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Effect of Aggregate Shape, Size and Texture on Fracture Parameters of High Strength Concrete

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ABSTRACT: Effect of morphological characteristics of aggregates namely shape, size and texture on fracture parameters of high strength concrete is studied in this study. As aggregates are major constituents of concrete, their influence on fracture parameters of concrete is inevitable. Here, this effect has been studied for concrete with compressive strength of 60 MPa. Three point bending tests are performed on 24 notched specimens of size 150 x150 x 600 mm. The beam specimens are prepared with varying aggregate size, shape and surface texture. The manufactured sand and natural sand are used in the design mix of the concrete. Aggregate shape and texture are quantified using Index of Aggregate Particle Shape and Texture (IAPST). It is observed that fracture energy (G_f), fracture toughness (K_{1c}), critical crack tip opening displacement ($CTOD_c$) and characteristic length (l_{ch}) of concrete increase with maximum size of the coarse aggregate. Specimen prepared with manufactured sand gives higher values fracture energy, fracture toughness, critical crack tip opening displacement and characteristic length compared with that of concrete made with natural sand.

KEYWORDS: Fracture energy, Fracture toughness, Surface texture, Three Point Bending, Two Parameter Fracture Model.

I. INTRODUCTION

Concrete is generally regarded as three phase material composed of aggregates, binding material and interfacial transition zone between them. Therefore, concrete properties depend on these component phases and interaction between them. Aggregate occupies 60-70% volume of concrete mix. Therefore, aggregates have more effect on fracture behavior of concrete including rheological properties, mechanical behavior and durability of concrete mix.

II. LITERATURE REVIEW

Many researchers (Tasong et al. 1999; Perry and Gillot 1977; Prokopski and Halbinial 2000) concluded that the type of aggregates used in concrete mix can strengthen or weaken the interfacial transition zone of concrete mix; and they also affect fracture mechanics parameters of concrete. Aitcin and Mhehta (1990) found that the stiffer and stronger aggregates give higher elastic modulus of concrete. Coarse aggregates with proper mineralogy and surface texture can improve concrete compressive strength. Jenq and Shah (1985) observed practically that concrete is neither perfect elastic nor perfect brittle material, but some strain softening occurs in the concrete. Hillerborg (1985) shows increased values of concrete fracture energy for largest aggregate size. Appa Rao and Raghu Prasad (2002) investigated an effect of maximum aggregate sizes on fracture properties of high strength concrete and concluded that the fracture energy, fracture toughness, characteristic length and compressive strength of concrete increase with increasing largest size of aggregates. Zhou et al. (1995) (8); Zhou et al. (1995) (9) found increase in values of fracture energy with maximum aggregate size. Chen and Liu (2004) and Chen and Liu (2007) studied influence of maximum aggregate size and aggregate volume fraction on fracture properties of high strength concrete using acoustic emission technique and concluded that fracture energy and fracture toughness values are increasing with larger aggregate size which attained greatest values at 60% of aggregate content. Tasdemir et al. (1996) concluded that fracture energy and characteristic length increase with largest coarse aggregate size for concrete without silica fume; whereas in case of concrete with silica fume, fracture energy and characteristic length decrease with maximum size of aggregates. However brittleness increases significantly with maximum size of aggregates as per their findings. Elices and Rocco (2008) reported that the fracture energy increases as the aggregate size increases. RILEM TC 50 - FMC (1985) recommended method for determining fracture energy using three point bending test and found that maximum size of aggregates is an influencing factor for fracture energy. Nikbin et al. (2014) found that with increase of coarse aggregate volume, fracture energy increases also effect of coarse aggregate content on fracture performance of self-compacting concrete was studied by Work of Fracture Method (WFM) and Size Effect Method (SEM). Beygi et al. (2014) investigated that fracture energy and fracture toughness both increases as largest aggregates size increases and also brittleness index increases in self-compacting concrete. They also found that fracture toughness increases when volume of coarse aggregates increases from 30-60%. Chang et al. (1998); Hassanzadeh M. (1998) concluded that certain quantity and size of aggregates are favourable to the strength and fracture energy for the different composite materials.

