

The effect of coarse aggregate hardness on the fracture toughness and compressive strength of concrete

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Abstract. Coarse aggregate is the dominant constituent in concrete. Aggregate hardness is a variable needed to investigate in determining its effect on the critical stress intensity factors (K_{IC}), dissipated fracture energy (G_f) and compressive strength (f_c') of the concrete. The hardness of coarse aggregate based on Los Angeles abrasion values of 16.7%, 22.6%, and 23.1% was used incorporated with Portland Composite Cement (PCC), and superplasticizer to create specimens. Cubes of 150x150x150 mm were employed to determine the f_c' , and four beam sizes: 50x100x350 mm, 50x150x500 mm, 50x300x950 mm and 50x450x1250 mm were engaged to determine K_{IC} and G_f . The f_c' and G_f of specimens manufactured by three different hardness of coarse aggregates were 45, 43, 40 MPa and 89.4, 54.0, 56.3 N/m respectively. K_{IC} of specimens was 138.9, 119.4 and 114.1 MPa.mm^{1/2} for beam size of 50x100x350 mm; 148.2, 115.8 and 108.8 MPa.mm^{1/2} for beam size of 50x150x500 mm; 230.9, 183.1 and 157.9 MPa.mm^{1/2} for beam size of 50x300x950 mm; and 293.2, 248.1 and 244.3 MPa.mm^{1/2} for beam size of 50x450x1250 mm. Experimental results showed that decreasing hardness of coarse aggregate was found to have significant effect on the fracture toughness rather than on the compressive strength of concrete.

1 Introduction

Concrete as a composite material is created by constituents' materials such as cement, aggregate and water. Those materials are relatively easy to find around. Thus concrete has been a well-known material in construction industry. More than 70% of the concrete mix is occupied by aggregate [1, 2]. The physical and chemical properties of aggregate whether fine or coarse aggregate then affect physical and mechanical characteristics of fresh and hardened concrete. The effect of shape and texture [1, 3, 4], grading [5], strength and stiffness [6], maximum size [7], relative density (specific gravity), soundness and toughness [8] on either fresh concrete or compressive strength of the concrete has been extensively investigated by researches.

Fracture toughness is a property of material to resist propagation of cracks [9, 10]. This is a parameter used to indicate failure of the material in Linear Elastic Fracture Mechanics (LEFM), stress intensity factors (K_{IC}) by calculating the amount of stress happened on the initial crack [11]. However, the fracture toughness of concrete can also be described using energy principles in terms of dissipated fracture energy (G_f) needed until failure of material. Investigation has been widely conducted to show the influence of aggregate properties on the fracture toughness of the hardened concrete [12, 13, 14, 15, 16]. The hardness of aggregate is one of influential properties to create an intended strength of hardened concrete. However, there is lack information around the

hardness of aggregate related to fracture toughness of the concrete.

As compressive strength of the concrete is dominant mechanical property of the hardened concrete, thus, a lot of investigations have been conducted to show the relationship between compressive strength and fracture toughness of the concrete ignoring other variables such as properties of material constituents. In addition, Model Code 2010 proposed a model to calculate predicted fracture energy value which is based on compressive strength of the concrete solely [17]. In other word, fracture toughness of the concrete is only relied on the compressive strength of the concrete. Therefore, this research conducted to investigate the effect of coarse aggregate hardness on fracture toughness and compressive strength of concrete.

2 Experiments

2.1. Materials and specimens

The natural fine aggregate used in this study was from Palu River with silt content of 0.6%. The coarse aggregate with particle size of 20 down to 5 mm was engaged. Three different quarries of coarse aggregate employed were from Loli, Taipa and Labuan Stone Crusher (SC). The hardness of coarse aggregates was approached by using Los Angeles abrasion test machine. The Los Angeles abrasion value of Loli, Taipa and

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Labuan SC quarries was 16.7%, 22.6%, and 23.1%, respectively. The Portland composite cement (PCC) binder was employed along with superplasticiser type of mid-range reducing water in order to achieve adequate workability and compaction of the concrete. The concrete mixes produced for creating samples are shown in Table 1.

