The effect of aggregate gradation on concrete fracture energy using the work of fracture method

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Abstract. The micro-cracks that commonly occur in concrete structures are a potential source of crack propagation which leads to the possibility of catastrophic failure. Concrete cracks that occur propagating mainly along the interface zone that significantly conditioned by aggregate characteristics. Aggregate characteristics as concrete fillers have a significant role as a strain energy release medium known as fracture energy. This research is using an experimental investigation about the fracture characteristics of concrete using different gradations with a maximum diameter of 25 mm and 20 mm. The experiment includes a compressive strength test and a fracture parameter test. Three-point bend test was selected based on RILEM recommendations to calculate fracture parameters. The result has shown that the aggregate gradations used in concrete mixtures should take into account the effect on compressive strength and total fracture energy. Uniform gradations with smaller maximum sizes have high compressive strength but low fracture energy.

1. Introduction

Concrete is classified as a material consisting of two main parts, namely aggregate as a filler and a matrix which is a mixture of sand, cement, and water as a binder where the two components are connected through a zone called the interface zone.

The material whose composition mostly affects the strength of concrete is aggregate. About 60-70% of the weight and volume of concrete material consists of aggregates. Thus, the characteristics of the aggregate from geometry, specific gravity, maximum size to gradation greatly affect the ability of concrete.

The usual planning stage is based on material properties in the form of: modulus of elasticity, Poisson Ratio, and permit stress. However, Permit crack lengths in concrete can also be affected by other material properties such as static, dynamic or repeatable load types, the ability of the material to withstand crack growth and structural geometry [1].

In the viewpoint of fracture mechanics it is explained that because the maximum stress does not only depend on the nature of the material, but also structural geometry and boundary conditions, the criterion of force failure in terms of nominal stress is not suitable for structures made with brittle material. The use of strength-based failure criteria is not always appropriate and can result in designs that are not conservative for large size structures. when quasi-brittle material is used, structural failure is also characterized by developing a fracture processing zone in the critical section. similar to brittle
material, structural failure must be explained in terms of energy rather than strength. Interface zones that are significantly conditioned by aggregate characteristics such as surface type, stiffness/hardness, angularity, geometry, etc. have an impact on traction as a medium for the rate of release of strain energy or what is known as energy fracture [1].

Several studies discuss the effect of aggregate characteristics of both shape and gradation on concrete characteristics such as compressive strength and fracture performance: Fracture properties for aggregate and independent specimen size, only if certain minimum specimen dimensions are exceeded. However, it seems to depend on the form and type of aggregate. More energy is needed to break down sub-angular aggregates than to eliminate rounded aggregates based on 2 types of aggregates used [2].

In concrete with rounded aggregate, traction (in the terminology of fracture mechanics known as closing pressure) is relatively absent, energy absorbed during loading is solely used for the formation of cracks that are released instantaneously cutting both the aggregate and its matrix. Specimens with rounded aggregates have higher compressive strength compared to angular ones [3].

The aggregate gradation used in the concrete mixture affects the parameters of the hardened concrete fracture. The significant effect is on normal strength concrete rather than on high strength concrete. concrete that uses a coarser aggregate gradation has greater \( F_c \) and \( G_f \) values and with the same aggregate composition, the ability of normal concrete to withstand fracture loads is better than high quality concrete [4].

The relative critical stress intensity factor is not affected by the aggregate size distribution. However, the proportion using coarser grain sizes tends to increase the value of \( K \). Based on the measured \( G_f \) and \( K \) values, the aggregate size distribution and the \( w/b \) ratio affect the level of ductility of concrete quality high. The maximum value of \( G_f \) for high quality concrete is limited by aggregate strength [2].

Most of the previous studies of fracture energy on concrete used the size effect method and different variables in their research [5-8]. Siregar and Siregar uses the same method but with different variables from this study [2,4]. The purpose of this research is to determine the performance of concrete through aggregate gradations in the fracture energy of concrete.

2. Method

In this study concrete is made using a mixture of concrete with uniform gradation and continuous. The maximum aggregate size used is a uniform gradation of 20 mm (20 S), 25 mm (25 S) and a continuous gradation of 25 mm (25 M). For continuous gradation, gradation curves are obtained by comparing research results from the literature related to coarse aggregate gradation. The literature used is the Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1.91). Effect of content and particle size distribution of aggregate aggregates on the compressive strength of concrete [9]. So, we get the formula in determining the coarse aggregate gradation curve as (1).

\[
P_d = 100\left(\frac{d}{D_{\text{max}}}ight)^n
\]