Barr et al. (1986) investigated impact of largest aggregate size on fracture toughness and result shows that the fracture toughness is not dependent on coarse aggregates size. Akcaoglu et al. (2004) reported that the critical stress at which crack propagation initiates has no significant effect with increasing aggregate size in low strength concrete whereas in case of high strength concrete critical stress is less and decreases with increasing size of aggregates. Amparano et al. (2000) observed that with increase in range of aggregates volume fraction (45% - 75%), fracture energy varies within 25% and concluded that maximum fracture energy is not achieved with any critical volume fraction. They also stated that fracture energy decreases with more aggregate content; it reaches minimum value at 65% of aggregate volume and then starts getting more values of fracture energy. Petersson (1980) concluded that the fracture energy is not influenced by greatest size of aggregates but more values of characteristic length obtained for greater aggregates size. Kim et al. (1997) studied aggregate size distribution, shape and texture of manufactured sand and concluded that the fracture energy was less influenced by the type of fine aggregates. Wolinski et al. (1987) reported that aggregates of size 2 mm to 32 mm have insignificant effect on fracture parameters of concrete.

(Jing Hu et al. 2006) suggested a reliable and economic method for characterization of aggregate shape by using stereological method and Fourier analysis for different types of coarse aggregates. The work of (Swift 2007) involves comparative study between physical test, ASTM standard and AASHTO standard for determination of shape, angularity and texture of coarse aggregates. Morphological characteristics are captured by a few researchers by digital image processing techniques (Tafesse Solomon et al.; Snehal Chaudhari 2016; Maria Leon and Fernando Ramirez 2010; Mangulkar and Jamkar 2016). (Wang 2003) proposed Fourier morphology analysis method to quantify shape, angularity and texture of aggregates. (Dallas Little et al. 2003) also used image analysis method for quantifying aggregate shape, angularity and surface texture also they studied their performance. Hossain et al. (1999) provided comparable measures of aggregate particle shape, angularity and surface texture. Several manual methods of ASTM C 136, ASTM D 4791, ASTM D 3398, ASTM C 1252 are indirect methods for measurement of physical properties of aggregates. ASTM D 3398 (2006) is used to determine particle index for various aggregate shapes and surface textures.

III. EXPERIMENTAL PROCEDURES

1. Materials

Portland cement of grade 53 was used. Fine aggregate, manufactured sand and natural sand, having fineness modulus 2.96 and 2.90 respectively were used in this work. Specific gravity of manufactured sand and natural sand was 2.74 and 2.69 respectively. The coarse aggregates were used of specific gravity 2.91 and 2.94, with 10 mm, 20 mm aggregate sizes respectively. The silica was used as 5% by weight of cement. Fly ash as mineral admixture is used. Conplast (SP430 (NE)) superplasticizer was used to prepare the M 60 grade concrete.

2. Aggregate shape and texture

In the present work the shape and texture of fine aggregates are quantified using ASTM D 3398-2006. This is manual method for determination of particle index which represent shape and surface texture characteristics of aggregates. The cylindrical mold, tamping rod and weighing balance is used in this method.

I_a = Index of aggregate particle shape and texture (IAPST) for manufactured sand and natural sand is obtained as 15.63 and 11.40 respectively.

3. Specimen Preparation

RILEM TC 89 – FMT (1990) has given recommendations of specimen geometry and test procedure for determining concrete fracture energy using three point bending test. Four different batches of beam specimens were prepared considering all the variables. Batch I and II specimens were prepared with 10 mm and 20 mm largest size of coarse aggregates with manufactured sand. Batch III and IV specimens were prepared with same sizes of coarse aggregates with natural sand. Compositional proportions of concrete mixes for all batches of beam specimen are listed in Table 1.

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| Volume 10, Issue 2, March 2023|

Initially all dry materials were mixed thoroughly in proper proportion. Water was added in mix to prepare uniform concrete mix. Fresh concrete was poured in beam molds of size 150 X 150 X 600 mm having span to depth ratio is 4. Manual tamping was used for compaction of concrete in mold. After a day of casting, the beams were removed from molds and curing done in water tank for 28 days at ambient temperature. After 28 days of complete curing, beam specimens were taken out of water tanks. At the middle bottom of specimens initial notch was made with diamond cutter. Beam specimen of size 150 X 150 X 600 mm was prepared with notch depth of 36 mm.

Table 1. Concrete mixture details per cubic metre.

