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Effect of Aggregate Size and Shape on Fracture Properties of Concrete – A Review

¹Poonam V. Nimbolkar *, ²M. G. Shaikh

¹ Research Scholar, Government Engineering College Aurangabad, New Osmanpura Aurangabad, Maharashtra India

² Government College of Engineering and Research, Avasari Khurd, Taluka - Ambegaon, Maharashtra, India

ABSTRACT: This paper presents critical review of literature on effect of aggregate size and shape on fracture properties of concrete. Review includes various fracture models, fracture parameters; various approach of fracture mechanics based on crack propagation and softening models. Fracture parameters includes fracture energy, fracture toughness, characteristic length, brittleness number, crack tip opening displacement and parameters characterized by softening curves. Many studies have been conducted on cohesive crack model to study fracture characteristic of concrete using Linear Elastic Fracture Mechanics (LEFM) principles. Mechanical properties of concrete explained experimentally as well as analytically based on size, shape, surface texture and aggregate strength. It has been observed that there is significant effect of ingredients of concrete like aggregate content on fracture properties.

KEYWORDS: Aggregate, Concrete fracture, fracture toughness, Fracture energy, Brittleness number.

I. INTRODUCTION

Concrete is generally regarded as three phase material composed of aggregates, hardened cement paste and transition zone between them. Properties of concrete depend on the component phases and interaction between them. Basically concrete consist of fine aggregates, coarse aggregates, cement paste and transition zone between them. So, each ingredient of concrete affects fracture parameters of concrete. Aggregate occupies 60-70% volume of concrete mix. Therefore, aggregate is an important ingredient of concrete and can be regarded as skeleton of concrete. Aggregates have great effect on fracture behavior of concrete including rheological properties, mechanical behavior and durability of concrete mix. Different types of aggregates used in concrete structures like natural and artificial aggregates. Artificial aggregates obtained by crushing a large parent rock. So, many engineering properties of concrete based on the properties of parent rock. Fracture properties of concrete includes fracture energy G_f , fracture toughness K_{IC} , characteristic length l_{ch} , brittleness number B , Elastic Modulus E & some parameters that characterized the concrete strain softening curve.

1.1 Lattice Model:

Lattice model is discretization of continuum by line segment & can transfer forces and moment for each line element. Heterogeneity & complex structure of concrete is given in three types as micro, meso and macro given in Fig. 1 by VidyaSagar and Raghu Prasad [37],

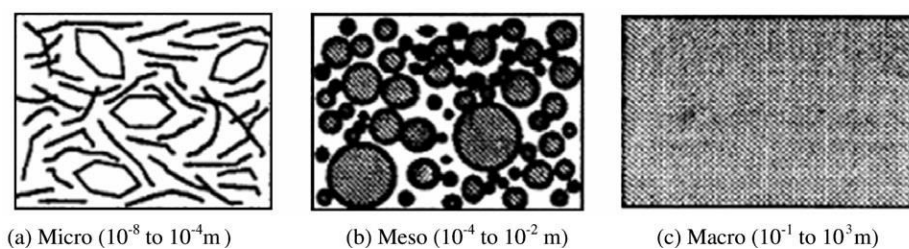


Fig. 1. Three level approach according to VidyaSagar and Raghu Prasad [37]

Using these scales, a lattice model distinguishes between cement paste, fine aggregates, coarse aggregates & bond between them. Heterogeneity in continuum is incorporated in lattice model by assigning different strength and stiffness values to separate lattice element given by VidyaSagarand Raghu Prasad [37] and result gives microcracking, crack pattern, crack branching, crack tortuosity and bridging during fracture process.

1.2 Fracture Parameters:

Fracture energy [G_F] is defined as energy absorbed to create unit area of fracture surface. Fracture toughness [K_{IC}] defined as the critical value of stress intensity factor shown by Chen and Liu [3]. Fracture energy determined by means of three point bending test according to RILEM TC 50-FMC [39] Fracture energy of concrete can be calculated as,

$$G_f = \frac{W_0 + mg \delta_{max}}{A_{lig}} \text{Eq. (1)}$$

W_0 = Area under load deflection curve (N-m)

mg = Self weight of specimen between supports (Kg)

δ_{max} = Maximum displacement (m)

A_{lig} = Fracture area [$d(b - a)$] (m^2)

b = Width of beam, d = Height of beam, a = Depth of notch.