Table 1. Mix Proportion

Mix	w/c*	Unit weight (kg/m ³)			Super plasticizer (ml)
		Total Aggregate	Cement	Water	
A1*	0,4	1506	679	272	30
A2*	0,4	1506	679	272	30
A3*	0,4	1506	679	272	30

A1 = coarse aggregate of Loli SC quarry, A2 = coarse aggregate of Taipa SC quarry, A3 = coarse aggregate of Labuan SC quarry, w/c = water per cement ratio.

Cubes of 150x150x150 mm were employed to determine compressive strength of the hardened concrete following BS EN 12390-3 (2001). Fracture toughness of the hardened concrete was determined according to three-point bend (TPB) test method proposed by RILEM TC 50-FCM Recommendation [18] with beam specimens of 50x100x350 mm, 50x150x500 mm, 50x300x950 mm, and 50x450x1250. Water cured of all specimens was carried out for 30 days prior to testing.

2.2. Test set up and procedure

The compressive and TPB test were carried out using compression test machine, Figure 1, and the Universal Testing Machine (UTM) C091-08, Figure 2. Figure 3 and Table 2 show the associated test set up and the beam specimen geometry of TPB. The width (b), the depth (D), the total length (L), the total length (S), and the notch (a_o) of the beam are presented on Table 2.



Fig. 1. Compression test machine



Fig. 2. UTM C091-08

In this study, four different specimen sizes were engaged to calculate K_{IC} as the effect of maximum diameter aggregate used in producing beam specimens was concerned. Distribution of subjected load in the specimens can affect the K_{IC} value while the ratio of width of the beam (b) and maximum diameter of coarse aggregate (d_a), b/d_a ratio is inappropriate [20].

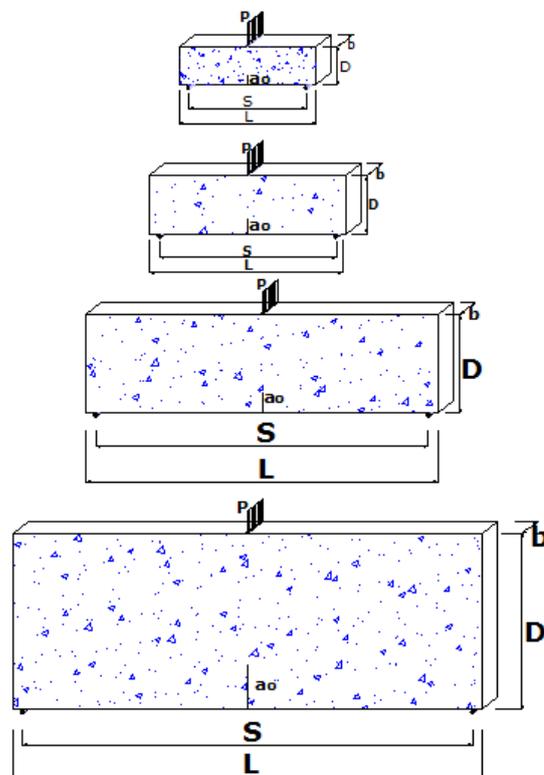


Fig. 3. Geometry of specimen and test set up

Table 2. Dimension of beam specimens

Mix	Beam size	N*	b mm	D mm	L mm	S mm	a ₀ mm
A1	1	5	50	100	350	300	25
	2	5	50	150	500	450	33
	3	5	50	300	950	900	75
	4	5	50	450	1250	1200	100
A2	1	5	50	100	350	300	25
	2	5	50	150	500	450	33
	3	5	50	300	950	900	75
	4	5	50	450	1250	1200	100
A3	1	5	50	100	350	300	25
	2	5	50	150	500	450	33
	3	5	50	300	950	900	75
	4	5	50	450	1250	1200	100

