical characteristics of both fine and coarse aggregate. Figure 1 (a) and (b) displays the fine and coarse aggregate, respectively. The mechanical properties of SFA used as coarse aggregate are given in Table-2 and chemical composition of SFA, cement OPC 43 grade, silica fume and EAF slag fine aggregate is given in Table-3.

(a) (b)

Fig. 1. (a) Fine aggregate (stone dust) and (b) Coarse aggregate (granite)

(a) (b)

Fig.2 . (a) Sintered fly ash lightweight aggregate, Fraction: 4-8 mm and (b) Sintered fly ash lightweight aggregate, fraction: 8-16 mm

(a) (b)

Fig. 3. (a) Electric Arc Furnace (EAF) Slag Fine Aggregates and (b) processing of Electric Arc Furnace (EAF) steel slag

The SFA is brown in color as shown in Figure-2 and has black core. The EAF slag as fine aggregate sample is shown in Figure-3 (a). The processing of EAF slag is displayed in Figure-3 (b). The microstructure of SFA is shown in Figure-4. The samples of SFA (two fractions 8-16 mm and 4-8 mm) have been utilized as coarse aggregate. For preparation of concrete mixes for lightweight concrete, the fine aggregate (crushed stone) used in study conforms to IS: 383-2016. For lightweight concrete; as per IS 383:2016, zone-II crushed fine aggregate [30] was used. The polycarboxylic ether based chemical admixture (Auramix 300 PC) conforming to Indian Standard IS:9103[31] was used for all concrete mixes.

Table 1. Aggregates properties

Property		Granite		Sintered Fly ash Lightweight Aggregate		Fine Aggregate	
		20 mm	10 mm	8-16 mm	4-8 mm	Natural Stone dust	EAF Slag
Specific gravity		2.81	2.82	1.49	1.47	2.65	3.39
Water absorption (%)		0.3	0.3	17.93	17.50	0.59	1.16
Sieve Analysis Cumulative Percentage Passing (%)	20mm	98	100	100	100	100	100.00
	10	2	68	30	100	100	100.00
	4.75	0	2	0	13	99	99.00
	2.36	0	0	0	2	89	89.00
	1.18	0	0	0	0	64	61.00
	600 µ	0	0	0	0	43	36.00
	300 µ	0	0	0	0	26	20.00
	150 µ	0	0	0	0	14	11.00
	Pan	0	0	00	0	0	0.00

Table 2. Mechanical properties of sintered fly ash lightweight aggregate used in study

Fraction	LWA designation	Specific gravity	Water absorption at 24 hours (%)	Loose bulk density (kg/m^3)	Crushing Strength (N/mm^2)	10 % Fines (Ton)
4-8 mm	LWA-I	1.47	17.50	813	8.80	-
8-16 mm	LWA-II	1.49	17.93	849	7.70	3.60

Table 3. Chemical composition of sintered fly ash lightweight aggregate and OPC cement

Component	CaO (%)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	SO_3 (%)	MgO (%)	Na_2O Equivalent (%)	Loss of Ignition
Sintered fly ash lightweight aggregate	2.45	62.50	25.85	4.19	0.29	0.53	0.77	1.48
Cement OPC 43 grade	59.60	21.22	7.19	4.25	2.50	1.90	1.05	1.94
Silica fume	-	95.02	-	0.80	-	-	-	1.16

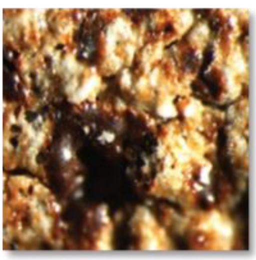



Fig. 4. Microstructure of sintered fly ash lightweight aggregate (10 µm and 1.5x)

3. Concrete Mix Design

3.1. Concrete Mix Design

3.1.1 Normal Concrete Mix Design

The w/b for concrete mix preparation was 0.6 and 0.4 for producing normal weight concrete (NWAC) mixes using granite as coarse aggregate. The slump was maintained in 75 -100 mm range. The mix design for normal weight concrete was done as per procedure given in IS: 10262-2019 [32]. Table 4 provides the concrete mix details.

3.1.2 Lightweight Concrete Mix Design with Natural Fine Aggregates and with EAF Slag as Fine Aggregates

The w/b ratio used for concrete mix preparation was 0.6 and 0.4 for producing lightweight concrete (LWAC) mixes using SFA with natural fine aggregates and with EAF slag as fine aggregates. The sintered fly ash lightweight aggregate, due to its porous nature, exhibits comparatively higher water absorption than natural aggregates. The use of lightweight coarse aggregates in dry condition with water correction equal to water absorption of aggregate leads to segregation of mix in fresh state and increase in net free water to cement ratio leading to reduction in strength of concrete. Other than this, the direct correction of water absorption fails to consider the impact of cement paste and in actual scenario it is cement paste and not water alone which dictates the water absorption potential of lightweight aggregates. This issue can be resolved by use of lightweight aggregate in dry state condition with proper correction in water absorption taking into account the effect of cement paste for given w/b of concrete mix. The mix design for lightweight concrete with SFA was done in accordance with procedure given in Indian Standard IS: 10262-2019 [32] and curve was developed for water absorption correction of aggregate. The sintered fly ash lightweight aggregate used in present study is highly porous and its water absorption is about 18 percent. In the present study, the combined aggregate grading given in IS: 9142-2018 [33] has been adopted. The absorption potential of sintered fly ash lightweight aggregate has been determined in the study wherein moisture content of lightweight aggregates was known. Initially the moisture content and initial weight of the aggregate were recorded. The mortar pastes of w/b 0.7 was prepared and placed in container. Twenty-five aggregates were first placed in a cement paste present in the container for the period of 5, 15, 30, 45 and 60 minutes to decide optimum absorption period (soaking period). After the specified period of absorption, the lightweight aggregates were removed from the paste and the excess paste attached to the outer surface of aggregates was separated with help of nylon brush. The removal time of excess paste was kept not more than one minutes in order to not absorb the water trapped in the aggregates particles which takes part in further hydration of cement paste. Thereafter, weight of aggregates was measured. After this the aggregates were placed inside an oven for period of 48 hours at a temperature of 105°C. Finally, dry weight of aggregate was determined and aggregate absorption values were determined. The total absorption by the lightweight coarse aggregate in terms of percentage is calculated as difference of mass of aggregate after 45 minutes of soaking and initial mass of aggregate before soaking divided by initial mass of aggregate before soaking multiplied by 100. The total water absorption by the lightweight coarse aggregate in terms of percentage is calculated as difference of mass of aggregate after 45 minutes of soaking and the oven-dried aggregate's mass divided by oven-dried aggregate's mass multiplied by 100. The difference between the percentage of total absorption by the lightweight coarse aggregates and total water absorption by the lightweight coarse aggregate is termed as total paste absorption potential of lightweight coarse aggregate. The water absorption values at water to cement ratio of 0.70 for absorption period of 5, 15, 30, 45 and 60 minutes were 12.84. 13.84, 14.36, 14.86, 14.90, respectively. Based on this study, 45 minutes absorption period for sintered fly ash lightweight aggregate has been considered in this study as the absorption capacity of the aggregates beyond this period was almost negligible.