Fracture toughness is given by

$$K_{IC} = 3 (P_{max} + 0.5 W) \frac{S (\pi ac)^{1/2} F(a)}{2d^2b} (N m^{-3/2}) \text{Eq. (2)}$$

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

$$\alpha = \frac{ac}{d},$$

P_{max} = Maximum load (N)

$W = W_0 S / L$ (N)

W_0 = Self weight of beam (N)

Hillerborg proposed a brittleness number

$$B = \frac{l}{l_{ch}} \text{Eq. (3)}$$

l = any structural dimension, l_{ch} = Material parameter called as characteristic length

$$l_{ch} = \frac{E G_f}{F_t^2} \text{Eq. (4)}$$

Elastic Modulus can be determined by the initial slope (P/Δ) of the $P - \delta$ curve of three point bend beam given by

$$E = \frac{P}{\Delta} \frac{S^2}{4bd^2} \left(6V \left(\frac{a}{d} \right) + \frac{S}{d} \right) \text{Eq.(5)}$$

Where S is the span of specimen (m), b and d are the height and width of the beam, respectively; a is the depth of the notch. The slope was obtained by linear regression of the curve of $P - \delta$. Fracture process zone has strong effect on fracture energy for concrete with coarse aggregate content. Fracture mechanics based approaches proposed to determine the fracture parameters of concrete studied by Tasdemir&Karihaloo [31] and Wolinski et al. [40].

Brittleness of concrete evaluated by the parameter called characteristic length shown by AppaRao and Raghu Prasad [16]. Influence of various factors on characteristic length of concrete studied by AppaRao and Raghu Prasad [15] using dimensional analysis. Modified characteristic length given as,

$$l_{ch, mod} = \frac{EG_f}{f_c f_t} \text{Eq. (6)}$$

Modified characteristic length reduces as the brittleness of concrete increases, due to bonding in cement paste and aggregates also, stated that the ductility of concrete increases with size of aggregates and load carrying capacity increases as maximum size of coarse aggregate increases given by AppaRao and Raghu Prasad [15]. An experiment carried out on different specimens to study influence of aggregate size on fracture energy, tensile strength and elasticity modulus by Elices and Rocco [30]

II. LITERATURE REVIEW

Mechanical properties of concrete are based on shape, surface texture, porosity and adsorption, interface bond strength and strength of aggregates. Fracture energy increases with increasing strength of concrete for given type of coarse aggregates, with increasing strength of concrete and also characteristic length decreases and brittleness of concrete increases reported by Ru Wu [27]. Elastic properties of concrete influenced by elastic properties of ingredient materials of concrete and ITZ between aggregates and paste concluded by Alexander and Milne [32].

Compressive strength of concrete is mainly depends on mortar and surface properties of aggregates reported by Aitcin and Mehta [35], Zhou et al. [13], Ozturan and Cecen [42]. In high strength concrete, coarse aggregates with proper texture and mineralogy improves the compressive strength of concrete given by Aitcin and Mehta [35]. Types of aggregates as well as aggregate stiffness have great influence on elastic modulus of concrete reported by Ru Wu [27]. As strength of concrete reduces, the influence of aggregate on elastic modulus of concrete becomes decreases. Crack bridging is given by maximum size of aggregates also it influences tail of load deflection curve concluded by Navalurkar et al. [38] and Zhang & Wu [9]. The tail part of load deflection curve decreases with increasing notch to depth ratio (a/w), concluded by Navalurkar et al. [38] and Zhang & Wu [9] shown in fig 2.

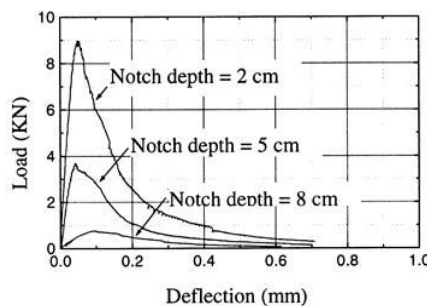


Fig. 2. Variation of load and deflection with notch depth of specimen: Navalurkar et al. [38] & Zhang & Wu [9].

The complex behaviors arising from microcracking and macrocracking are difficult to characterize in term of continuum. Influences of concrete aggregate structures as a particle model have been developed as discrete element method. This method is used to study fracture of non-homogeneous continuous media having spherical or circular particles. According to discrete element method, aggregates can be modeled as rigid macro particle or deformable group particle. The discrete element method was initially introduced to study discontinuous rock. Behavior of assemblies of particles with different deformation properties and contact properties under uniaxial tensile and compression test investigated and particle assembly using Discrete element method shown in fig. 3.