Components	Batches			
	I	II	III	IV
Cement (Kg/m^3)	450	450	450	450
Water (l/m^3)	194	194	194	194
Manufactured sand / crushed sand (Kg/m^3)	537	537		
River sand / Natural sand (Kg/m^3)			537	537
Max. Size of coarse aggregate 10 mm (Kg/m^3)	1225	1225		
Max. Size of coarse aggregate 20 mm (Kg/m^3)			1225	1225
Total Aggregates (Kg/m^3)	1762	1762	1762	1762
Silica (Kg/m^3)	25	25	25	25
Mineral composition (Kg/m^3)	100	100	100	100
Superplasticizer (l/m^3)	4.5	4.5	4.5	4.5

Compressive strength was measured by testing concrete cube and splitting test was also performed to measure tensile strength of concrete. All the mechanical properties of beams are listed below in Table 2.

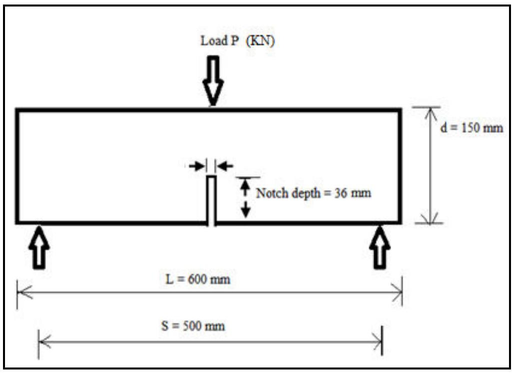
Table 2. Mechanical properties of specimen

Mechanical Properties	Compressive strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (MPa)
Batch I	61.8	4.44	39.08
Batch II	61.78	4.44	40.32
Batch III	58.98	4.33	45.11
Batch IV	58.18	4.29	47.63

4. Testing Equipment

The three point bending tests were carried out on notched specimens on MTS 201.20 machine. A closed loop linear servo hydraulic testing machine with LVDT was used. Generally clip gauge is advised for measurement of crack mouth opening displacement. As per RILEM recommendation, LVDT can be used as a replacement of clip gauge if clip gauge is not available. Crack mouth opening displacement was measured using LVDT, which is mounted at the face of the crack. The deflection was recorded at midspan using a LVDT placed underside of the tested TPB specimen. LVDT was connected to data acquisition system which gives reading of crack mouth opening corresponding to applied load. To avoid error caused due to rotational effect of LVDT, the gauge length is kept as small as possible. The applied load and CMOD readings are recorded simultaneously by data acquisition system, which were used to determine fracture properties of concrete. Rate of loading for test was 0.1 mm/min. Figure 1 shows schematic diagram of three point bending of beam.

Figure 1. Specimen Geometry for Three Point Bending Test



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| Volume 10, Issue 2, March 2023|

5. Two Parameter Fracture Model: This model given by Jenq and Shah (1985), known as two parameter fracture model is a combination of LEFM and Nonlinear model. They stated that the effective crack is present ahead of the real visible crack and effective crack gives actual process zone. Effective crack length (a_e) can be determined using compliance or flexibility. Crack tip opening displacement (CTOD) exists at the tip of real visible crack. The criteria for advancement of the crack, as per this model, are $K_I = K_{Ic}$ and CTOD = $CTOD_c$. Thus, the two parameter fracture model (TPFM) is proposed to incorporate slow crack growth by calculating the critical stress intensity factor (K_{Ic}) at the tip of effective crack (a_e). The second parameter is the critical crack tip opening displacement ($CTOD_c$). These parameters are used to predict most of the experimental outcomes of crack opening mode. The effective crack (a_e) is defined as the crack tip opening displacement at the tip of initial crack attains critical value of CTOD ($CTOD_c$). It is presumed that load and CMOD is approximately linear till nearby half of the peak load and corresponding CTOD is zero. The load and CMOD curve is used to determine Elastic modulus, effective crack length and stress intensity factor from compliance suggested by them.