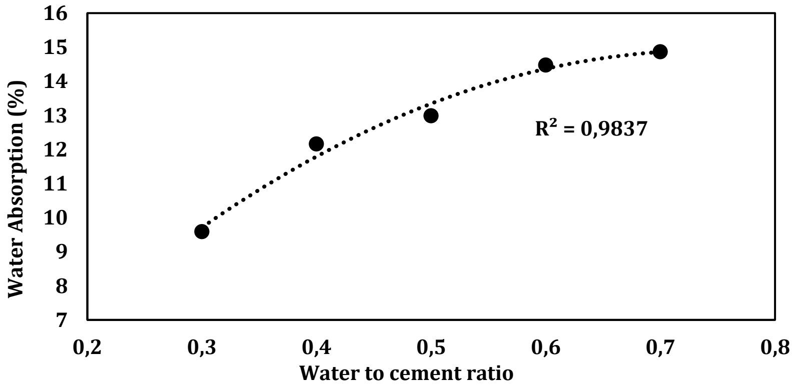


Fig. 5. Relationship between water absorption of sintered fly ash lightweight aggregate with water to cement ratio for 45 minutes absorption period

Thereafter, this exercise was repeated for mortar paste of w/b ratio of 0.3, 0.4, 0.5 and 0.6. Thereafter, correlation was developed between sintered fly ash lightweight aggregate water absorption potential and different w/b ratios. The correlation developed is presented in Figure-5 for absorption period of 45 minutes. The correlation developed is to be used in water absorption correction of sintered fly ash lightweight aggregate utilized as coarse aggregate in concrete mix. The mix design details of both normal and lightweight concrete is given in Table-4. In table-4, NC denotes normal concrete, LC denotes lightweight concrete with (SFA) and natural fine aggregate and LCEAF denotes lightweight concrete with SFA and EAF as fine aggregates (100 % replacement with natural fine aggregate). A 60 kg batch of concrete has been prepared for each concrete mix. Firstly, in the pan mixer the fraction of lightweight coarse aggregates, fine aggregates and cement was mixed to obtain homogenous mix and thereafter 80 percent water was added and mixing was performed for a duration of 2-3 minutes [34]. Subsequently, the leftover 20 percent water and the admixture were introduced, and the mixing process was extended for another 2 to 3 minutes.

Table 4. Concrete mix design for normal and lightweight concrete

Mix ID	w/b	Cementitious Content [Cement + Silica Fume] (kg/m³)	Water Content (kg/m³)	Chemical Admixture % by weight of cement	Fine Aggregate (kg/m³)	Coarse Aggregate (kg/m³) 10 mm	20 mm
NC-0.6	0.60	285 (271+14)	170 (After Correction 175)	0.60	765	492	738
LC-0.6	0.60	285 (271+14)	170 (After Correction 258)	0.70	785	245	370
LCEAF-0.6	0.60	285 (271+14)	170 (After Correction 262)	0.50	788	241	368
NC-0.4	0.40	425 (382+43)	170 (After Correction 175)	1.00	580	515	775
LC-0.4	0.40	425 (383+42)	170 (After Correction 239)	0.90	733	229	345
LCEAF-0.4	0.40	425 (383+42)	170 (After Correction 243)	0.80	735	230	346

It is to be noted that the initial mixing period is critical for sintered fly ash lightweight aggregate due to its absorption characteristics. Adjustment was done to mixing water to accommodate water absorption of the aggregates. The mounds were cleaned properly and concrete cube was compacted on vibration table wherein each of three layers were properly compacted. After 24 hours, the concrete cubes were taken out of the molds. The environmental conditions of laboratory were 27±2^{o}C temperature and 65% or more relative humidity. The concrete cube specimen was tested in surface dried saturated condition as per IS: 516 (part-1/sec-1) [35]. The concrete developed has a slump in between 75-100 mm.

4. Details of Specimen

The concrete specimens of various size were prepared for different tests discussed hereunder as per the standards and literature. The 28-day cube compressive strength was determined as per procedure given in IS:516 on cube size of 150 mm x 150 mm x 150 mm. The concrete cylinders of size 150 mm diameter and 300 mm height are cast for evaluating stress strain behavior of concrete, modulus of elasticity and split tensile strength of concrete as per IS: 516. For fracture study at 28-day age as per literature and RILEM procedure, the three-point bend tests were performed on beam of 100 mm cross section and 500 mm length with 35mm notch (Figure-6 and 7). Table 5 gives details of specimens and Figure 5 displays the cast samples with molds.

Table 5. Details of specimen and tests performed

Sl.	Type of Sample	Sample size (mm)	Parameter evaluated
1.	Cube	150 mm	28-day age compression test
2.	Cylinder	150 Diameter x 300 height	Split Tensile Strength, Modulus of Elasticity, Stress-Strain at 28-day age
3.	Beam	100 mm cross section and 500 mm length	Three-point bend test for flexural strength and fracture study

Fig. 6. Concrete cubes, cylinders, and beams in molds

Fig. 7. Notched beam sample

5. Experimental Method

The method adopted for determining compressive strength, stress strain behavior, split tensile strength, modulus of elasticity and fracture parameters are discussed in this section.

5.1. Compressive Strength, Stress Strain Behavior, Modulus of Elasticity and Split Tensile Strength

The 28-day cube compressive strength, split tensile strength, modulus of elasticity and stress strain behavior was determined as per IS: 516. These tests were carried out on a compression testing machine of capacity 3000 KN. The test setup for stress strain behaviour and modulus of elasticity of concrete is given in Figure 8.

Fig. 8. Test setup for stress strain behavior and modulus of elasticity of concrete of concrete

5.2. Study on Fracture Behavior Using Three-Point Bending Test

The three point bend test was performed on notched beams of size 100 x 100 x 500 mm for both normal weight and lightweight concrete. The plot of Load vs CMOD (Crack Mouth Opening Displacement) and Load vs deflection were utilised for determination of fracture behaviour of both types of concrete using various standards and RILEM recommendations. Fracture performance was evaluated by determining modulus of elasticity, fracture energy, initial load compliance, stress intensity factor, energy release rate and characteristic length. In Figure-9, the three point bend test diagram and in Figure 10 the test set up in laboratory has been shown.

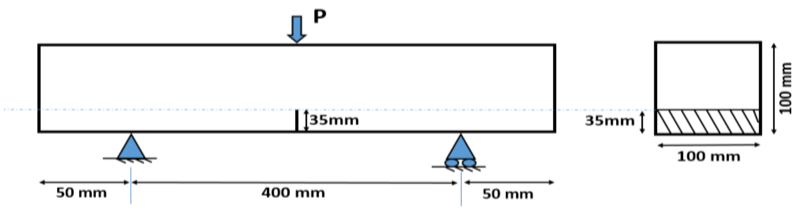
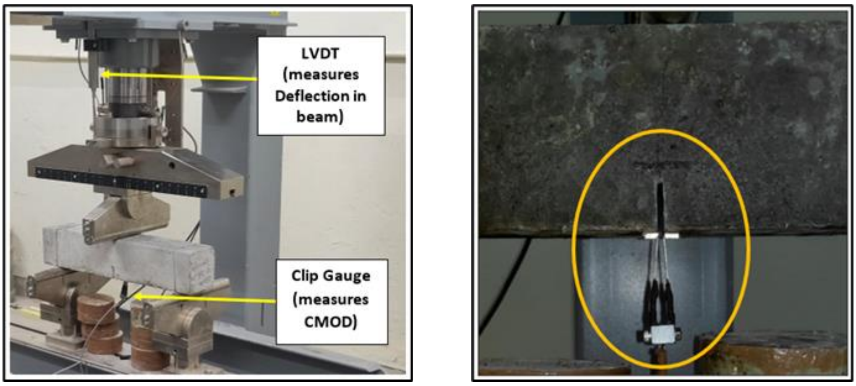


