Effect of water-cement ratio on fracture energy based on work of fracture

A D Arianti¹, R B Muin¹*, and A H Patty²

¹ Department of Civil Engineering, Universitas Mercu Buana, Jl. Meruya Selatan, Kec. Kembangan, Jakarta Barat, DKI Jakarta 11650, Indonesia
² Department of Civil Engineering, Universitas Katolik Widyakarya Malang, Jl. Bondowoso 2-Malang No.2, Kec. Klojen, Malang, Jawa Timur 65115, Indonesia

*resmi.bestari@mercubuana.ac.id

Abstract. Concrete is brittle material which generally consists of many micro cracks which are a potential source of crack propagation which leads to possible catastrophic failure and resulting fracture of concrete structures under service loads. The relationship of fracture energy to material properties has not been clearly identified, with most studies showing a relative insensitivity to the water-cement ratio, and concrete cracks propagate mainly along the aggregate-cement interface. This research is an experiment about the effect of water-cement ratio on fracture energy based on the RILEM method. The fracture energy is measured by testing under three bend points with the notch depth ratio is 0.25 and loading rate is 0.05 mm/sec using a closed-loop testing machine to produce load-displacement curve. Concrete used crushed stones with a maximum size of 19 mm which was tested at 56 days of age and has a water-cement ratio (w / cm) of 0.30, 0.40 and 0.6. The correlation between fracture energy and water-cement ratio are insensitive to each other. This can be seen when concrete containing a lower water-cement ratio (0.3) tends to have increased compressive strength but decreases fracture energy.

1. Introduction
Concrete is brittle material which generally consists of many micro cracks which are a potential source of crack propagation which leads to possible catastrophic failure (rapidly or continuous) and resulting fracture of concrete structures under service load, accidental load and/or exposure to environmental conditions. The failure mechanism can be studied by measuring the energy consumed in crack propagation and the formation of new crack surfaces. In concrete structures, crack growth requires an amount of energy that can be studied through energy-based propagation criteria, which provides a fundamental theory for understanding the phenomenon of concrete cracking mechanisms [1].

The relationship of fracture energy and material properties has not been clearly identified, with most studies showing a relative insensitivity to the water-cement ratio. Zhang Dong explained in his research, if compressive strength increases, the pattern of concrete internal damage will vary [2]. This is indicated by most of the longitudinal cracks around the aggregates in normal strength concrete, and through the aggregates in high strength concrete. As a result, the behavior of concrete fractures also varies and changes [2]. This phenomenon was agreed by another research, that when the compressive strength of concrete increases, the energy stored in the material at the peak tensile load also increases, while the ability of the material to dispose of energy remains constant, causing the behavior of the material is
more fragile [3]. In other words, the ability of concrete in holding tensile strength is relatively lower than the compressive strength, this can be related to the phenomenon of deformation response of tensile stress of material, which the stress on brittle material will suddenly drop to zero when there is continuous cracking until the structure reaches peak load [4].

Cracks in concrete propagate prefer along the cement-aggregate interface zone so that the mechanical behavior of the fracture can be explained quantitatively using GF specific fracture energy, which is obtained from the load-displacement curve from the wedges splitting method [5]. Redistribution of plastic stresses occurs due to micro-cracking and in line with energy dissipation which quantitatively determines the rate of structural collapse. Plastic zones can be developed by increasing aggregate interlock. Imperfect bonding in the the area of contact between aggregate and cement paste (interface zone matrix), gives the possibility of an initial crack not being able to resist the stability of the crack propagation rate that occurs in the concrete.

This study was conducted to provide a significant explanation of the effect and better range of water-cement ratio on the binding reactions of aggregate and cement paste which impact on the ability of crack propagation or fracture energy based on real work. And also support previous research on similar indicators between research Zhang Dong, David Darwin and Wei Dong where each other give a different results [2,3]. Especially at issue, whether the performance of the fracture along with increasing compressive strength.

2. Method

This study was an analytical-experimental with several testing is compressive strength, modulus of elasticity and flexural strength. Concrete mixture used crushed stone with a maximum size of 19 mm was tested at 56 days of age and had a water-cement ratio (w/cm) of 0.30, 0.40 and 0.6. Three point bend test uses a beam measuring 20x10x120cm as shown in Figure 1 with a placement length between 113 ± 0.5cm based on the literature "Fracture Mechanic of Concrete, Surendra P. Shah [4]" table 6-1 recommendation sizes of beams for measuring GF for aggregates with a maximum size of 16.1-31 mm. The setting of notch ratio is 0.25 of the beam height with a loading rate of 0.05 mm/sec to produce a load-displacement curve.