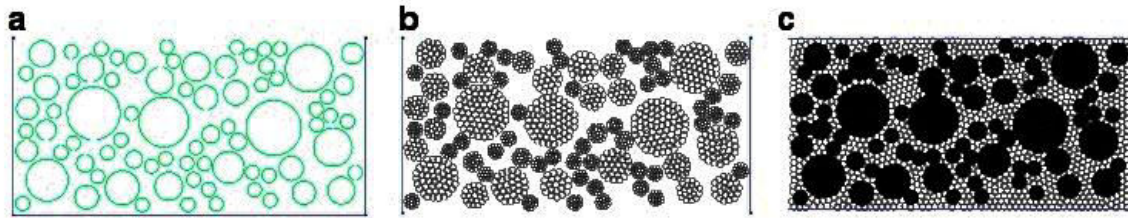


Fig. 3. Particle assembly structure
(a) Circular aggregate, (b) Aggregate discretization and (c) Compact assembly: Azevedo [33].

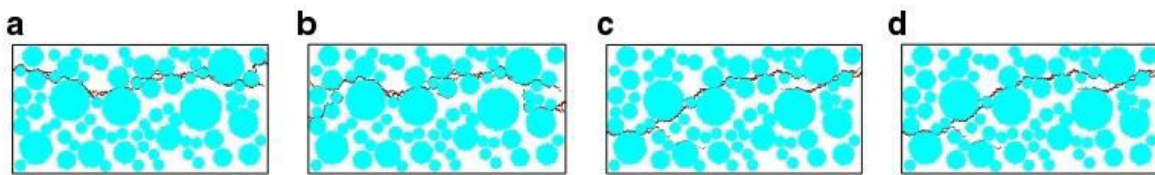


Fig. 4. Crack pattern of aggregate assembly: Azevedo [33].

Fig.4 shows crack propagation for a given particle assemblies, initial crack starts on the weaker contact between cement and aggregate particles, cracking process starts at an early stage, before maximum load reached. It was found that crack may start at the weakest contact under tensile loading studied by Azevedo et al. [33].

Effect of coarse aggregates on elastic modulus of concrete given by Zhou et al. [14]. Tail of softening curve is higher, when large size of aggregates used in concrete given by Van Mier[24]. Material phase structure changes for different densities of particle. As density of particle increases aggregate becomes nearer and bond zones around neighboring particles are joined to form clusters which is increasingly larger in size, Figure5 shows the heterogeneity of concrete and its meshing for different percentage of aggregate contents by Prado and Van Mier[10].

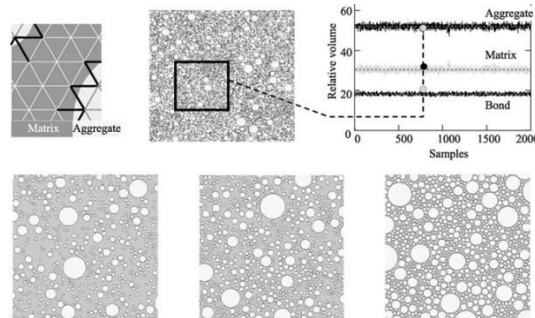


Fig. 5. Heterogeneity mapping, sample extraction and mesh for aggregate content 35 %, 51 %, 83%: Prado & Van Mier [10]

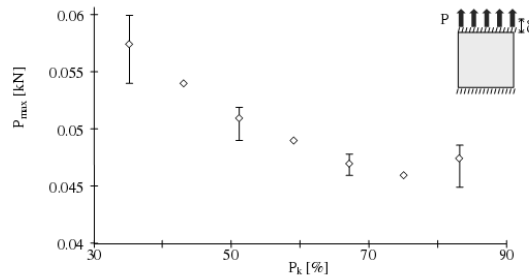


Fig. 6. Effect of aggregate content on peak load: Prado & Van Mier [10]