Fig. 9. Three-point bend test diagram

The beam of 100 mm cross section and 500 mm length with 35mm notch [13, 36] was created in middle of beam and clear span was kept as 400 mm. The load on beam specimen was given through a displacement mode operated machine of 30T capacity. The mid-point beam delfection was recoded using CMOD and Linear Variable Displacement Transducer (LVDT) (Figure-10a). The clip gauge using two nos. steel type knife edges were placed at the bottom beam's bottom for CMOD measurement as represented in Figure 10(b). 18 nos. concrete beams were evaluated for fracture performance study and out of which for each mix given in Table 4, the three beams were tested.



(a) (b)

Fig. 10 (a) Typical setup for three-point bend test and (b) CMOD measurement using clip gauge

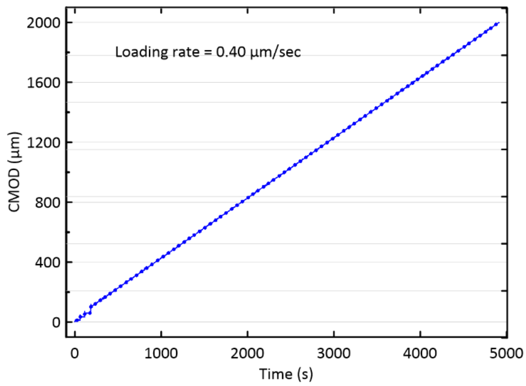


Fig. 11. Crack Mouth Opening Displacement (CMOD) vs time plot for the test

Figure 11 illustrates the plot of CMOD vs time.. The test was conducted in displacement operated mode in machine and loading rate for CMOD was maintained at 0.40µm/s. The experiment continued to point of failure of beam or to point where CMOD was 1000 µm.

6. Test Results and Discussions

Properties of fresh concrete, including workability and air content, were assessed for each of the six concrete mixes. Workability was measured in terms of slump at various intervals—specifically at 0, 30, 60, 90, and 120 minutes after the mix preparation. The results of are provided in Table 6.

The concrete mixes were formulated to attain initial slump of 75 to 100 mm using suitable dosages of commercially available PCE based chemical admixture. Concrete mixes incorporating EAF slag as sand instead of natural fine aggregate showed similar trend and rate of slump loss as compared to their equivalent normal concrete mixes and mixes of lightweight concrete with natural fine aggregate and SFA. The reason for such behavior may be attributed to similar grading and zone of EAF slag as sand and conventional fine aggregate (crushed sand), as both are of zone II grading as per IS 383: 2016. All the six mixes showed almost similar and comparable air content (around 2.3 to 2.9%). All the mixes were observed to be homogenous and no signs of bleeding and segregation were observed.

Table 6. Workability and air content of concrete mixes

Mix ID	w/b	Workability of concrete (slump in mm)					Air Content, %
		0 Min	30 Min	60 Min	90 Min	120 Min	
NC-0.6	0.60	100	80	65	45	25	2.5
LC-0.6	0.60	90	70	50	40	20	2.3
LCEAF-0.6	0.60	80	60	40	30	20	2.5
NC-0.4	0.40	100	70	55	30	25	2.7
LC-0.4	0.40	90	70	55	35	20	2.6
LCEAF-0.4	0.40	85	70	55	30	20	2.9

6.1. Mechanical Properties and Stress Strain Behavior

This section presents the mechanical properties of concrete as determined by IS: 516, including its modulus of elasticity, split tensile strength, compressive strength, and stress-strain behavior. Table 7 gives the test findings. Figure 12 displays the fracture specimen following the split tensile test.

Table 7. Compressive strength, elastic modulus and split tensile strength of concrete

w/b	Type	28-day in (MPa)		
		Cube Strength	Split Tensile Strength	Modulus of elasticity
0.60	NC-0.6	28.33	2.28	28270
0.60	LC-0.6	25.00	2.22	18860
0.60	LCEAF-0.6	26.50	2.15	19094
0.40	NC-0.4	47.55	4.17	32852
0.40	LC-0.4	37.87	3.09	20940
0.40	LCEAF-0.4	38.50	2.64	22423

Table 7 gives results of the 28-day cube compressive strength, elastic modulus and split tensile strength of (a) lightweight concrete with natural fine aggregate and SFA as coarse aggregates, (b) lightweight concrete with SFA as coarse aggregate and EAF as fine aggregate and (c) normal concrete with natural granite and fine aggregate. The split tensile strength and compressive strength for all the above concrete mixes with w/b of 0.6 are comparable in case of both normal and lightweight concrete with natural and EAF slag as fine aggregate.

Fig.12. Fractured lightweight concrete specimen after split tensile test

The split tensile strength, compressive strength and elastic modulus for normal concrete mix with w/b 0.4 are more than both lightweight concrete with SFA and natural fine aggregate as well as lightweight concrete with SFA and EAF slag as fine aggregate. The modulus of elasticity of SFA based concrete for both types of fine aggregate i.e. natural sand

and EAF slag as sand are around 30-40% lower compared to normal weight concrete. However, modulus of elasticity, split tensile strength and compressive strength are comparable for both lightweight concrete with SFA, natural fine aggregates and lightweight concrete with SFA and EAF slag as fine aggregate. From the results it is seen that split tensile to compressive strength ratio lies in between 5-10% for lightweight concrete. Whereas in conventional concrete this ratio lies between 5- 10%. This indicates that the tensile strength of normal concrete and lightweight concrete is nearly same [37-39]. The observation of splitted surface of specimen indicates that the fracture path gets transferred via aggregates in lightweight concrete (Figure-12).

In case of lightweight concrete, it can be inferred that the bonding within the cement paste matrix and sintered fly ash lightweight aggregate are higher than the aggregate's strength. Because of lower crushing strength in sintered fly ash lightweight aggregates compared to natural aggregate, the lightweight concrete could not give similar split tensile strength for similar w/b ratio. The important parameter of any concrete is its elastic modulus and its depends upon the moduli of both aggregates and paste matrix. In lightweight concrete, the elastic modulus of aggregate is the weakest link and it leads to overall reduction of elastic modulus of lightweight concrete. In the lightweight concrete, the elastic modulus of aggregate and paste are closer to each other compared to normal weight concrete leading to uniform stress distribution, simultaneously reducing concentration of stress and destruction occurs at the weakest link which is aggregate in case of lightweight aggregate. Figure 13 illustrates the stress-strain responses of each concrete mix at various w/b ratios.

