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Determination of Fracture Parameters of Self-Compacting Lightweight Concrete Considering Maximum Aggregate Size by Work of Fracture Method

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Abstract - *This paper presents a study about the determination of fracture parameters of self-compacting lightweight concrete(SCLC) by considering the maximum size of the coarse aggregate, by using the method called work of fracture method. By using three-point bending tests on notched beam specimens of varying size but with geometrical similarities, the peak loads were observed and the values are used for evaluating the fracture parameters of SCLC. The test results showed that with the increase in the size of coarse aggregates used, there is an increase the fracture energy of the specimens and this can be explained in terms of changes in fractural dimensions of the specimen.*

Key Words: SCLC, Fracture Energy, Fracture Zone Length, Crack-tip Opening Displacement. Light Weight Expanded Clay Aggregate(LECA).

1. INTRODUCTION

Self-Compacting Lightweight Concrete(SCLC) can be defined as the concrete in which the light weight coarse aggregate(LWC) and the normal fine aggregates are embedded in to it in a highly flowable state, so that they will be having the ability to flow through the obstacles and fills the complex shapes under its own weight without bleeding and segregation [1]. SCLC comprises the advantages of LWC, such as reduced dead loads, high insulation capacity, improved durability, resistance against fire and chemical attack, provision of large span structures and reduction in member dimensions with self-compacting characteristics that are reflected into the material's filling and passing ability and its segregation resistance. In this regard, SCLC may be an answer to the increasing construction requirements of densely reinforced structures and precast elements [2]. Taking in to consideration the weight reduction and ease of placement, SCLC may be the answer to the increasing construction requirements of slenderer and more heavily reinforced structural elements. Furthermore, vibration of lightweight concrete tends to be less efficient, which makes SCLC potentially more competitive.

Apart from the above mentioned advantages, the use of high amounts of ultra-fine particles, light weight aggregates and powerful super plasticisers, there arises a difference in the overall performance and properties of Normal Aggregate Concrete (NAC), SCC, LWC and SCLC. These differences may causes changes in the crack pattern, mechanical as well as fracture behavior of SCC, NAC, LWC and SCLC.

1.1 Fracture Mechanics

Fracture study, commonly called as fracture mechanics, is the field of study concerned with the development and propagation of cracks in materials. It applies the physics of stress and strain behavior of materials, in particular the theories of elasticity and plasticity, to the microscopic crystallographic defects found in real materials in order to predict the macroscopic mechanical behavior of those materials. The prediction of crack growth is at the heart of the damage tolerance mechanical design discipline [3].

Fracture behavior of concrete as quasi-brittle material is an important aspect to be considered for the analysis and design of engineering structures especially dams, nuclear power plants, tunnels and bridges. It has been proved that increase of paste volume in concrete may lead to decrease in aggregate bridging and interlock across the crack resulting in the reduction in the energy absorption. The elastic-plastic fracture mechanics is used for the determination of fracture properties of concrete. The major fracture parameters considered in this study are fracture energy, length of fracture process zone, brittleness number, fracture toughness and crack-tip opening displacement [3].

- Fracture Energy: Fracture energy is the energy required to open unit area of crack surface [3].
- Length of Fracture Process Zone: In concrete there is some intermediate space between cracked and uncracked portion and this region is called the fracture process zone [3].
- Brittleness Number: It is a number that is used to define the degree of brittleness of a number. [4].
- Fracture Toughness: It is the ability of a material to resist fracture [3].
- Crack-tip opening displacement: It is the displacement at the original crack tip and 90º intercept. It is the only parameter that accommodates crack tip plastically [3].

2. METHODS FOR THE EVALUATION OF FRACTURE PARAMETERS

2.1 Work of Fracture Method

One of the simplest methods to determine the fracture energy, as the most important fracture parameter of concrete, is work of fracture method introduced by the technical committee RILEM 50-FMC [5] during 1985. In this method, using three-point bending test on notched beams and determining the work needed to create a crack with unit surface area projected in a plane parallel to the crack direction, as the beam is broken in two parts, the specific fracture energy is determined by Eqn 1

$$G_f = \frac{W_f}{b(d - a_0)} \tag{1}$$

Where W_f is the total amount of work of fracture in the test when the beam is halved which is equal to the area under load–displacement curve, b is the beam width, d is the beam height and a_0 is the notch depth. The length of fracture process zone is calculated by the Eqn 2.

$$L_{ch} = \frac{E G_f}{f_t^{2}} \tag{2}$$

Where E is the modulus of elasticity, f_t is the tensile strength and G_f is the fracture energy.