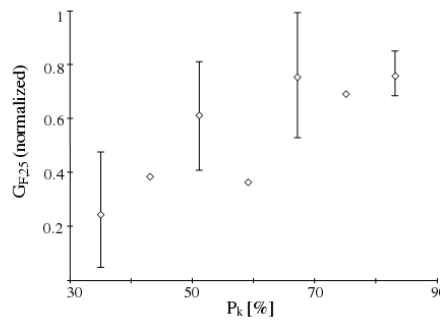


Fig. 7. Effect of aggregate content on fracture energy G_f : Prado & Van Mier [10]

Fig. 6 shows that aggregate content adversely affected by peak loads. According to Figure 7 shows that increase in particle density in concrete increases fracture energy G_f . Debonding occurs mostly near the supports or where neighboring aggregates closer. As large number of aggregate particles or more density of particles, there is possibility of crack propagation along straight line path is very rare reported by Prado and Van Mier [10]. For intermediate density of aggregates ranges from 51 – 59 % mechanical response is generally more stable concluded by Van Mier and Noor-Mohamed [23].

Prado and Van Mier [10] shows that density of particle in concrete have significant effect on pre critical crack process which leads to short or long hardening regime. Modulus of elasticity of mortar and coarse aggregates are different. Due to this mismatch property stress gets concentrated at the interfaces given by AppaRao and Raghu Prasad [16]. Length of descending portion of softening curve increases with increase in size of coarse aggregate. The modulus of elasticity of concrete increases by increasing maximum size of coarse aggregates concluded by AppaRao and Raghu Prasad [15]. As size of coarse aggregate increases the bond stress at the cement paste-aggregate interface is higher whereas, for smaller size of coarse aggregate the bond stress at the interface is less. Therefore, the crack path is more tortuous in large size aggregate concrete given by AppaRao and Raghu Prasad [15].

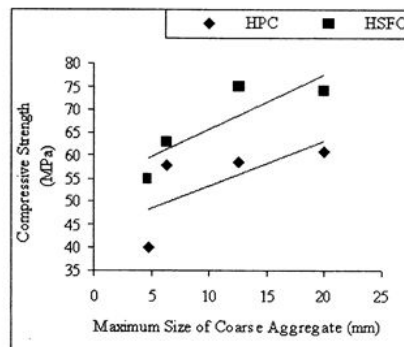


Fig. 8. Variation of compressive strength with maximum size of coarse aggregates in HPC and HSFC: AppaRao & Raghu Prasad [15]

Figure 8 shows a plot of maximum size of coarse aggregates with compressive strength of various concrete mix with and without silica fumes shown by AppaRao and Raghu Prasad [15]. Many investigators studied influence of coarse aggregates on fracture energy, fracture toughness with different types of specimen and found that as maximum size of coarse aggregate increases, fracture toughness also increases in HSC concluded by AppaRao and Raghu Prasad [15], Giaccio et al. [17] and Zhou et al. [13]. Prediction of effect of aggregates size distribution on concrete compressive strength by proposed probabilistic mechanical model given and according to proposed model of Miled et al. [26] and found that for same cement paste and same aggregate volume fraction, the concrete strength increases and obtained by decreasing maximum size of aggregate and percentage of coarse aggregates. For HSC cracks can also observed in aggregates. Compressive strength of concrete increases, when volume fraction of aggregates and aggregates maximum packing density increases also decreases when maximum size of aggregates increases concluded by Miled et al. [26].

AppaRao and Raghu Prasad [16] reported that use of aggregates having rough surfaces in concrete increases crack deformation also interface fracture energy increases. Orientation of surface of aggregates with direction of loading causes increase in interface energy under mode II loading shown by AppaRao and Raghu Prasad [16]. Use of well-polished aggregates introduces weak bond for mechanical interaction. Stress intensity factor at the maximum load is called as critical stress intensity factor or fracture toughness. Increase in roughness of aggregate surfaces, increases ductility of specimen whereas smooth or polished aggregate shows less ductility given by AppaRao and Raghu Prasad [16] also load and CMOD plot shows that up to peak load, response is linear. Petersson [36] concluded that fracture energy increases with decrease in w/c ratio and increase in age of concrete and also given that fracture energy & characteristic length have strong influence of type and quality of aggregates. Influence of different types of aggregates and their interface with cement paste on fracture performance of notched beam given by Rossello & Elices [6]. Concrete made with soft aggregates with strong interfaces shows all aggregate in the path of crack were broken. When interface was weak 10 % of aggregates broke and 50 % broken aggregates with normal interfaces investigated by Rossello & Elices [6] also stated that strong aggregate with well bonding matrix increases as toughness of concrete specimen. As strength increases, the different surface textures of aggregate increases bond strength between cement paste and aggregates and higher value of modulus of elasticity is obtained by preparing concrete with stiffer aggregates studied by Giaccio & Zerbino [18]. Tensile strength as fracture parameters not depends on shape and size of aggregates studied by Rocco & Elices [8].