Flexural testing is based on the RILEM technical committee 89-FMT 1990 which provides material fracture parameter recommendations [6], where a close-loop testing machine with CMOD (Crack Mouth Opening Displacement) will give a signal to stable failure. Clip gauge controls or LVDT tools are needed to measure CMOD that is continuously recorded during testing. As shown in Figure 2. The fracture energy (GF) is determined as below:
\[ G_F = \frac{W_0 + 2P_w \delta_0}{(D - a_0)t} \]

Where \( GF \) is Energy Fracture; \( W_0 \) is the area of the load-displacement relationship curve; \( P_w \) is the concrete load and \( \delta_0 \) is the concrete displacement.

2.1. Material

In this study used coarse aggregate material from split rumpin with a maximum diameter of 19 mm, and the type of fine aggregate used was belitung sand available at material stores, as well as portland cement type 1. Properties testing was carried out in accordance with SNI procedures. The results of testing the material properties is:

| Property                  | Coarse Aggregate | Fine Aggregate | Portland Cement Type 1 | Water |
|---------------------------|------------------|----------------|------------------------|-------|
| Water Content (%)         | 2.23             | 4.44           | -                      | -     |
| Mud Content (%)           | -                | 1.00           | -                      | -     |
| Specific Gravity (gr/cm³) | 2.49             | 2.63           | 2.99                   | 1.00  |
| Absorption (%)            | 3.55             | 0.60           | -                      | -     |
| Unit Weight (gr/cm³)      | 1.46             | 1.67           | -                      | -     |

2.2. Mix design

This study divides concrete into 2 categories based on a mixture composition design method; normal strength concrete (with w/cm ratio 0.4 and 0.6) and high strength concrete (with w/cm ratio 0.3). The proportion of normal concrete mixes used SNI 7656-2012 [7] which adopted ACI R-211-1.91 [8], whereas for high quality concrete using modified proportions based on the proportions available in the study in his book entitled "Concrete: Microstructure, Properties and Materials" Table 12-5 Mix Proportions of High-Strength Concrete Used in Four Different Metropolitan Areas of North America [9]. The proportion of material used in this study is:

| Code | Portland Cement | Fine Aggregate | Coarse Aggregate | Fly Ash | Superplasticizer | Water | w/c | Slump |
|------|-----------------|----------------|------------------|---------|------------------|-------|-----|-------|
| NSC  | 320             | 927            | 906              | 0       | 0                | 192   | 0.6 | 48    |
| MSC  | 507             | 726            | 909              | 0       | 0                | 203   | 0.4 | 44    |
| HSC  | 382             | 546            | 1153             | 160     | 3                | 163   | 0.3 | 32    |

NSC: normal strength concrete; MSC: middle strength concrete; HSC: high strength concrete.

3. Result and Discussion

Concrete compressive strength tested by Compression Testing Machine in 7 days (to estimate an early strength of concrete), 42 days and 56 days. While the modulus of elasticity is the ratio of normal tensile or compressive stress to strain, test method uses a reference from ASTM C469-94.

| Code | w/c | Compressive Strength (f'c) (N/mm²) | Modulus Elasticity (E) (N/mm²) | Slump (mm) |
|------|-----|----------------------------------|-------------------------------|------------|
|      | 7 days | 42 days | 56 days |                     |           |
| NSC  | 0.6  | 26.01     | 22.21   | 32.09             | 5524      | 48    |
| MSC  | 0.4  | 28.96     | 40.01   | 41.87             | 8758      | 44    |
| HSC  | 0.3  | 40.21     | 47.17   | 46.85             | 7746      | 32    |
The concrete divided into 3 categories, low strength (LS), middle-high strength (MHS), and high strength (HS). The result of concrete compressive strength using a lower water-cement ratio has a relatively greater compressive strength value of 1-2% per 0.01 increase in w/c ratio [2,3,10]. If based on pattern of concrete collapse or cracking, concrete with water-cement ratio 0.25 have a similar explosive failure mode with no cracks seen until failure [11]. High strength concrete resulting in greater compatibility in terms of strength and stiffness between cement paste and aggregate, thus leading to lower stress concentrations at the interface-aggregate matrix [3].