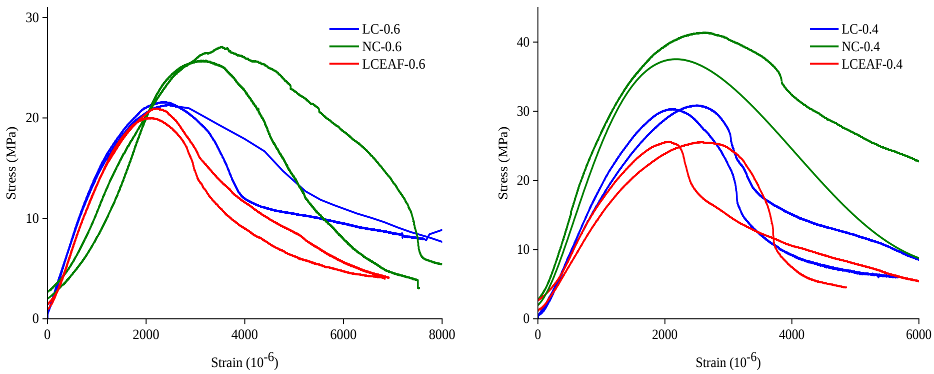


Fig. 13. Stress-strain curve

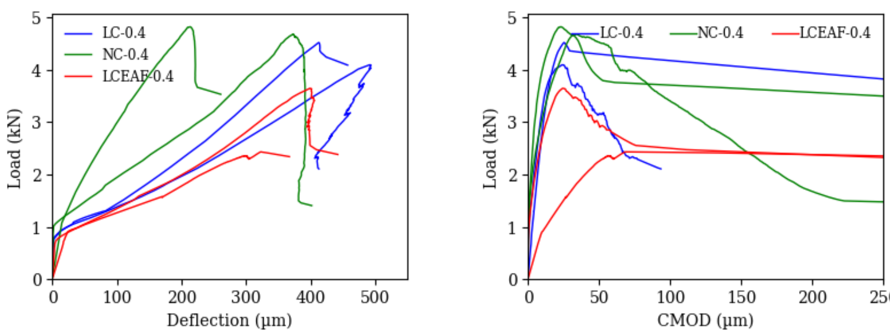
In comparison to normal weight concrete, which shows linear behavior up to 35-50% of maximum load, the stress strain plot of lightweight concrete depicts linear behavior up to 70-80% of maximum load for each lightweight concrete with SFA and natural fine aggregate as well as lightweight concrete with EAF slag as fine aggregate and sintered fly ash lightweight coarse aggregates. The study conducted in past [40] has shown the linear behavior up to 90-95% of peak load for lightweight concrete. The high level of linearity observed compared to the present study can be explained by the small maximum size of the lightweight aggregate used in the concrete mix. The size of aggregate used by Domagala et al. was 4-8 mm whereas in present study the size range of lightweight aggregate used is 4-16 mm. The surface characteristics of lightweight aggregate and its porous nature as well as internal curing in lightweight concrete system makes superior interfacial transition zone as well monolithic product leading to prolonging the rising branch of curve representing concrete stress strain.

The failure of lightweight concrete happens in brittle manner once fracture initiates due to inferior aggregate interlocking mechanism wherein crack passes through the aggregates compared to normal concrete where fracture initiates at the interface of aggregate and mortar [41]. The past studies [41] has shown that fracture in lightweight aggregate is bound to happen through the aggregate but in case of sintered fly ash lightweight aggregate-based concrete, the fracture is happening around the aggregate. In general, the lightweight concrete stress strain behavior can be categorized into three parts. The first part is linear portion which is up to 70-80% of maximum load associated to strain of approximately 90-95% where macro crack initiates in the central portion of cylindrical specimen. The second part is the portion of stress strain curve where stress increases steadily and strain increases at faster rate. In this part the concrete continues to crack and cracks formed are more than normal concrete because of lower strength of porous lightweight aggregate. The third part of curve indicates the point beyond the peak stress, where stress decreases at faster rate and reaches to almost half of the peak load indicating brittle and shear type of failure in case of lightweight concrete. Thereafter, the stress gradually decreases with increasing strain because of the cracks getting capacity through the residual stress and frictional resistance mainly.

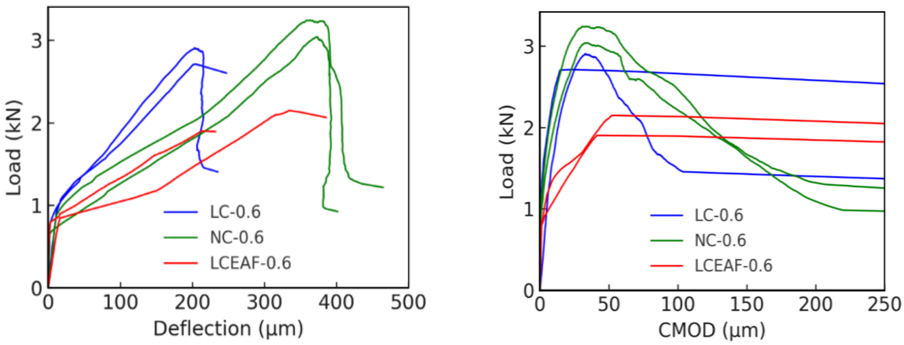
6.2 Load-CMOD and Load-Deflection Behavior of Lightweight Concrete and Normal Concrete

This section presents the plot of load vs deflection and load vs CMOD behavior of normal concrete (NC), lightweight concrete with SFA and natural fine aggregate (LC) and lightweight concrete with SFA and EAF as fine aggregate (LCEAF) for w/b ratio of 0.4, 0.6 in Figure 14. These graphs implemented for the assessment of fracture indicator to the point of failure. The failure point is addressed by sudden change in deflection that happens without a load increment in Load-Deflection curve or sudden change in CMOD that happens without a load increment in Load-CMOD curve.

The plot load vs deflection and load vs CMOD curves are comparable for both lightweight concrete with SFA and natural fine aggregate and lightweight concrete with SFA and EAF slag as fine aggregate. The non-linear ascending and descending branches in flexural curves of lightweight concrete with SFA including difference in results and pattern can be correlated with the non-linearity in tensile mode stress-strain behavior and formation of the process zone of fracture in front of the initial notch. In case of lightweight concrete, larger fracture process zone gets formed before the peak because of weaker aggregate to paste bond.



(a) Load Vs deflection plot (b) Load Vs CMOD plot



(a) Load Vs deflection plot (b) Load Vs CMOD plot

Fig. 14. Load Vs deflection plot & Load Vs CMOD plot for w/b of 0.4 and 0.6

The exact reason behind the flat flexural curves in lightweight concrete in comparison to normal weight concrete is not fully understood and one of the reasons can be tortuous crack path in lightweight concrete in comparison to normal concrete.

6.3 Fracture Energy

Fracture energy is referred to as the quantum of energy needed to create a crack with unit area, it is denoted by G_f. It is a critical parameter that is used to examine and assess concrete crack resistance, brittleness and toughness. Fracture energy is calculated by the formula from RILEM 50 [12, 43] given below;

$$G_f(N/m) = (W_o + mg\delta_o)/A_{lig} \tag{1}$$

Where W_o = Area below load and deflection plot as shown in Figure 15, m = Beam mass between the support, g = The gravitational acceleration, i.e., 9.81 m/s^2, δ_o = Failure deflection of specimen and A_{lig} = Ligament area.