Due to scarcity of natural fine aggregates in construction, other source of fine aggregate are needed. Use of crushed fine stone, furnace bottom ash and fine recycled aggregates as fine aggregate to study properties of concrete given by Shi-Cong & Chi-Sun [28]. As aggregate size increases, the compressive strength of concrete tends to decrease and causes higher stresses at the interface between aggregate and cement paste studied by Sabnis & Mirza [19]. Lower cohesion and higher voids in the interface between aggregate and cement paste observed in lightweight aggregates compared to natural normal weight aggregates. Aggregate interlock action and crack distribution is considerably poor, regardless of maximum size of aggregates in lightweight concrete reported by Sim et al. [22], Aitcin & Mehta [35], Zhou et al. [13], with increase of maximum aggregate size, the crack length developed around the aggregates tends to increase also better crack distribution in normal weight concrete was observed by Sim et al. [22] and reported that crack distribution in normal weight concrete somewhat affected by maximum size of aggregates and independent of size of aggregates in case of lightweight concrete given by Sim et al. [22]. Akcaoglu et al. [41] investigated effect of coarse aggregates and

water cement ratio of matrix on formation of interfacial transition zone (ITZ) and failure process of concrete were studied under uniaxial loading.

Properties of aggregates like shape, size, surface texture, mineralogy etc. have important significance on properties of interfacial transition zone. Tensile strength decreases as the aggregate size increases. Effect of aggregate size on tensile strength is higher in HSC concluded by Akcaoglu et al. [41]. Rough surface texture of aggregates increases mechanical interlocking with the cement paste reported by Donza et al. [20]. Compressive strength of concrete depends on the strength of phase. Crushed sand concrete perform better than natural sand concrete because for same mortar strength, strength of crushed sand is higher than natural sand given by Donza et al. [20]. Ozturan&Cecen [42] observed that for same properties of paste, different types and shapes of CA, texture of CA, mineralogy of CA and strength of CA gives different concrete strength.

Effect of different types of coarse aggregates on compressive strength, fracture energy, splitting tensile strength, characteristic length and elastic modulus of concrete studied by Ru Wu et al. [27]. Effect of volume fraction of aggregates and notch size on fracture energy of concrete studied by Akcay et al. [2] and fracture energy obtained from boundary effect model and meso mechanical approach compared. With increase in coarse aggregate content (upto 75 % of aggregate volume) both stress intensity factor (SIF) and fracture energy increases reported by Feng et al. [34]. With increasing 45 -75 % of total aggregate content, fracture energy varies within 25 % and no any critical volume fraction gives maximum fracture energy also concluded that fracture energy decreases with increase in aggregate content and after 65 % of volume of aggregates, fracture energy starts increasing given by Amparano et al. [12] and observed that with increasing aggregate content FPZ decreases. Expression for fracture energy given by Akcay et al. [2]

$$G_f = \frac{w_0 + \delta_0 m g_{grav} \frac{S}{L}}{B (w - a)}$$

B, w, S, L, a, m, δ_0 and g_{grav} are width, depth, span, length, notch depth, mass, deflection of beam, gravitational acceleration respectively. With increasing aggregate content modulus of elasticity, splitting tensile strength and net bending strength increases concluded by Bayramov et al. [11]. Increase in aggregate content from 40 – 66 % results in 37 % increase in splitting tensile strength of concrete concluded by Akcay et al. [2] with shallow notch of beam specimen, bending strength increases than deep notch. Compressive strength of concrete increases with increase in aggregate volume from 40 – 58 % but further reduces with again increase in aggregate content reported by Akcay et al. [2]. Compressive strength of concrete decreases with increasing aggregate content due to development of fracture planes parallel to the loading axes in 3D case given by Akcay et al. [2], Tasdemir&Karihaloo [31].