5.1 Calculation of Elastic Modulus (E)
Elastic modulus of concrete is determined from Load-CMOD plot

$$E = \frac{6S\,(a_0+H_0)V_1(\alpha)}{C_i B\, d^2} \tag{4}$$

H_o = Thickness of knief edge used for holding clip gauge

$V_1(\alpha)$ is the function established from finite element calculations

$$\alpha = \frac{a_0}{d}, \quad V_1\left(\frac{a_0}{d}\right) = 0.760 - 2.28\left(\frac{a_0}{d}\right) + 3.87\left(\frac{a_0}{d}\right)^2 - 2.04\left(\frac{a_0}{d}\right)^3 + \frac{0.66}{\left[1-\left(\frac{a_0}{d}\right)\right]^2}$$ B

= Beam width in mm, d = Beam depth in mm, S = Loading span of beam (mm)

a_0 = initial notch depth (mm), C_i = Initial compliance of load CMOD curve

5.2 Calculation of Effective length of crack (a)

$$E = \frac{6S\,(a+H_0)\,V_1(\alpha)}{C_u B\, d^2} \tag{6}$$

H_0 = Thickness of clip gauge =0

$$E = \frac{6S\,(a)\,V_1(\alpha)}{C_u B\, d^2} \tag{7}$$

a = Effective critical length of crack, a = a_0 + Stable growth of crack at maximum load

C_u = unloading compliance at maximum load which is at 95 % of peak load in post peak stage

5.3 Critical stress intensity factor

$$K_{IC} = \frac{3\,P_{max}\,S}{2Bd^2}\sqrt{\pi a}\,F(\alpha) \tag{8}$$

a = Effective critical crack length (mm), P_{max} = Maximum load (kN)

$$F(\alpha) = \frac{1}{\sqrt{\pi}}\,\frac{1.99-\alpha(1-\alpha)(2.15-3.93\alpha+2.7\alpha^2)}{(1+2\alpha)(1-\alpha)^{3/2}} \tag{9}$$

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| Volume 10, Issue 2, March 2023|

5.4 Critical crack tip opening displacement ($CTOD_c$)

$$CTOD_c = \frac{6P_{max}\, S\, a}{d^2\, B\, E} V_1(\alpha)\,\{(1-\beta)^2 + (-1.149\,\alpha + 1.081)(\beta - \beta^2)\}^{1/2} \quad (10)$$

$$\alpha = \frac{a}{d} \qquad \beta = \frac{a_0}{a}$$

$$V_1(\alpha) = 0.760 - 2.28\,(\alpha) + 3.87(\alpha)^2 - 2.04(\alpha)^3 + \frac{0.66}{[1-(\alpha)]^2} \quad (11)$$

5.5 Fracture Energy: Fracture energy is defined as the ratio of work of fracture W_F and cross section area of initial uncracked ligament A_{lig}. Fracture energy is the energy required to create a crack of unit area. Work of fracture energy can beobtained as the area under the load – CMOD diagram. Fracture energy was found as per RILEM TC 50 – FMC using three point bending test.

$$G_F = \frac{W_0 + mg.\ \delta_{max}}{A_{lig}} \quad (13)$$

$$A_{lig} = [d\,(B - a_0)]\ \ mm^2 \quad (14)$$

B = Beam width mm, d = Beam depth mm, a_0 = depth of notch mm, W_0 = Area under load deflection curve N-m, mg = Self weight of specimen kg, δ_{max} = maximum displacement m.

5.6 Characteristic length: Characteristic length is proportional to fracture energy and inversely proportional to tensile strength of cube and modulus of Elasticity. Length of fracture process zone at growth of crack is approximately same as characteristic length. Characteristic length is a material property. It is given by expression

$$l_{ch} = \frac{E\, G_F}{F_t^{\,2}} \quad (16)$$

F_t = Tensile strength of concrete by splitting test, E = Modulus of Elasticity

IV. RESULTS AND DISCUSSION

Summary of both mechanical and fracture properties of concrete for different shape, size and surface texture of

aggregates is given in Table 3 - Table 6.

1. Fracture Toughness:

(Nallathambi et al. 1984) found increase in fracture toughness with largest aggregate size due to increase in resistance for the propagation of crack. (Appa Rao and Raghu Prasad 2002) reported that increase in fracture toughness with increasing largest size of aggregates. Fracture toughness for concrete using 10 mm and 20 mm aggregate size with manufactured sand (MS) are observed as 2.83 MPa√m and 3.25 MPa√m. In case of concrete using 10 mm and 20 mm aggregate size with natural sand or river sand (RS) are observed as 2.80 MPa√m and 3.18 MPa√m. It results that the fracture toughness shows larger values with increasing largest size of aggregates. Due to increase in size of aggregates, the resistance in propagation of crack increases which results in more fracture toughness for 20 mm aggregate size.