N = number of samples

3 Fracture toughness of concrete

3.1. Stress Intensity Factors (K_{IC})

Fracture toughness of the hardened concrete is determined by calculating K_{IC} of samples based on the three-point bend test method in regard to the RILEM TC89-FMT recommendation [2] as follows

$$K_{IC} = \frac{3(P_c + 0.5W)(S(\pi a_0)^{0.5} g(\frac{a_0}{D}))}{2D^2 b} \quad (1)$$

in which

$$g(\frac{a_0}{D}) = \frac{1.99 - (\frac{a_0}{D})(1 - \frac{a_0}{D})[2.15 - 3.93(\frac{a_0}{D}) + 2.70(\frac{a_0}{D})^2]}{\sqrt{\pi} \left[\left[1 + 2(\frac{a_0}{D}) \right] \left[1 - (\frac{a_0}{D}) \right]^{\frac{3}{2}} \right]} \quad (2)$$

where, P_c is the critical applied load, W is the self-weight of the beam, S is span of specimen, a_0 is notch length of the beam, D is depth of the beam, and b is width of the specimen.

3.2. Fracture Energy (G_f)

Dissipated fracture energy of the specimens is determined based on the three-point bend test method in regard to the RILEM TC89-FMT recommendation which is based on size effect model of Bazant et al. (1995) [9].

$$G_f = \frac{g(\alpha_0)}{EA_B} \quad (3)$$

where: E is modulus elasticity of concrete, A_B is the slope value of linear regression of four different beam sizes, $g(\alpha_0) = \frac{S^2}{b} \pi \alpha_0 [1.5g_1(\alpha_0)]^2$, α_0 is ratio of notch to depth of the beam, and $g_1(\alpha_0)$ is a factor determined by ratio of span to the depth of the beam [9].

4 Results and Discussion

Table 3 and Figure 4 show the compressive strength of the hardened concrete manufactured by three different qualities of coarse aggregates. Although the quality value of coarse aggregate was approached by LA

abrasion value, it can be used to describe the effect of coarse aggregate hardness on the compressive strength of hardened concrete. In this study, hardened concrete manufactured by available coarse aggregate with LA abrasion value of 16.7%, 22.6%, and 23.1% produced average compressive strength of 45, 43, and 40 MPa respectively. Although the range of LA abrasion value of aggregates used in this study was not evenly distributed, this experimental result showed that the use of less LA abrasion value of coarse aggregate in concrete mix tends to produce higher compressive strength of the hardened concrete. Thus, the quality of aggregate used in concrete mix shows to have a certain influence on the intended compressive strength of the hardened concrete.

Table 3. K_{IC} and f_c' value of specimens

Beam Size (mm)	Quarry	LA Abrasion value	K_{IC} (MPa.mm ^{1/2})	Stdev	f_c' (MPa)	Stdev
50x100x350	Loli SC	16.7%	138.9	17.2	45	2.4
	Taipa SC	22.6%	119.4	3.7	43	1.0
	Labuan SC	23.2%	114.1	8.6	40	4.9
50x150x500	Loli SC	16.7%	148.2	8.0	45	2.4
	Taipa SC	22.6%	115.8	8.0	43	1.0
	Labuan SC	23.2%	108.8	10.6	40	4.9
50x300x950	Loli SC	16.7%	230.9	13.8	45	2.4
	Taipa SC	22.6%	183.1	28.7	43	1.0
	Labuan SC	23.2%	157.9	6.1	40	4.9
50x450x1250	Loli SC	16.7%	293.2	19.5	45	2.4
	Taipa SC	22.6%	248.1	12.5	43	1.0
	Labuan SC	23.2%	244.3	6.6	40	4.9

Fracture mechanism of concrete is initiated from cracks in the concrete in which initial crack is occurred. In this study notch of the beam specimen is represented an initial crack of the concrete. A stress concentration is occurred on the top of the notched beam when external load is applied, and then crack is initiated on the top of notch. This initial crack propagates to line the weakest link in the concrete either passing through aggregate particles or surrounding aggregate particles. Type of propagation mechanism relates to critical stress intensity of concrete (K_{IC}) which is one of parameters to determine the fracture toughness of the concrete. Four different beam sizes were employed of concern on the effect of ratio of maximum aggregate size to width of beam specimen (b/d_a) as pointed out by Bazant and Oh (1983) [19] and Siregar et al. (2016) [20]. In this study, the ratio of b/d_a was 2.50. K_{IC} value of all specimens is shown in Table 3. All sizes of the concrete beam show to have a same tendency that the K_{IC} value of less abrasion value is to have a high K_{IC} value. Although this is not an appropriate quantitative investigation, number of aggregate failures on the cross section of the beam specimen is carried out by using magnifying glass in order to determine either failure on aggregate or not, Figure 4. Percentage of aggregate failure is computed of the number of broken aggregates divided by all visible coarse aggregates on the broken cross section beam, Table 4.