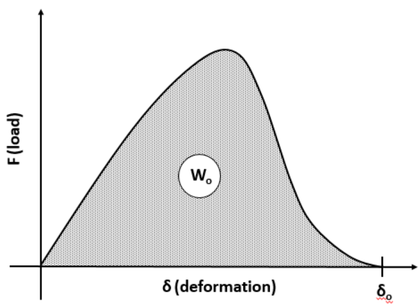


Fig. 15 Area within load and mid-point deflection plot of beam [32]

The comparison of fracture energy of the normal concrete (NC), lightweight concrete with SFA and natural fine aggregate (LC) and lightweight concrete with SFA and EAF as fine aggregate for both w/b 0.4 and 0.6 is presented in Figure 16. It has been suggested by Mazloom et al. [42] that the correction in fracture energy related parameters can yield accurate results where the peak loads of geometrically similar beams which defines the initial fracture energy with respect to corresponding peak loads are adjusted considering the effect of the specimen weight. In present case correction has not been considered as here only the relative comparison is made for fracture parameters of various concrete systems with different types of aggregates.

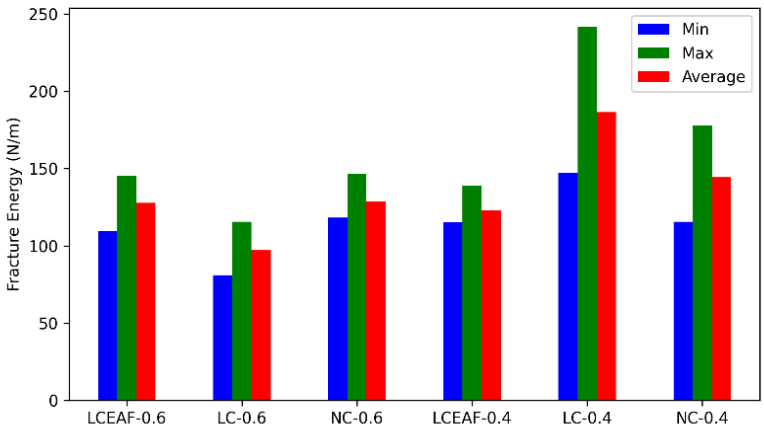


Fig. 16 Fracture energy for w/b ratio of 0.6 and 0.40

Normal concrete and lightweight concrete exhibit comparable fracture energy. For w/b ratio of 0.6, the average fracture energy for all the six concrete mixes varies from 100 to 125 N/m. For w/b ratio of 0.4, the average fracture energy for all the six concrete mixes varies from 125 to 180 N/m. The average fracture energy is comparable for both lightweight concrete with SFA and natural fine aggregate and lightweight concrete with SFA and EAF slag as fine aggregates. The past studies [14-15] has shown that fracture in lightweight aggregates is bound to happen through the aggregate but in case of sintered fly ash lightweight aggregate-based concrete, the fracture is happening around the aggregate. The reason behind this theory can be attributed to development of large stress at interface of lightweight aggregate and cement matrix due to incompatibility of modulus of elasticity of both aggregate and cement matrix. Additionally, some crack resistance is also provided by the hard-outer shell of sintered fly ash lightweight aggregate.

6.4 Modulus of Elasticity and Initial Compliance

Initial compliance represented by Ci, is defined as the reciprocal of gradient of initial linear segment of load versus CMOD curve. Equation (2), as given by [12], is used to get the MOE for the concrete beams with midpoint notch using the Ci.

$$E\ (MPa) = 6S\,\frac{\alpha V_1(\alpha)}{C_i d b^2} \tag{2}$$

Where $\alpha = a/d$, a= initial notch depth, d= beam depth. The computation of the gradient of the load-CMOD curve's initial straight segment is displayed in Figure 13. Equation (3) provided by Tada et al. [25] is used to determine V1(α) as follows:

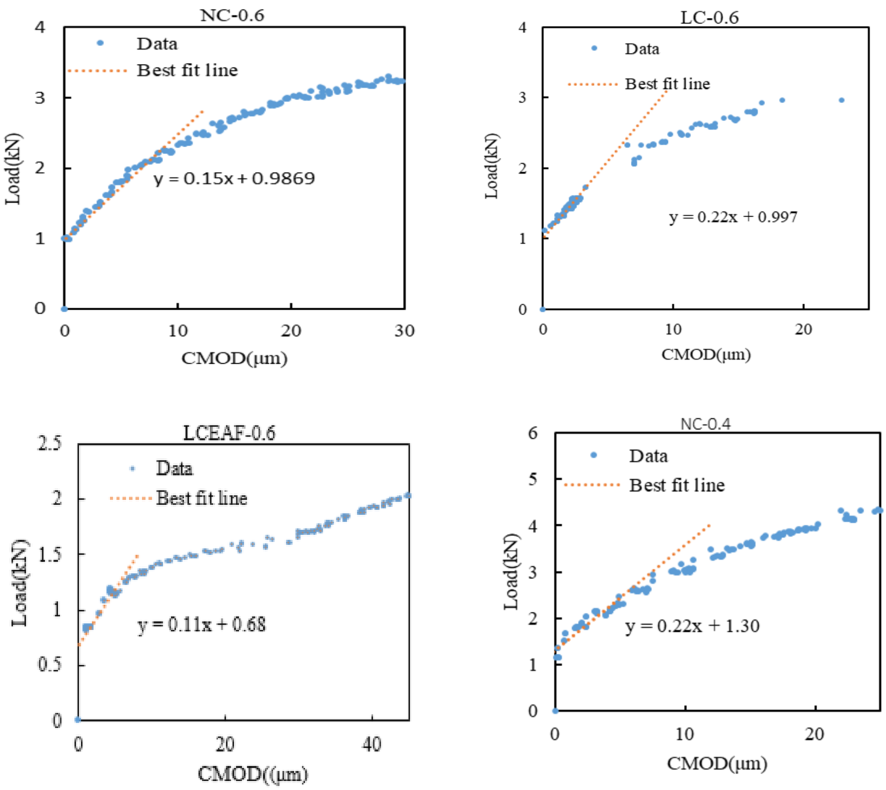
$$V_1(\alpha) = 0.76 - 2.28\alpha + 3.87\alpha^2 - 2.04\alpha^3 + \frac{0.66}{(1-\alpha)^2} \tag{3}$$

The Table 8 presents the value of MOE as obtained from initial compliance by using equation 2. It can be observed that Load-CMOD compliance method for MOE gives higher result than the actual as concrete exhibits greater strength. The MOE by this method is not accurate and reliable, therefore actual MOE is used for calculation of subsequent parameters in the study.

Table 8. Elastic Modulus and initial compliance of concrete

w/ b ratio	Cube compressive strength (MPa)	Initial compliance Ci (10-9 m/N)	Modulus of elasticity, GPa [cmod test]	Modulus of elasticity (GPa) [As per Arora et al. For NWC [26] / IS: 9142-2018 for LWC [24]]
NC-0.6	28.33	6.67	24.0	28.27
LC-0.6	25.00	4.54	35.3	18.86
LCEAF-0.6	26.02	9.09	17.7	19.09
NC-0.4	47.55	4.48	35.8	32.85
LC-0.4	37.87	3.92	40.9	20.94
LCEAF-0.4	36.51	6.06	26.5	22.42

The compliance method suggested by RILEM is complicated, difficult, and sensitive to various test parameters. It requires a high degree of measurement sensitivity in mechanical bend tests, in the order of (10^{-9}} meters. Compliance is a function of the initial slope, which can vary slightly based on individual graph analyses. Even a little deviation in measuring the initial level slope in Load-CMOD curve significantly affects the MOE. Figure 17 represents best representative curve for calculating the starting gradient of the Load-CMOD curve for different w/b ratios of the mix. From this study, it is evident that this method for determining MOE should not be preferred and is limited to use for comparative analysis only. Other well-known standard empirical methods should be used for MOE calculations.