Fracture toughness is more for manufactured sand or crushed sand (CS) as compared to natural sand (NS) due to higher interlock between angular aggregates and rough surface texture of aggregate hence more resistance in the propagation of crack in beam specimen.

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| Volume 10, Issue 2, March 2023|

Table 3. Summary of test results for largest size of coarse aggregate (10 mm) and manufactured sand

Sr. No.	IAPST	P (KN)	δ (mm)	CMOD CMOD (mm)	a (mm)	FPZ (mm)	K_{IC} (MPa√m)	CTOD (mm)	G_f (N/m)	Fc (MPa)	Ft (MPa)	l_{ch}	E (MPa)
1	13.87	12.93	1.84	0.0438	89.04	54.21	3.0	0.0483	114.23	64.0	4.53	184.16	33.09
2	14.54	12.35	1.57	0.0509	87.12	52.12	2.33	0.0434	114.61	66.0	4.61	185.53	34.37
3	15.79	17.10	1.67	0.0484	110.7	74.77	3.25	0.0777	113.65	61.0	4.41	203.24	34.82
4	16.45	14.20	1.58	0.0484	79.49	43.57	2.69	0.0308	113.49	60.2	4.38	296.95	50.21
5	16.74	15.29	1.75	0.0484	119.9	84.34	2.88	0.0596	113.45	60.0	4.37	257.08	43.33
6	16.38	15.20	0.91	0.0476	65.67	30.57	2.87	0.0337	113.36	59.6	4.36	231.01	38.67

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| Volume 10, Issue 2, March 2023|

Table 4. Summary of test results for largest size of coarse aggregate (10 mm) and river sand

Sr. No.	IAPST	P_{max} (KN)	δ (mm)	CMOD (mm)	a (mm)	FPZ (mm)	K_{IC} (MPa√m)	CTOD (mm)	G_f (N/m)	Fc (MPa)	Ft (MPa)	l_{ch}	E (MPa)
1	10.16	10.91	1.5	0.052	97.81	62.81	2.54	0.0351	113.90	62.3	4.46	243.83	42.65
2	10.63	12.37	1.78	0.050	102.34	67.18	2.88	0.0366	113.40	59.8	4.36	290.22	48.74
3	10.37	14.13	1.38	0.057	44.02	50.19	2.48	0.0114	113.37	59.6	4.36	317.17	53.09
4	11.70	13.01	1.77	0.047	88.05	53.22	3.02	0.0296	112.46	55.3	4.18	344.74	53.57
5	13.21	12.48	1.76	0.048	72.75	37.91	2.89	0.0350	113.22	58.9	4.33	211.03	34.91
6	12.36	12.88	1.68	0.046	85.21	50.35	2.99	0.0408	113.04	58	4.29	231.46	37.71

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| Volume 10, Issue 2, March 2023|

Table 5. Summary of test results for largest size of coarse aggregate (20 mm) and manufactured sand

Sr. No.	IAPST	P_{max} (KN)	δ (mm)	CMOD (mm)	a (mm)	FPZ (mm)	K_{IC} (MPa√m)	CTOD (mm)	G_f (N/m)	Fc (MPa)	Ft (MPa)	l_{ch}	E (MPa)
1	13.87	10.74	1.87	0.0819	91.52	56.60	2.49	0.0357	150.14	61.30	4.42	294.62	38.41
2	14.54	14.92	3.48	0.0636	68..85	30.85	3.65	0.0298	150.01	60.80	4.40	333.76	45.65
3	15.79	13.60	0.92	0.0384	93.14	55.94	3.28	0.0439	150.58	63.00	4.49	299.69	40.84
4	16.45	13.00	0.84	0.0425	91.43	55.53	3.07	0.0469	150.27	61.80	4.44	260.37	35.55
5	16.74	16.67	1.37	0.0553	97.70	62.72	3.88	0.0555	150.32	62.00	4.45	301.49	41.15
6	16.38	13.44	1.09	0.050	90.88	61.15	3.14	0.0469	150.03	60.89	4.44	286.47	39.18