3. MATERIALS AND METHODS

3.1 Cement

The cement used is OPC 53 grade. The tests were conducted according to Indian Standard recommendations [6].The physical properties of cement are tabulated in Table 1

Table -1: Physical Properties of Cement

Tests	Results	Acceptable Limits
Specific Gravity	3.15	3.10-3.16[7]
Standard Consistency	31%	26-33[8]
Setting Time	45 minutes	≥30 minutes[8]
	350 minutes	≤600 minutes[8]
Compressive Strength	55MPa	>53 MPa(672 hrs)[8]

3.2 Fine Aggregate

Fine aggregate used for the present study is manufactured sand. Fine aggregate under saturated surface dry condition was used for casting. The physical properties of fine aggregate were tabulated in Table 3.2

Table -2: Physical Properties of Fine Aggregate

Tests	Results	Acceptable Limits
Specific Gravity	2.61	2.4-3[9]
Water Absorption	1.3%	0.1 – 2%[10]
Bulk Density (Loosely Packed Aggregate)	1460 kg/m³	1450-1650 kg/m³[9]
Bulk Density (Tightly Packed Aggregate)	1500 kg/m³	1450-1650 kg/m³[9]

3.3 Coarse Aggregate (Light Weight Expanded Clay Aggregate)

The coarse aggregate used is light weight expanded clay aggregate and Fig 1 shows the typical photograph of it.

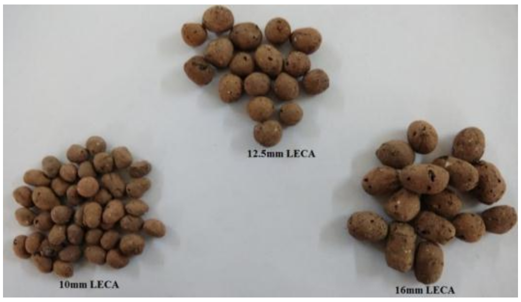

Fig -1: Typical Photograph of Light Weight Expanded Clay Aggregate

The physical properties of light weight coarse aggregate is given in Table 3

Table- 3: Properties of Expanded Clay Aggregate

Tests	Results	Acceptable Limits
Specific Gravity	1.1312	0.6 – 1.35%[11]
Water Absorption	18%	2 - 26.5%[11]
Bulk Density (Loosely Packed CA)	304 kg/m³	<880 kg/m³[11]

Bulk Density (Tightly Packed CA)	350 kg/m^3	<1480 kg/m^3[11]
Aggregate Crushing Value	32%	< 45 % [10]

3.4 Fly Ash

The constituents of fly ash are tabulated in Table 4.4.

Table-4: Constituents of Fly Ash (As Given by the manufacturer)

Ingredients	Percentage
Silicon dioxide(SiO_2)+ Aluminum oxide (Al_2O_3)+Iron oxide (Fe_2O_3)	11.8
Silicon dioxide(SiO_2)	59
Reactive silica	27
Magnesium oxide (MgO)	1.62
Total Chloride	0.0096

3.5 Superplasticiser

The super plasticizer used was Master Glenium SKY 8233. The physical properties of superplasticizer are tabulated in table 5.

Table -5: Properties of Superplasticiser

PROPERTIES	SPECIFICATION(Provided by the manufacturer)
Appearance	Light Brown Liquid
pH	≥6
Relative Density	1.08 ±0.01 at 25º*C*
Chloride ion content	<0.2%

4. MIX DESIGN OF SCLC

There is no standard method for mix design of SCLC and many academic institutions, ready-mixed, precast and contracting companies have developed their own mix proportioning methods. In this study, the mix design procedure was carried out by using modified Nan Su method [18], which satisfied the requirements of EFNARC guidelines [30]. The mix proportion of unit volume of concrete was tabulated in Table 6.

Table -6 : Proportions of M30 Grade SCC (for 1 m^3 volume of concrete)

Cement		375 kg		
Fine Aggregate		835.704 kg		
Coarse Aggregate	Class	SCLC 1	SCLC 2	SCLC 3
	4.75 mm – 10 mm	174 kg	74 kg	74 kg
	10 mm – 12.5 mm	-	100 kg	50 kg
	12.5 mm – 16mm	-	-	50 kg
Fly ash		384.3 kg		
Water		286.68 *l*		
Superplasticiser		0.6% of powder content.		