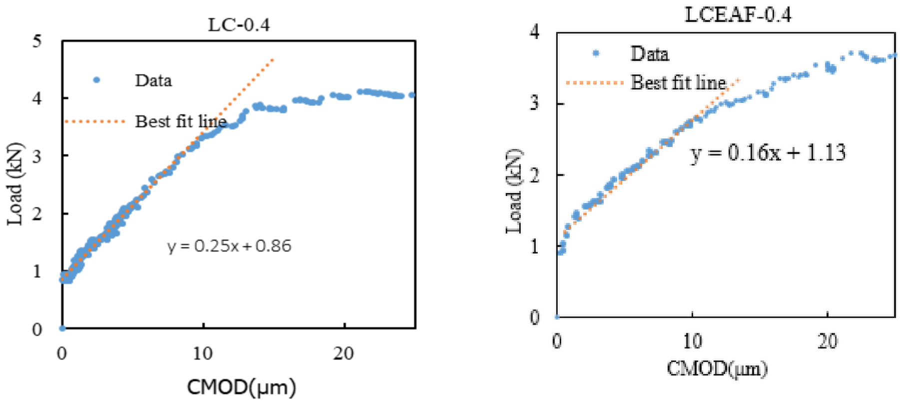


Fig. 17. Initial compliance calculation from Load-CMOD curves

6.5 Stress Intensity Factor (K_{Ic})

It is defined as stress measurement adjacent to the crack and computed using equation-4 [12]. It represents the state of stress and crack propagation rate in the neighborhood of the crack or notch tip. The specimen with higher (K_{IC}) shows higher stress is distributed in the vicinity of the crack representing less brittle the material.

$$K_{IC}\,(MPa\,\sqrt{m}) = 3(P_{Nmax} + 0.5W)\frac{S\sqrt{\pi a}}{2d^2\,b}f(\alpha) \tag{4}$$

Where P_{Nmax} = Peak load beam with midpoint notch in N, W = Total weight of the beam between the supports, S = Span of the beam in m, α = a/d = 0.35, f(α) = Geometric adjustment concerning the bending load. For calculation of f(α) Finite Element Method is required for varying property of material, size and notch depth [27]. But in the present study equation (5) is used for comparative analysis because of simplicity and wide acceptance of this:

$$f(\alpha) = \frac{1.99 - \alpha(1-\alpha)(2.15-3.9\alpha+2.7\alpha^2)}{\sqrt{\pi}(1+2\alpha)(1-\alpha)^{3/2}} \tag{5}$$

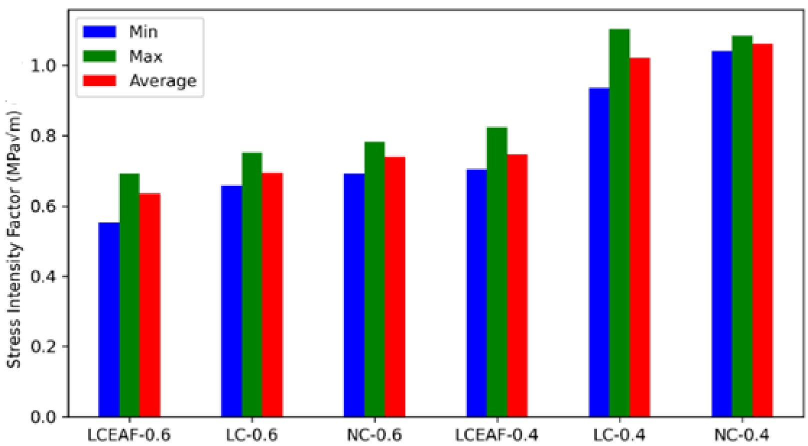


Fig. 18. Stress intensity factor

Figure 18 shows the test results of stress intensity factor. The graph shows that the average stress intensity factor of both normal concrete and lightweight concrete are comparable. The average stress intensity factor is comparable for both lightweight concrete with SFA and natural fine aggregate and lightweight concrete with SFA and EAF slag as fine aggregate. The reduction in w/b ratio leads to increase in the K_{IC} for both normal weight concrete and lightweight concrete. It is also seen that K_{IC} increases with increase in compressive strength of the concrete because formation of initial cracks depends upon the tensile strength of the beam. The stress intensity factor for w/b ratio in case of LCEAF samples are less dominant in comparison to lightweight concrete with natural fine aggregate and normal concrete with natural coarse and fine aggregates.

6.6 Critical Energy Release Rate (G_{IC})

It is defined as rate of change of energy when new fracture surface is created. It quantifies the energy change associated with crack growth. It is important parameter to predict fracture toughness and crack growth behavior. The equation given by RILEM [12, 27] and mentioned below in eq. (6) is adopted for calculation of G_{IC}:

$$G_{IC}(N/m) = \frac{{K_{IC}}^2}{E} \tag{6}$$

Figure 19 shows that the energy release rate in case of lightweight concrete is higher as compared to normal weight concrete for both w/b ratios. It indicates that in the lightweight concrete the strain energy release with formation of new crack will be higher in comparison to normal weight concrete which was evident in stress strain behavior also where a greater number of crack formation occurs at peak stress. The average energy release rate is comparable in case of w/b ratio 0.6 and 0.4 for both lightweight concrete with SFA and natural fine aggregate and lightweight concrete with SFA and EAF slag as fine aggregate.

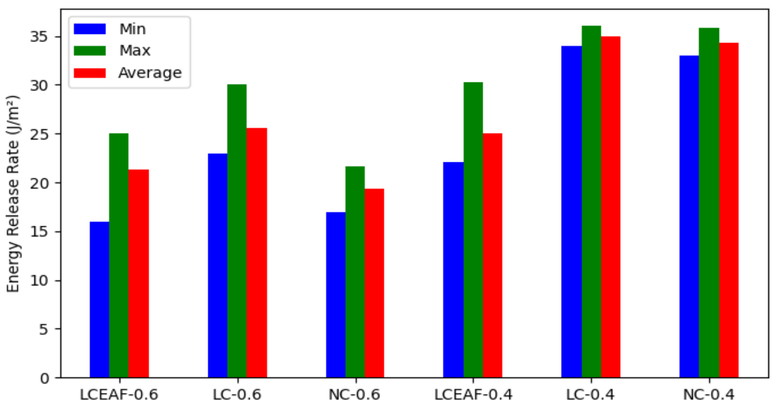


Fig. 19. Energy release rate

6.7 Characteristic Length of Concrete

Characteristic length is inherent property of material which indicates smallest possible width of a zone where damage occurs in a non-local continuum model [26]. It indicates the smallest possible spacing of fracture in discrete fracture model. It is calculated to understand and compare the brittleness of two different materials. The lesser the characteristic length, the lesser the spacing of fracture due to easier crack propagation and more brittle the material. It helps to predict how materials will behave when they start to break. The following formula (7) from [27] can be used to compute it. Here f_{st} is split tensile strength, G_f is fracture energy and E is elastic modulus.