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| Volume 10, Issue 2, March 2023|

Table 6. Summary of test results for largest size of coarse aggregate (20 mm) and river sand

Sr. No.	IAP ST	P_{max} (KN)	δ (mm)	CMOD (mm)	a (mm)	FPZ (mm)	K_{IC} (MPa√m)	CTOD (mm)	G_f (N/m)	Fc (MPa)	Ft (MPa)	l_{ch}	E (MPa)
1	10.16	11.08	1.66	0.0483	73.36	38.36	2.58	0.0357	149.74	59.8	4.36	240.75	30.92
2	10.63	12.70	1.38	0.0352	60.37	25.87	2.93	0.0265	150.01	60.8	4.40	283.20	36.62
3	10.37	14.56	2.22	0.0330	92.85	57.73	3.39	0.0575	147.82	53.0	4.08	291.31	32.87
4	11.70	13.34	1.99	0.0430	129.7	93.36	3.17	0.0489	148.98	57.0	4.25	219.31	50.93
5	13.21	15.99	1.94	0.0390	141.8	106.0	3.77	0.1044	149.25	58.0	4.29	252.51	31.16
6	12.36	14.15	1.90	0.0465	119.5	84.99	3.26	0.0483	149.74	59.8	4.36	289.14	49.50

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| Volume 10, Issue 2, March 2023|

In case of rounded aggregates, particles with roundness and smooth texture of aggregates results lower interlocking in concrete. Variation of fracture toughness with aggregate shape and texture index is shown in figure 2 and 3.

Figure 2. Fracture toughness Vs Aggregate shape and texture index for 10 mm size of aggregate (Manufactured sand and River sand)

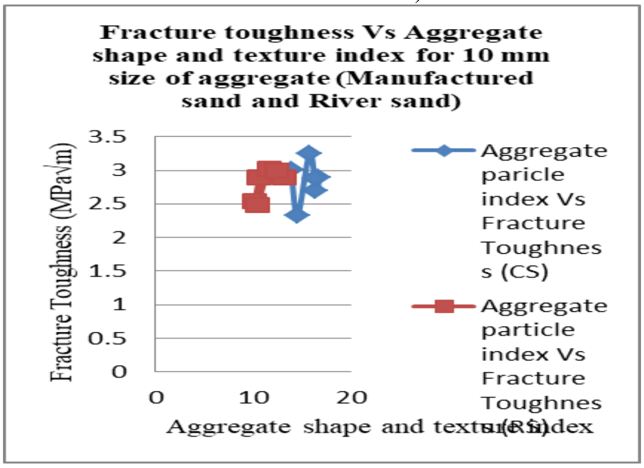
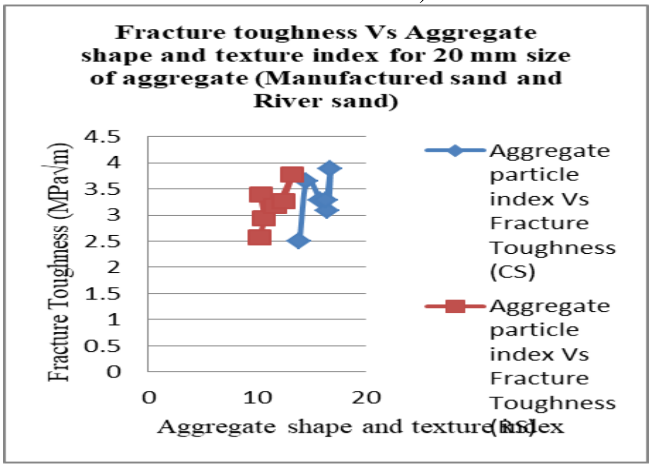


Figure 3. Fracture toughness Vs Aggregate shape and texture index for 20 mm size of aggregate (Manufactured sand and River sand)



2. Critical crack tip opening displacement:

It is observed that critical CTOD is more for 10 mm size of aggregates than 20 mm size of coarse aggregate. Due to more resistance provided by 20 mm aggregate size than 10 mm aggregate size the values of CTOD is more for larger size of aggregates. Variation of Critical crack tip opening displacement with aggregate shape and texture index is shown in Figure 4 and 5, which indicates that critical crack tip opening displacement is more for manufactured sand due to proper interlock of manufactured or crushed sand (CS) which is angular in shape and rough textured.