The results of compressive strength testing in this study, concrete with lower w/cm ratio has relatively increased compressive strength, with the model of failure and cracking of concrete can be seen in Figure 3, is relatively through in the aggregate matrix. Whereas for concrete with medium and low strength, crack patterns spread around the aggregate and show a more stable collapse behavior. This is due to the hydration reaction process between cement and water, where the compounds in the cement particles interact and bind to one another, which then causes the components to become solid and specifically form a sturdy structure.

![Figure 3. Pattern of specimen damage on concrete compressive test (a) w/cm ratio 0.3, (b) w/cm ratio 0.4 and (c) w/cm ratio 0.6.](image)

3.1. Fracture energy

Flexural test with three-point bend (TPB) was chosen to determine the concrete fracture energy, where the geometry of the beam specimen as described above and tested with a closed loop testing machine with a capacity is 20 tons. From these tests the results obtained between load-displacement curves are as follows:

![Figure 4. Load-displacement curve for w/c ratio variations in NSC, MSC and HSC concrete.](image)
The work of fracture is a method used to provide material characteristics to structural fractures or collapse by measuring the total energy energy and the cracking of concrete cracks with a notch opening to achieve total collapse. The results of fracture energy (GF) in this study is below:

| Code | Age | Weight \((Pw)\) | w/c ratio | Beam Dimension | Length of Notched \((ao)\) | Area of Curve \((Wo)\) | Displacement \((\delta o)\) | GF \((N/m)\) |
|------|-----|----------------|-----------|----------------|-----------------------------|------------------|-----------------|--------|
| NSC  | 56  | 521.95        | 0.6       | Height 0.2     | Width 0.1                  | Length 1.2       | 0.05 2.55       | 0.0027 357.51 |
| MSC  | 56  | 536.06        | 0.4       | Height 0.2     | Width 0.1                  | Length 1.2       | 0.05 4.90       | 0.0023 491.13 |
| HSC  | 56  | 539.78        | 0.3       | Height 0.2     | Width 0.1                  | Length 1.2       | 0.05 1.91       | 0.0019 267.52 |

In this study it was found that the fracture energy in MS concrete with w/c ratio 0.4 tended to be greater than NS and HS concrete. This approaches the results of previous studies summarized as follows:

| Description | w/c ratio | Research Study | Previous Research |
|-------------|-----------|----------------|--------------------|
| FC' \((N/mm2)\) | 0.50-0.60 | Wei Dong (2018) | David Darwin (2001) | Zhang Dong (2001) |
|             | 0.35-0.40 | 32.09          | 28.90              | 42.3                |
|             | 0.25-0.30 | 41.87          | 59.68              | 51.6                | 58.00 |
| GF \((N/m)\) | 0.50-0.60 | 46.85          | 83.90              | 87.6                | 83.60 |
|             | 0.35-0.40 | 357.5          | 104.87             | 133                 | 158.0 |
|             | 0.25-0.30 | 491.1          | 147.97             | 127                 | 153.9 |

Based on the type of coarse aggregate it can significantly influence the strength and area of the load-displacement curve and show almost identical peak loads. When based on strength specimens, the relationship of load-displacement curves to energy fractures can be seen in high strength specimens which show a much higher peak load, whereas normal strength specimens show less breakable behavior. The relationship of fracture energy compared to the ratio w/cm and age shows that the energy of a concrete fracture containing w/cm in medium strength is consistently greater than the energy of a concrete fracture containing a ratio of w/cm low and high strength where, in fact, on average, concrete with the lowest w/cm ratio indicates the lowest GF value. Surface failure in a fracture test is similar to that of a compression and flexural test [3].

In this study, the results obtained by David Darwin (2001) and Wei Dong (2018) are not appropriate, but are more supportive and similar to the study of Zhang Dong (2001), where the fracture energy or fracture properties of a material with medium strength with a water-cement ratio 0.4 have more results good and tend to be smaller for high strength concrete. In high strength range, the fracture energy does not increase with a steep compressive strength as predicted by the MC90 formula [2].
4. Conclusion

The results in this study show that increasing the compressive strength of concrete does not give the same results in fracture energy. This occurs in harmony with the increase in tensile energy stored in the material but the ability to dispose of that energy remains, thereby causing instability in the structure. Supported by post-test specimens showing identical crack propagation patterns such as the study of Zhang Dong [2]. Crack paths in HS concrete propagate and give rupture to the aggregate-paste matrix, can be seen in Figure 6. In other words, energy fractures are not too sensitive to compressive strength. This was said similarly by Kim et al. in 1997 who obtained results tended to be the same in their research.

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