$$L_{ch}(mm) = \frac{EG_f}{{f_{st}}^2} \quad (7)$$

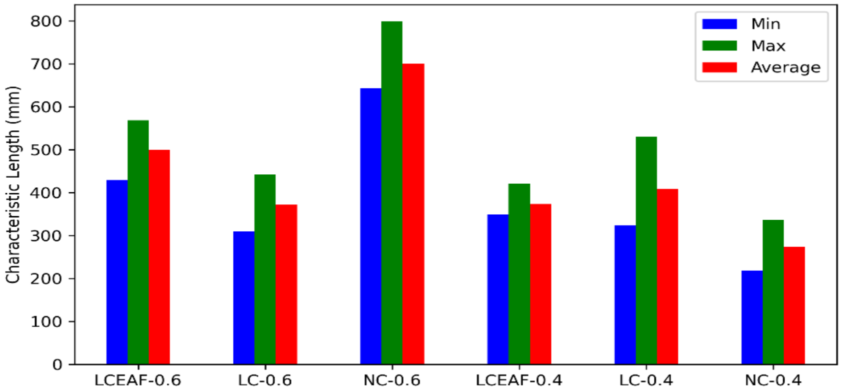


Fig. 20. Characteristic length

The characteristic length of lightweight concrete is shorter than normal concrete for w/b ratio 0.6. However, the difference in characteristic length of lightweight concrete is less in comparison to normal concrete for w/b ratio 0.4. For w/b ratio of 0.6, the average characteristic length for all the six concrete mixes varies from 380 to 700 mm. For w/b ratio of 0.4, the average characteristic length for all the six concrete mixes varies from 290 to 400 mm. The average characteristic length is comparable for both lightweight concrete with SFA and natural fine aggregates and lightweight concrete with SFA and EAF slag as fine aggregate.

7. Conclusions

From the experimental study on mechanical behavior of normal weight and lightweight concrete in terms of compressive strength, split tensile strength, modulus of elasticity, stress strain behavior and fracture parameters using three different concrete systems namely (a) normal concrete (NC), (b) lightweight concrete with SFA and natural fine aggregates (LC) and (c) lightweight concrete with SFA and electric arc furnace slag as fine aggregate (LCEAF); following conclusions are drawn:

- Split tensile strength tests revealed that lightweight concrete exhibits a split tensile to compressive strength ratio between 5% and 7%, while this ratio ranges from 5% to 10% for normal weight concrete. The elastic modulus in case of lightweight concrete is about 60-70% of elastic modulus of normal weight concrete.
- As compared to normal weight concrete, which shows linear behavior up to 35-50% of maximum load, the stress strain plot of lightweight concrete depicts linear behavior up to 70-80% of peak load for lightweight concrete. The fracture in case of lightweight aggregate with sintered fly ash lightweight aggregate-based concrete is happening around the aggregate due to internal curing and prolonged hydration happening because of porous nature of sintered fly ash lightweight aggregate.
- The comparison of load-CMOD and Load Deflection behavior of lightweight concrete and normal concrete for both w/b 0.4 and 0.6 indicates that ascending portion of Load–Deflection and load-CMOD plot of concrete with SFA slightly steeper and linear than normal weight concrete. The non-linear ascending and

descending branches in flexural curves of lightweight concrete with SFA can be correlated with the non-linearity in tensile mode stress-strain behavior and formation of the process zone of fracture in front of the initial notch.

- The fracture energy of both normal concrete and lightweight concrete are comparable. For w/b ratio of 0.6, the average fracture energy for all the six concrete mixes varies from 100 to 125 N/m. For w/b ratio of 0.4, the average fracture energy for all the six concrete mixes varies from 125 to 180 N/m. In case of sintered fly ash lightweight aggregate-based concrete, the fracture is happening around the aggregate. The reason behind this phenomenon can be attributed to development of large stress at interface of lightweight aggregate-paste matrix due to incompatibility of elastic modulus of both aggregate-paste matrices.
- The average stress intensity factor is comparable for both lightweight concrete with SFA and natural fine aggregate and lightweight concrete with SFA and EAF slag as fine aggregate. As the w/b ratio decreases the KIC for both lightweight concrete and normal weight concrete increases. It is also seen that KIC increases with increase in concrete's compressive strength because formation of initial cracks depends upon the tensile strength of the beam.
- The lightweight concrete shows higher energy release rate in comparison to normal weight concrete for both w/b ratios. It indicates that in the lightweight concrete the strain energy release with formation of new crack will be higher than normal weight concrete which was evident in stress strain behavior also where a greater number of crack formation occurs at peak stress.
- The characteristic length of lightweight concrete is smaller than normal concrete for w/b ratio 0.6. However, the difference in characteristic length of lightweight concrete is smaller in comparison to normal concrete for w/b ratio 0.4.
- The mechanical and fracture behavior of lightweight concrete is different from normal concrete in terms of elastic modulus, stress strain characteristics, crack propagation process zone and characteristics length and needs to be considered appropriately in design of concrete depending upon type of application. However, mechanical and fracture behavior of lightweight concrete with SFA and natural fine aggregates and lightweight concrete with SFA and EAF slag as fine aggregate is comparable.

References

[1] Singh B, Singh SB, Barai SV. Performance of concrete made using sintered fly ash lightweight aggregate-A review. Indian Concrete Journal. 2023;97(7):41-59.
[2] Ojha PN, Singh B, Behera AK. Sintered fly ash lightweight aggregate-Its properties and performance in structural concrete. Indian Concrete Journal. 2021;95(6):20-30.
[3] Mazloom M, Mirzamohammadi S. Fracture of fibre-reinforced cementitious composites after exposure to elevated temperatures. Magazine of Concrete Research. 2020;73:701-713. https://doi.org/10.1680/jmacr.19.00401
[4] Mazloom M, Saffari A, Mehrvand M. Compressive, shear and torsional strength of beams made of self-compacting concrete. Computers and Concrete. 2015;15:935-950. https://doi.org/10.12989/cac.2015.15.6.935
[5] Mazloom M, Mirzamohammadia S. Computing the fracture energy of fiber reinforced cementitious composites using response surface methodology. Advances in Computational Design. 2021;6(3):225-239.
[6] Hillerborg A, Modeer M, Peterson PE. Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cement and Concrete Research. 1976;6(6):773-782. https://doi.org/10.1016/0008-8846(76)90007-7