Compressive strength of concrete is a predominant mechanical parameter to consider the quality of a hardened concrete was carried out, Figure 5. It is shown that low hardness of the coarse aggregate (high abrasion value) used in the concrete mix produces low concrete strength compared to that of the high hardness of the coarse aggregate (low abrasion value). On the other hand, Figure 6 shows the K_{IC} value of four different sizes of concrete beam manufactured with three different hardness of coarse aggregate. All beam sizes are to have a same trend which is the value of K_{IC} decline as the hardness of coarse aggregate decline. Beam sizes of 50x100x350 mm and 50x150x500 mm give a relatively similar K_{IC} value, but 50x300x950 mm and 50x450x1250 give higher K_{IC} value.

The slope of linear regression line of Figure 5 is less than the slope that of Figure 6. This shows the influence degree of the hardness of coarse aggregate is much more on the fracture toughness than that of the compressive strength of the hardened concrete. Therefore, the use of hardness of coarse aggregate in concrete mix is to have a significant effect on the fracture toughness rather than on the compressive strength of the hardened concrete.

Table 4. Aggregate failure on beam specimen

Beam size (mm)	Quarry	Aggregate failure (%)
50x100x350	Loli SC.	38
	Taipa SC.	49
	Labuan SC.	52
50x150x500	Loli SC.	40
	Taipa SC.	41
	Labuan SC.	41
50x300x950	Loli SC.	46
	Taipa SC.	61
	Labuan SC.	41
50x450x1250	Loli SC.	36
	Taipa SC.	49
	Labuan SC.	54

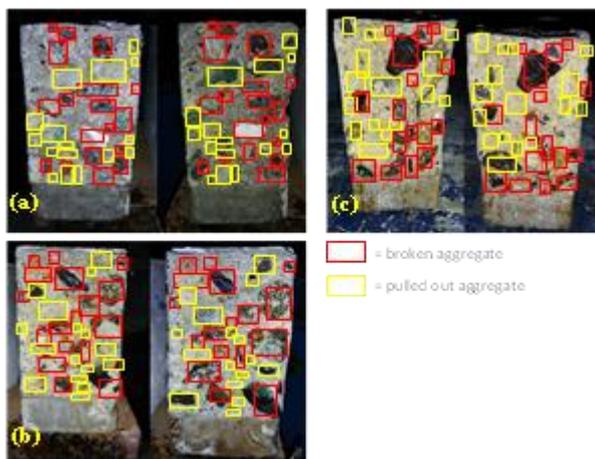


Fig. 4. Typical fracture of beam specimen manufactured by coarse aggregate of (a) SC. Loli, (b) SC Taipa, and (c) Labuan

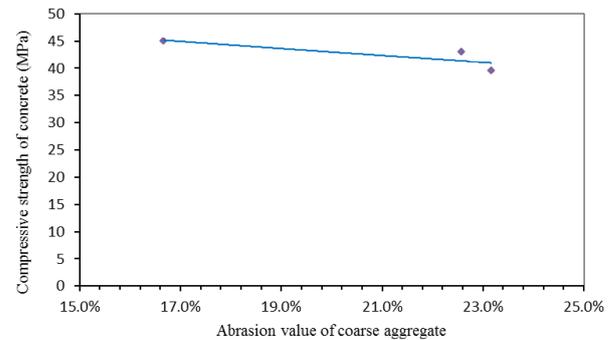


Fig. 5. Compressive strength of hardened concrete using three different coarse aggregates