Fracture toughness of beam specimen is independent of size of coarse aggregates given by Barr et al. [5] and also concluded that with increasing size of test specimen fracture toughness value increases. Now a day industrial by product like slag, fly ash and condensed silica fume are widely used in concreting practice as supplementary cementing materials. Critical stress intensity factor K_{IC} increases with increasing compressive strength of concrete given by Zhou et al. [13] and influence of varying silica fume and aggregate content on fracture properties studied. A plot of load-displacement given that, displacement at peak load is independent on size and type of aggregates given by Giaccio et al. [17] also relation between compressive strength of concrete and characteristic length gives concrete strength increases with decrease in characteristic length.

Tasdemir et al. [7] noticed that brittleness index increases with decrease in fracture energy for large size of aggregates. An experimental investigation of effect of aggregate content on fracture behavior of concrete carried out by Amparano et al. [29] and result of experiment were analyzed by size effect method. Amparano et al. [12] concluded that with increasing volume fraction of aggregates in range 45 – 75 % compressive strength decreases 15 %, fracture energy varies within 25 % and there is no critical volume fraction of aggregates which gives maximum fracture energy. Fig. 9 shows crack patterns for different aggregate content and at different loading condition.

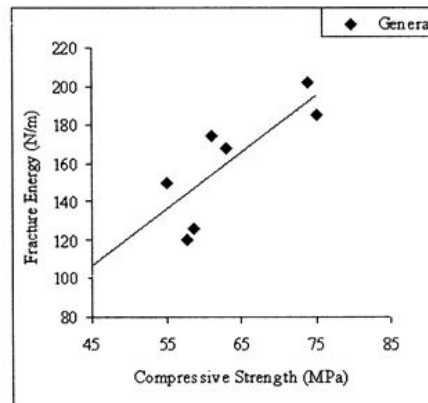


Fig. 9. Variation of fracture energy with compressive strength in HSC: AppaRao& Raghu Prasad [15]

Effect of maximum size of aggregate and types of loading on fracture parameters studied by Wolinski et al. [40]. He observed that crack always propagate through the cement matrix along aggregate surfaces and sometimes through aggregate particles also and observed that smoother crack surface for concrete with small size of aggregates and rough surface for large size of aggregates and concluded tensile strength is about 20 % and fracture energy about 35 % more for concrete than mortar, whereas the Young's modulus, peak strain and characteristic length are same for concrete and mortar.

Characteristic length increases with decrease in compressive strength of concrete observed in AppaRao& Raghu Prasad [15]. Hillerborg [1] concluded that fracture energy increases with maximum size of aggregates from 8 mm to 20 mm. Effect of use of different types of coarse aggregates like quartzite, granite and river gravel on compressive strength of concrete was investigated by Abdullahi [29]. Strength of concrete at interfacial zone depends on integrity of cement paste and nature of the coarse aggregates and concluded that maximum strength obtained for concrete made with crushed quartzite, followed by river sand and minimum strength obtained by using crushed granite. Influence of size of aggregates on fracture parameters of concrete using 3D acoustic emission technique and result shows that the FPZ already in existence at the peak load and FPZ increases as the crack grows reported by Mihashi et al. [21]. Acoustic emission techniques used to study effect of maximum size of coarse aggregate on FPZ and fracture parameters at the crack tip under three point bending test and concluded that fracture energy and size of FPZ of concrete increases with increasing size of aggregate shown by Chen and Liu [4].

III. CONCRETE FRACTURE MODELING

3.1 Linear Elastic Fracture Mechanics (LEFM): Concrete is heterogeneous material composed of hardened cement paste, aggregates and water, Hence essentially a non-homogeneous and nonlinear material. Concrete can be modeled at micro and meso level. These levels are not suitable for practical applications using fracture mechanics. Application of fracture mechanics for concrete is treated as a homogeneous isotropic material containing flaws. The application of fracture mechanics started from linear elastic fracture mechanics. Very first investigation in fracture mechanics was to determine linear elastic fracture mechanics parameters using small specimen. Secondly, it leads to the investigation or experimentation on servo-controlled equipment to get softening of tensile stress-strain curve of concrete. Thirdly attempts were made to understand fracture of concrete based on softening response of concrete during uniaxial tensile tests. Presence of roughness and irregularity inside the concrete material causes formation of cracks. Crack length is much more than assumed straight length. More amount of energy is required to create a new fractured surface. Due to irregularity and complexity present in fractured surface of concrete, it is idealized as 2D plane in fracture mechanics research. Fracture surface plays an essential part to evaluate fracture mechanics properties of concrete material.