[7] Jenq YS, Shah SP. Two parameter fracture model for concrete. Journal of Engineering Mechanics. 1983;111(10):1227-1241. https://doi.org/10.1061/(ASCE)0733-9399(1985)111:10(1227)
[8] Bazant ZP, Oh BH. Crack band theory for fracture of concrete. Materials and Structures. 1983;16(3):155-178. https://doi.org/10.1007/BF02486267
[9] Zhang MH, Gjorv OE. Mechanical properties of high strength lightweight concrete. ACI Materials Journal. 1991;88(3):240-247. https://doi.org/10.14359/1839
[10] Patel V, Singh B, Arora VV. Study on fracture behaviour of high strength concrete including effect of steel fiber. Indian Concrete Journal. 2020;94(4):1-9.
[11] Ojha PN, Singh B, Singh A, Patel V, Arora VV. Experimental study on creep and shrinkage behaviour of high strength concrete. Indian Concrete Journal. 2021;95(2):30-42.
[12] RILEM TC-50 FMC. Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. Materials and Structures. 1985;18:106-290. https://doi.org/10.1007/BF02472918
[13] Shah SP. Determination of fracture parameters (KIcs and CTODc) of plain concrete using three-point bend tests. Materials and Structures. 1990;23:457-460. https://doi.org/10.1007/BF02472029
[14] Sahoo S, Lakavath C, Suriya SS. Experimental and analytical studies on fracture behavior of fiber-reinforced structural lightweight aggregate concrete. Journal of Materials in Civil Engineering. 2021;33(5). https://doi.org/10.1061/(ASCE)MT.1943-5533.0003680
[15] Trivedi N, Singh RK, Jayant C. A comparative study on three approaches to investigate size independent fracture energy of concrete. Engineering Fracture Mechanics. 2015;138:49-62. https://doi.org/10.1016/j.engfracmech.2015.03.021
[16] Murthy AR, Ganesh P, Kumar SS, Iyer NR. Fracture energy and tension softening relation for nano-modified concrete. Structural Engineering and Mechanics. 2000;54(6):1201-1216. https://doi.org/10.12989/sem.2015.54.6.1201
[17] Gil DM, Golewski GL. Effect of silica fume and siliceous fly ash addition on the fracture toughness of plain concrete in mode I. In: IOP Conference Series: Materials Science and Engineering. Institute of Physics Publishing; 2018. https://doi.org/10.1088/1757-899X/416/1/012065
[18] Siregar APN, Rafiq MI, Mulheron M. Experimental investigation of the effects of aggregate size distribution on the fracture behaviour of high strength concrete. Construction and Building Materials. 2017;150:252-259. https://doi.org/10.1016/j.conbuildmat.2017.05.142
[19] IISI Steel Statistical Yearbook. Brussels, Belgium: International Iron and Steel Institute; 2004. Available from: http://www.worldsteel.org/
[20] Pellegrino C, Gaddo V. Mechanical and durability characteristics of concrete containing EAF slag as aggregate. Cement and Concrete Composites. 2009;31:663-671. https://doi.org/10.1016/j.cemconcomp.2009.05.006
[21] Abu-Eishah S, El-dieb A, Bedir M. Performance of concrete mixtures made with electric arc furnace (EAF) steel slag aggregate produced in the Arabian Gulf region. Construction and Building Materials. 2012;34:249-256. https://doi.org/10.1016/j.conbuildmat.2012.02.012
[22] Motz H, Geiseler J. Products of steel slags-an opportunity to save natural resources. Waste Management. 2001;21:285-293. https://doi.org/10.1016/S0956-053X(00)00102-1
[23] Pellegrino C, Cavagnis P, Faleschini F, Brunelli K. Properties of concretes with black/oxidizing electric arc furnace slag aggregate. Cement and Concrete Composites. 2013;37:232-240. https://doi.org/10.1016/j.cemconcomp.2012.09.001

[24] Faleschini F, De Marzi P, Pellegrino P. Recycled concrete containing EAF slag: environmental assessment through LCA. European Journal of Environmental and Civil Engineering. 2014;18. https://doi.org/10.1080/19648189.2014.922505
[25] Arribas I, Santamaria A, Ruiz E, Ortega-Lopez V, Manso JM. Electric arc furnace slag and its use in hydraulic concrete. Construction and Building Materials. 2015;90:68-79. https://doi.org/10.1016/j.conbuildmat.2015.05.003
[26] Adegoloye G, Beaucour LA, Ortola S, Noumowe A. Concretes made of EAF slag and AOD slag aggregates from stainless steel process: mechanical properties and durability. Construction and Building Materials. 2015;76:313-321. https://doi.org/10.1016/j.conbuildmat.2014.12.007
[27] Manso JM, Polanco JA, Losanez M, Gonzalez JJ. Durability of concrete made with EAF slag as aggregate. Cement and Concrete Composites. 2006;28:528-534. https://doi.org/10.1016/j.cemconcomp.2006.02.008
[28] Akinmusuru JO. Potential beneficial uses of steel slag wastes for civil engineering purpose. Resources Conservation and Recycling. 1991;5:73-80. https://doi.org/10.1016/0921-3449(91)90041-L
[29] Bureau of Indian Standards. Ordinary Portland Cement-Specification IS 269. 2015.
[30] Bureau of Indian Standards. Coarse and Fine Aggregate for Concrete-Specification IS 383. 2016.
[31] Bureau of Indian Standards. Concrete Admixtures-Specification IS 9103-1999. 1999.
[32] Bureau of Indian Standards. Concrete Mix Proportioning-Guidelines IS 10262. 2019.
[33] Bureau of Indian Standards. Artificial Lightweight Aggregate for Concrete-Specification Part 2: Sintered Fly Ash Coarse Aggregate IS 9142 (Part-2). 2018.
[34] Nadesan MS, Dinakar P. Mix design and properties of fly ash waste lightweight aggregates in structural lightweight concrete. Case Studies in Construction Materials. 2017;7:336-347. https://doi.org/10.1016/j.cscm.2017.09.005
[35] Bureau of Indian Standards. Hardened Concrete-Methods of Test Part-1, Testing of Strength of Hardened Concrete, Section-1: Compressive, Flexural and Split Tensile Strength IS 516 (Part 1/Sec 1). 2021.
[36] Karamloo M, Mazloom M. An efficient algorithm for scaling problem of notched beam specimens with various notch to depth ratios. Computers and Concrete. 2018;22:39-51.
[37] Arora VV, Singh B, Jain S. Experimental studies on short term mechanical properties of high strength concrete. Indian Concrete Journal. 2016;90(10):65-75.
[38] Arora VV, Singh B, Patel V, Trivedi A. Evaluation of modulus of elasticity for normal and high strength concrete with granite and calc-granulite aggregate. Structural Concrete. 2021;22(S1). https://doi.org/10.1002/suco.202000023
[39] Ojha PN, Singh P, Singh B, Singh A, Mittal P. Fracture behavior of plain and fiber-reinforced high strength concrete containing high strength steel fiber. Research on Engineering Structures and Materials. 2022.
[40] Domagała L. Modification of properties of structural lightweight concrete with steel fibres. Journal of Civil Engineering and Management. 2011;17(1):36-44. https://doi.org/10.3846/13923730.2011.553923
[41] Liu X, Wu T, Liu Y. Stress-strain relationship for plain and fibre-reinforced lightweight aggregate concrete. Construction and Building Materials. 2019. https://doi.org/10.1016/j.conbuildmat.2019.07.135
[42] Mazloom M, Salehi H. The relationship between fracture toughness and compressive strength of self-compacting lightweight concrete. IOP Conference Series: Materials Science and Engineering. 2018; 431. https://doi.org/10.1088/1757-899X/431/6/062007
[43] Bazant Z P, Planas J. Fracture and Size Effect in Concrete and Other Quasibrittle Materials. Florida, CRC Press, First Published 1998.