Where \( P_d \) is Passing percentage; \( d \) is size of aggregate; and \( D_{\text{max}} \) is maximum size of aggregate. The sample of this study consisted of 6 samples of blocks 10 cm x 20 cm x 120 cm, 9 samples of cylinder measuring 15 cm x 30 cm and 6 samples of cubes measuring 15 cm x 15 cm x 15 cm. With each of the 2 beam samples, 3 cylindrical samples and 2 cube samples per mix. Concrete constituent materials obtained from several places including coarse aggregate obtained from PT. Tabarath Manunggal located in Bogor, Fine Aggregates obtained from PT Pionir located in Jakarta, Cement and fly ash obtained from PT JHS System in Jakarta.
2.1. Materials
Material inspection is needed before the process of making concrete is done, it aims to get the results of the properties of the material following the standards and as data for concrete mixture planning. Collected material samples of Concrete are examined using the following test methods:

Examination of the coarse aggregate is carried out visually and a specific gravity test (ASTM C-127), water content (ASTM C-556), and the weight of the coarse aggregate content (ASTM C 29); Fine aggregate examination includes specific gravity and absorption (ASTM C 128-98), water content (ASTM C 566-78), mud content (ASTM C 117-80), sieve analysis (ASTM C 33-93), weight content (ASTM C 29); Inspection of cement is carried out by visual means that cement is in a tightly closed condition and after opening there are no lumps and fine granules; The inspection of water is carried out visually, that is, the water must be clean, not containing mud, oil and salt according to the requirements. The results of the material inspection are presented in the following table:

| Table 1. Material properties. |
|-------------------------------|
| Spesific gravity (gr/cm³) | Berat Isi (gr/cm³) | Water content (%) | Absorption (%) | Mud content (%) | Grain Modulus |
| Split | 2.49 | 1.46 | 2.23 | 3.55 | - | 3.28 |
| Sand  | 2.63 | 1.67 | 4.4 | 0.6 | 1 | 2.79 |

2.2. Concrete mixing
In this study, the Mix design used is based on concrete microstructure references, properties and materials from Mehta and ACI 211.1.91 [10]. The planned mix design uses 3 types of aggregate gradations, namely continuous gradation with a maximum aggregate size of 25 mm (25 M) and uniform gradation with a maximum aggregate size of 25 mm (25 S) and 20 mm (20 S). mixture proportions as follows:

| Table 2. Mix design [10]. |
|----------------------------|
| Mix Code | Cement Kg/m³ | Fly Ash Kg/m³ | Sand Kg/m³ | Coarse Aggregate (Kg/m³) | Total Coarse aggregate Kg/m³ | Superplasticizer Kg/m³ | water Kg/m³ | w/c | Slump cm |
| 25 M | 348 | 146 | 603 | 289 | 359 | 231 | 278 | 1157 | 2.9 | 148 | 0.3 | 1 |
| 25 S | 348 | 146 | 603 | 1157 | - | - | - | 1157 | 2.9 | 148 | 0.3 | 1 |
| 20 S | 348 | 146 | 603 | - | 1157 | - | - | 1157 | 2.9 | 148 | 0.3 | 1 |

After a trial mix of the concrete mix planning with the above composition, the results of the slump are not in accordance with the plan so that the slump must be adjusted according to ACI 211.1.91. The results of adjusting slump with reference ACI 211.1.91 obtained the composition of the concrete mixture as follows:

| Table 3. Mix design. |
|----------------------|
| Mix Code | Cement Kg/m³ | Fly Ash Kg/m³ | Sand Kg/m³ | Coarse Aggregate (Kg/m³) | Total Coarse aggregate Kg/m³ | Superplasticizer Kg/m³ | water Kg/m³ | w/c | Slump cm |
| 25 M | 382 | 160 | 546 | 288 | 358 | 231 | 277 | 1153 | 3.2 | 163 | 0.3 | 5 |
| 25 S | 382 | 160 | 546 | 1153 | - | - | - | 1153 | 3.2 | 163 | 0.3 | 5 |
| 20 S | 382 | 160 | 546 | - | 1153 | - | - | 1153 | 3.2 | 163 | 0.3 | 5 |
2.3. Three point bend set up

Three point bend test (TPB) was chosen to determine the concrete fracture energy. Figure 1 shows the geometry of the beam specimen. The test was carried out in the Universal Testing Machine testing machine at the CIBE Engineering Institute Laboratory of the Bandung Institute of Technology with a displacement control of 0.05 mm / sec. The vertical deflection of the beam is measured at the loading point with the LVDT displacement transducer having a capacity and linearity of 7.5 mm and ± 0,0007 mm, respectively. In the cracks the beam clip gauge is installed to get CMOD (crack mouth opening displacement) data.