Figure 4. Critical crack tip opening displacement Vs Aggregate shape and texture index for 10 mm size of aggregate (Manufactured sand and River sand)

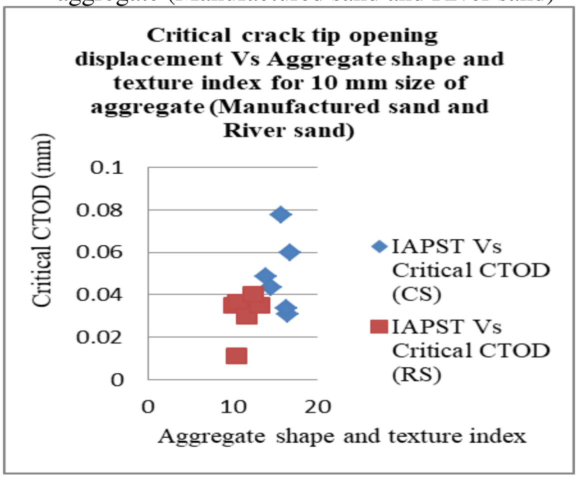
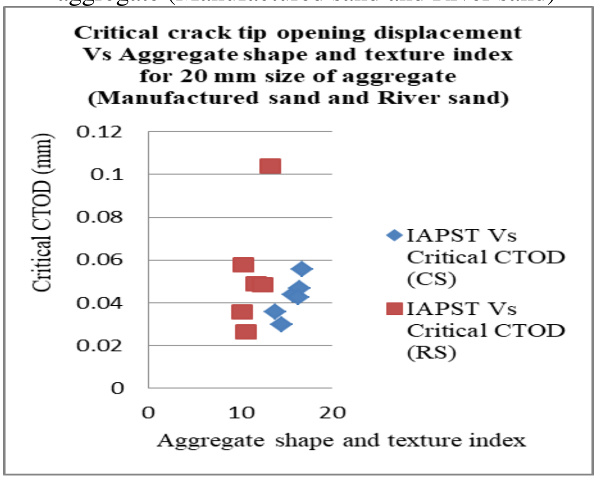


Figure 5. Critical crack tip opening displacement Vs Aggregate shape and texture index for 20 mm size of aggregate (Manufactured sand and River sand)



3. Fracture Energy: In present work fracture energy is calculated using the relation given by (Beygi et al. 2014),

$$G_f = 37.2\, a_{max}^{\;0.401} \left(\frac{F_c}{10}\right)^{0.107} \quad (15)$$

F_c = Compressive strength of concrete MPa, a_{max} = Largest aggregate size mm

Variation of fracture energy with aggregate shape and texture index is shown in Figure 6 and 7.

Figure 6. Fracture energy Vs Aggregate shape and texture index for 10 mm size of aggregate (Manufactured sand and River sand)

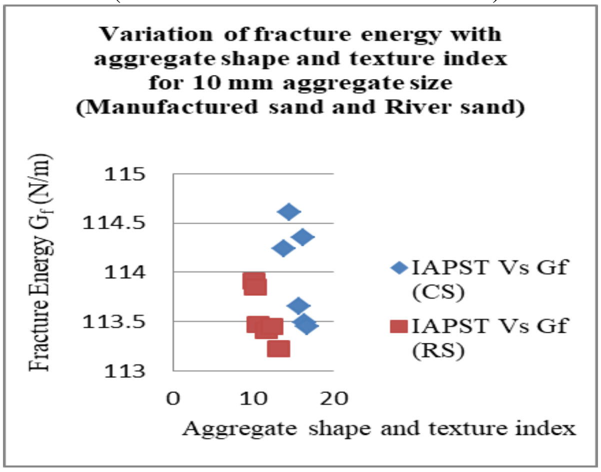
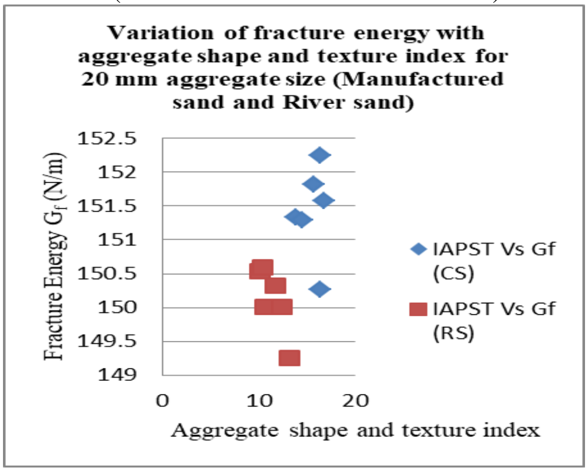