5. RESULTS AND DISCUSSIONS

5.1 Fresh Concrete Properties

As per EFNARC [12], SCC can be classified on the basis of slump-flow as SF1, SF2 and SF3, viscosity as VS1/VF1 and VS2/VF2 and on passing ability as PA1 and PA2.Fresh properties of mixes were tabulated in Table 7

Table – 7: Fresh Properties of SCLC

Properties / Designation	Slump-flow (mm)	T500 (s)	L – box test (mm)	V – funnel test (s)
	Value	Values	Value	Value
SCLC1	710	3	0.8	6
SCLC2	690	4	0.85	8
SCLC3	680	4	0.85	8

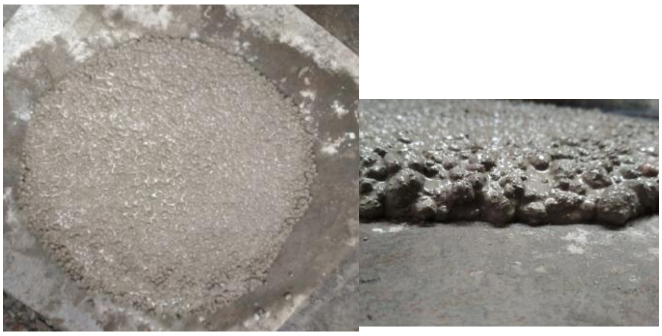

Fig -2: Typical Photograph of Slump – flow

5.2 Hardened Concrete Properties

5.2.1Compressive Strength

The variation of compressive strength foe the given three types of SCLC are shown in Fig.6.2.

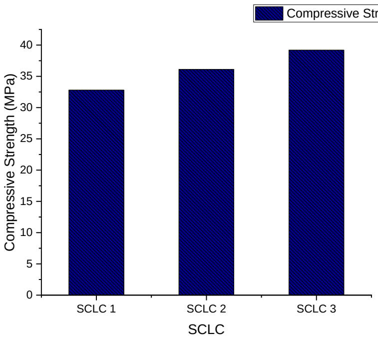

Fig -3: Compressive Strength Test Results for SCLC

Here with the increase in the maximum aggregate size of the specimens, there is an increase in the compressive strengths of the concrete. The compressive strength of SCLC 2 is about 109.75% as that of SCLC 1. Similarly the compressive strength of SCLC 3 is about 119.5% of SCLC1 and 108.8% of SCLC 2. This increment in compressive strength is because, with the decrease in aggregate size, the surface area of aggregates gets increased, which in turn decreases the stress in interfacial transition zone (ITZ). When concrete is under load, crack will prefer to pass through the weaker zones such as ITZ. With the increase in aggregate size there will be more concentration of stresses in ITZ and results in increase of its strength.

5.2.2 Three Point Bending Test Result

Three point bending tests are carried out in notched beam specimens for determing the fracture parameters of SCLC using WFM.

Fig -4: Typical Photograph of Failure of Notched Beam Specimens under Three- Point Loading

The results obtained for WFM is shown in Fig 5.

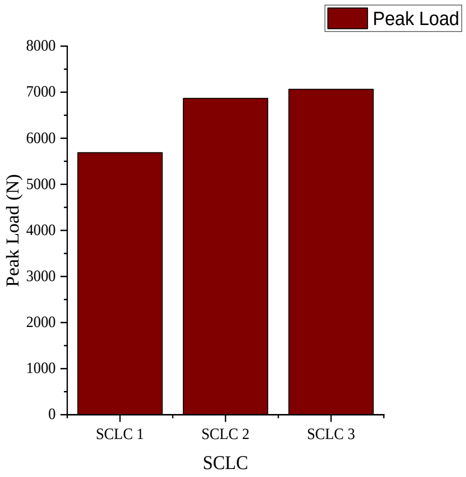

Fig -5: Three Pointe Bending Test Results for WFM

Here there is an increase in the peak load of the notched beam specimens with the increase in maximum aggregate size. Here SCLC 2 is having a peak load equal to 1.03 times as that of SCLC 1. Similarly the peak load of SCLC 3 is equal to 1.16 times the peak load of SCLC 2 and 1.20 times the peak load of SCLC 1. This can also be due to the changes in the ITZ charecteristics of SCLC.