![Figure 1. Three point bend set up.](image)

2.4. Test result

The results of testing the strength parameters of the concrete samples are presented in table 4 below. The fracture energy calculation is explained as follows:

| No | Code | Age (days) | Weight (gr) | Area (cm²) | Volume (cm³) | Weight Content (gr/cm³) | Dial (KN) | fc’ (Mpa) | Moduls of Elasticity |
|----|------|-----------|-------------|------------|-------------|------------------------|-----------|-----------|---------------------|
| 1  | 20 S | 56        | 12480       | 176.715    | 5301.438    | 2.354                  | 901.392   | 51.008    | 8.114               |
| 2  | 25 S | 56        | 12460       | 176.715    | 5301.438    | 2.350                  | 644.189   | 36.454    | 6.881               |
| 3  | 25 M | 56        | 12480       | 176.715    | 5301.438    | 2.354                  | 880.49    | 49.826    | 7.881               |

2.4.1. Fracture energy

The three point bend test results from this study are presented in the graphical form on figure 2:
Data processing using the graph above uses the fracture energy formula with the Work of fracture method with references from previous studies [11]:

\[
GF = \frac{w_o + m_g \delta_{max}}{A_{tg}}
\]  

(2)

Where GF is the total fracture energy; \(w_o\) is the area of the curve; \(m_g\) is the weight of the beam sample; and \(A_{tg}\) is the net area of the cross-section of the beam sample. This work of fracture method has been widely used by previous researchers [2,4,5]. The calculation results from the formula above are presented in the table 5:

表 5. Three point bend test result.

| Desc | Age | fc' | E | m.g | Wo | \(\delta\) | D | ao | t | GF |
|------|-----|-----|---|-----|----|--------|--|----|---|----|
| 25 S | 56  | 36.454 | 6.881 | 554.68 | 3.923 | 0.002 | 0.2 | 0.05 | 0.1 | 401.614 |
| 20 S | 56  | 51.008 | 8.114 | 542.528 | 3.386 | 0.001 | 0.2 | 0.05 | 0.1 | 334.098 |
| 25 M | 56  | 49.826 | 7.881 | 550.368 | 4.919 | 0.002 | 0.2 | 0.05 | 0.1 | 467.229 |

3. Result and discussion

The highest compressive strength is obtained from a concrete mix with a uniform gradation of 20 mm. This happens because the aggregate composition of the mixture with a maximum aggregate size of 20 mm fills the space between spaces in the concrete mixture so that the resulting concrete becomes denser. With the same maximum aggregate size, continuous gradation has greater compressive strength and modulus values, because the continuous aggregate distribution fills the space/cavity in the concrete mixture so that it is denser than the uniform gradation.

The results of this test are also in accordance with research conducted by Siregar that finer gradations produce higher compressive strength values because they fill cavities between spaces in concrete mixes so that they become denser [4]. Research conducted also results that aggregate characteristics are very influential in the ability of concrete to withstand loads [12]. Meddah also says that the ability of concrete in holding compressive strength is influenced by the maximum size of the aggregate [9]. For normal concrete, the greater the maximum aggregate size results in greater compressive strength and vice versa, in high-quality concrete, the smaller the maximum aggregate size results in greater compressive strength.

The results of the three-point bend test obtained the highest peak energy value obtained from a mixture with a continuous aggregate of 25 mm. This is because the composition of the distributed aggregate does not allow energy propagation at the interface zone so that the energy given is absorbed directly into the aggregate which can cause an immediate collapse if the absorbed energy exceeds the ability of the aggregate. The maximum aggregate size also has a significant effect on the energy of the
concrete fracture. Smaller grain size makes the composition of the aggregate denser, the same as continuous gradation, smaller aggregate size reduces energy propagation at the interface zone so that all energy is absorbed during loading and used to open cracks in concrete. As for large aggregate sizes and uniform gradations, the energy absorbed during loading is distributed in the relationship between the aggregate and the matrix, so that the peak energy obtained is lower than the continuous gradation with the same maximum aggregate size.

The results of this study support the results of research from Patty which results that concrete materials with small aggregate grains tend to be denser and monolithic [6]; all the energy absorbed during loading is used only for separation of the cracked area, then released immediately. In larger grains, it takes more energy when loading as a consequence of the obstacles in the form of traction. Siregar also states that By increasing the maximum aggregate size, the fracture energy increases [2]. This is because larger aggregates cause more energy absorption either by increasing the energy needed to break the aggregate or the extension of the crack propagation path to run around the aggregate.

4. Conclusion

The aggregate gradation used in concrete mixes affects the energy of concrete fractures. The highest peak energy is obtained by using continuous aggregate gradation. The maximum size of the aggregate also has a significant effect on fracture energy. The greater the maximum aggregate size in the concrete mixture, the higher the peak energy achieved.

Uniform gradations with smaller maximum sizes have high compressive strength but low fracture energy. This explains that the higher the compressive strength value of concrete, the more brittle the concrete. The result of is study can be used as a consideration in planning concrete structures. In addition to compressive strength, fracture energy must also be considered in planning because concrete structures commonly have cracks.

Acknowledgement

This paper is supported by Kementrian Riset dan Teknologi Perguruan Tinggi on the student Thesis Research Program. This research is also supported by PT. JHS System for providing Portland cement and Fly Ash. Additional Support was provided by Mercu Buana University.

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