Figure 7. Fracture energy Vs Aggregate shape and texture index for 20 mm size of aggregate (Manufactured sand and River sand)



4. Characteristic length: Characteristic length represents an index of brittleness of concrete. Variation of Characteristic length with aggregate shape and texture index is shown in Figure 8 and 9

Figure 8. Characteristic length Vs Aggregate shape and texture index for 10 mm size of aggregate (Manufactured sand and River sand)

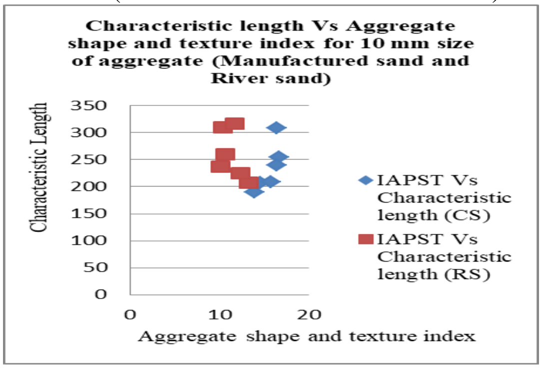
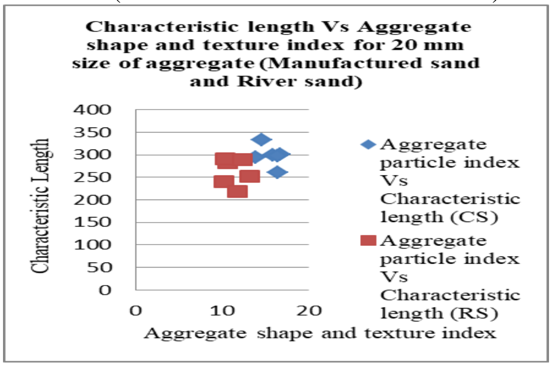


Figure 9. Characteristic length Vs Aggregate shape and texture index for 20 mm size of aggregate (Manufactured sand and River sand)



V. CONCLUSIONS

Two parameter fracture model (TPFM) has been successfully used to determine fracture parameters of high strength concrete. Using TPFM, critical stress intensity factor and CTOD has been calculated. Following conclusions can be drawn from an experimental investigation of three point bending test:

1. Manufactured sands exhibit higher aggregate shape and texture index while natural sands exhibit lower aggregate shape and texture index. Average Index of Aggregate shape and texture (IAPST) for manufactured sand and natural sand was obtained as 15.63 and 11.40 respectively.
2. Fracture energy and fracture toughness were greatly influenced by maximum dimension of coarse aggregates. Fracture energy and fracture toughness of notched concrete beam increases with the increase of aggregate size in concrete. It shows that maximum energy is required to initiate a crack for concrete with maximum dimension of coarse aggregate.
   Manufactured sand has angular shape and rough surface texture gives better mechanical interlocking which results in increasing bond strength. Hence, concrete specimen with manufactured sand gives more fracture energy and fracture toughness as compared to natural sand.

3. Critical crack tip opening displacement is decreases with increase in largest size of coarse aggregate. Due to more resistance provided by larger aggregate size the values of CTOD is more. Critical crack tip opening displacement is more for manufactured sand due to proper interlock of manufactured or crushed sand (CS) which is angular in shape and rough textured.
4. Characteristic length is proportional to fracture energy. It represents an index of brittleness of concrete. As characteristic length decreases, brittleness increases significantly. Increase in maximum dimension of coarse aggregate increases characteristic length. Concrete specimen with manufactured sand and river sand shows slight variation in characteristic length.
5. In high strength concrete, crack propagates through the surrounding of aggregates resulting in more rough and irregular fracture path. The natural sand has smoother surface than manufactured sand, resulting in weak mechanical interlocking. Hence, fracture energy, fracture toughness and compressive strength are less for concrete specimen with natural sand as filler material.

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