6. ANALYSIS OF TEST RESULTS USING WFM

For determining the fracture energy, the area under the load displacement curve of the notched beam specimens are evaluated and are substituted in the specified equations. The load deflection curve for the notched beam specimens of size 100mm×100mm ×500mm under three-point bending is shown in Fig **6.**

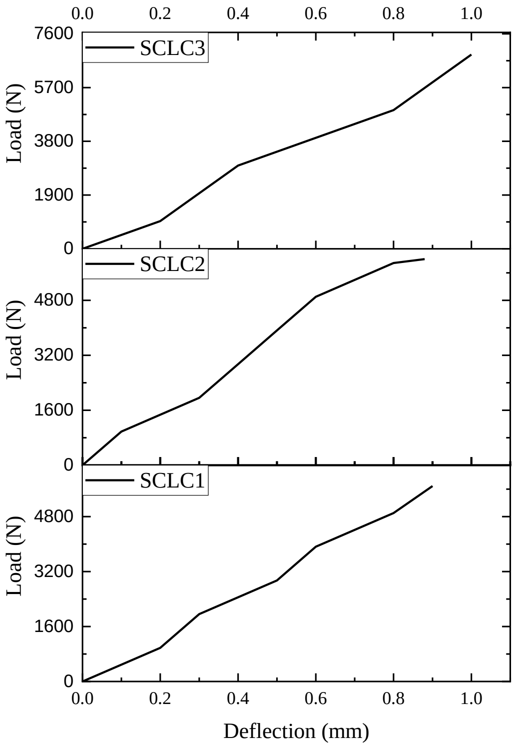

Fig -6 : Load – Deflection Curve for WFM

By using the area under the load-displacement graph, The work for fracture is determined, and hence the other fracture parameters. By using Eqns. 1 and 2, the fracture energy and characteristic length is determined and are shown in Fig -8.

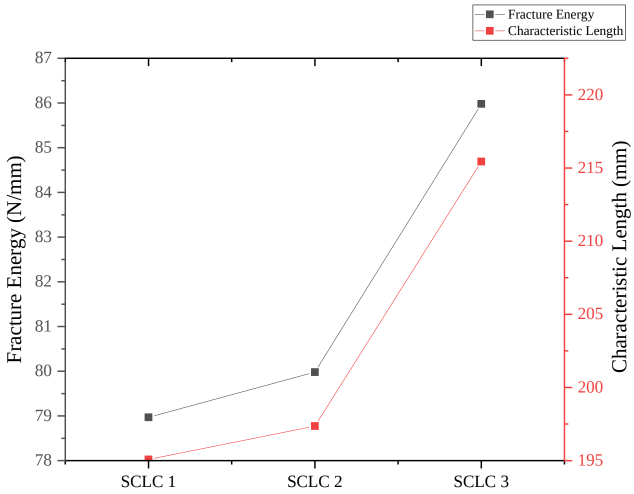

Fig -7: The variation of Fracture Energy and characteristic length for Various SCLC

From Fig -7, it can be seen that there is an increase in the fracture energy as well as characteristic length with the increase in maximum aggregate size. SCLC 1 and SCLC 2 have similar fracture energy but SCLC 3 have fracture energy equal to 109.19% of fracture energy of SCLC 1 and 107.51% of the fracture energy of SCLC 2. This increase in fracture energy with the increase in maximum aggregate size can be explained in terms of its ITZ characteristics. When concrete is under load, cracks prefer to pass through the weak zones such as ITZ and huge paste pores. As the aggregate size increases, the fracture path becomes complex and a high energy is required to overcome the strength of ITZ and thus the fracture energy increases [2].

Similar variation is also shown by the characteristic length with the various types of SCLC. There is a percentage increment of about 1.16% and 10.43% of characteristic length of SCLC 2 and SCLC 3 respectively with SCLC 1. The increase in the fracture energy with the increase in the maximum aggregate size of the specimen may lead to the increase in the characteristic length of the specimens with increase in aggregate sizes used.

7. CONCLUSIONS

In this study the effects of maximum size of coarse aggregate on the fracture characteristics of SCLC using notched beams of different sizes according to RILEM recommendations were investigated and the results obtained can be summarized as follows:

1. The compressive strength of SCLC increases with the increase in the maximum aggregate size used.
2. The results obtained through WFM indicate that there is an increase of about 10% in fracture energy and characteristic length for an increase of aggregate size from 10 mm to 16 mm.

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