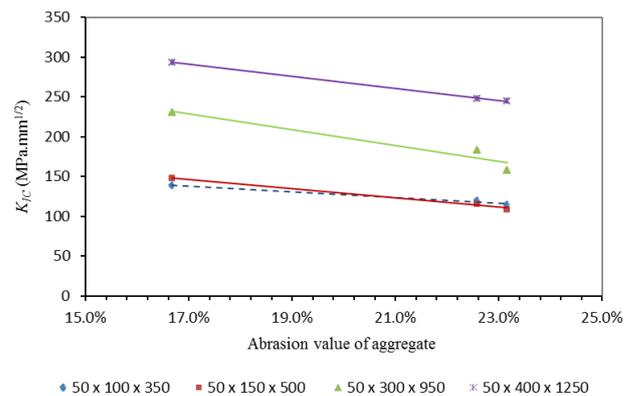


Fig. 6. K_{IC} value of specimens

Table 5. G_f and f_c' value of specimens

LA abrasion value (%)	G_f (N/m)	f_c' (MPa)
16.7%	89.4	45
22.6%	54.0	43
23.1%	56.3	40

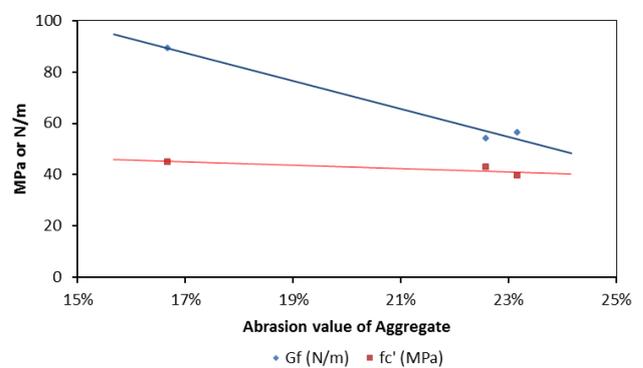


Fig. 7. G_f value of specimens

Energy needed to break the hardened concrete beam is shown in Table 5. Dissipated energy value (G_f) is dependent on the path of crack propagation. The propagation path is to follow the weakest link in the concrete which is dependent on property of the aggregate such as size, shape, surface texture, volume fraction and also water/cement (w/c) ratio [2]. Longer propagation of crack happened in concrete is to have greater G_f value of

concrete. This investigation engaged with that size, shape, surface texture, and volume fraction of the aggregate as well as w/b ratio used in concrete mix were same. Thus the hardness of coarse aggregate is then plays a role solely on propagation of initial crack of the specimen which shows amount of dissipated energy to break the beam specimens. Figure 7 shows the effect of hardness of coarse aggregate used in the concrete mix on the G_f value of the hardened concrete and demonstrates that the hardness of coarse aggregate tends to reduce the G_f value (blue line). However, the hardness of coarse aggregate used in concrete mix affects insignificantly to the compressive strength of the concrete (red line).

Concrete beam specimens manufactured with less hardness of coarse aggregate (higher LA abrasion value) is to have broken coarse aggregate much greater than that of higher hardness of coarse aggregate (less LA abrasion value), and vice versa, number of broken coarse aggregates for beam specimen manufactured with less hardness of coarse aggregate is tend to have a smaller amount than that of with higher hardness of coarse aggregate, Table 4. This indicates that propagation of initial crack in the beam specimens manufactured with higher hardness of coarse aggregate tends to follow surrounding coarse aggregate and as a consequence, having longer crack path. Therefore, specimens manufactured with higher hardness of coarse aggregate are to have greater value of G_f than that of with less hardness of aggregate.

5 Conclusions

In this study, some conclusion can be drawn regarding to the experimental results:

1. Increasing hardness of coarse aggregate by 6.5% affects increasing compressive strength, stress intensity factor, and dissipated fracture energy of the hardened concrete by 14%, 22%, and 59% respectively.
2. The effect of increasing hardness of coarse aggregate used in the concrete mix is much more on stress intensity factors and fracture energy rather than on the compressive strength of the concrete.
3. Fracture toughness of the concrete increases in a certain level as compressive strength of the concrete increases.

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