3.2 Fictitious crack model: Fictitious crack model and crack band model proposed by Hillerborg [1] are based on numerical approach technique. Some of the fracture models of concrete structures proposed by researchers are fictitious crack model (FCM), Crack Band Model (CBM), Effective crack model (ECM), Two-Parameter Fracture Model (TPFM), Size Effect Model (SEM). Cohesive crack model is called fictitious crack model (FCM) proposed by Hillerborg [1] also made pioneering work in simulating crack size due to concrete softening. Concrete fracture

properties are based on concrete strain softening, specimen size, material strength and loading condition. Concrete strain softening curve can be ascertain by tension test on specimen reported by Hillerborg [1]. Linear elastic fracture mechanics theory was ideally applicable to ideally brittle solids, the fracture process should be concentrated only at a point. In case of concrete the fracture process is spreads over process zone region. Linear elastic fracture mechanics can be applicable only when the size of process zone is very small as compared to the size of the structure. Such type of condition is possible only in case of larger structures like dams. In case of medium and smaller type of structures the size of process zone is comparable to the size of structures. Hence, LEFM is not applicable for smaller structures.

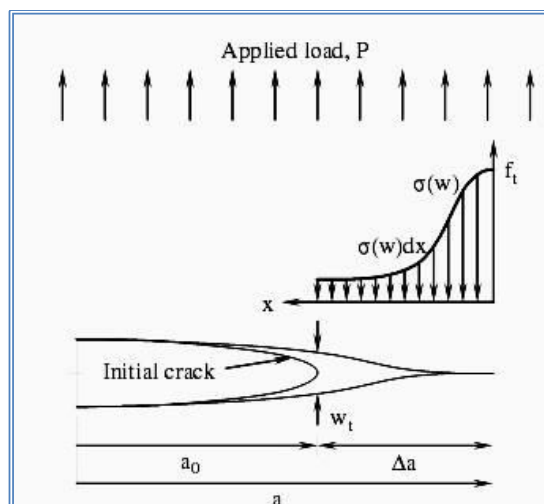
3.3 Non-Linear fracture models for concrete

Different researchers have observed that the region ahead of the tip of crack undergoes microcracking and develops a process zone. The consequence of this is that the flux of the energy into the crack tip is reduced while absorption of energy is increased in the process zone. Earlier theories were developed to account for yielding at the crack tip for metals. Those theories could not be applied to concrete as the zone of yielding in metals is small as compared to nonlinear zone in concrete. The inapplicability of LEFM principles to small and medium sized concrete structures results in the application of nonlinear fracture mechanics principle developed for concrete. With these concepts, crack tip opening displacement and J integral models are used. The existence of G_r is the starting point for non-linear theory of fracture. It is understood that the extensive microcracking results in the softening in the process zone ahead of the crack tip. Therefore, crack does not grow as soon as the stress at the crack tip reaches a limiting tensile stress. Fracture behavior of concrete is greatly influenced by its fracture process zone.

3.4 Two Parameter Fracture Model

This model, given by Jenq and Shah[25] , 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. The area in front of the crack tip undergoes micro cracking and develops crack process zone in nonlinear way. Crack opening at the tip of crack where stress goes suddenly zero is regarded as the material property (Figure 10).

Figure 10 : Cohesive stress model for a quasi-brittle crack (Dugdale’s Model



IV. DISCUSSIONS AND CONCLUSIONS

Concrete is a heterogeneous material made of aggregates, cement paste and interface between them. So, each ingredient of concrete has influence on fracture parameters of concrete. This paper gives technical review of aggregate content effect on fracture parameters. Mechanical properties of concrete based on shape, size, texture, porosity and strength of aggregates. As maximum volume is occupied by aggregates, effect of aggregate content is considerable. Review shows that fracture energy increases with increasing maximum size of aggregates. Some researcher shows that fracture energy decreases with increasing aggregate content and reached to minimum value with volume of aggregate content 65% and thereafter starts increasing. As aggregate volume increases from 40-80% fracture energy and fracture toughness of low strength concrete increases. Fracture toughness increases with increase in size of aggregates.

Density of aggregates also has significant effect on fracture energy. Increase in density of particle in concrete increases fracture energy & crack propagation along straight line is very rare. Aggregate size distribution has significant effect in HSC. Surface texture of aggregates affects concrete properties, increase in roughness of aggregate surface increases ductility compared to smooth or polished aggregates.

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