EXPERIMENTAL STUDY ON RELATIONSHIP BETWEEN TYPES OF CEMENT AND FRACTURE PROPERTIES OF CONCRETE

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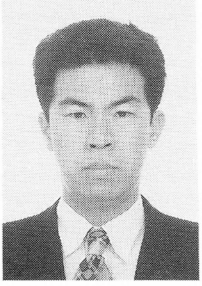

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The influence of types of cement on the fracture properties of concrete has been investigated experimentally in relation to the transition zone at the aggregate surface. Even at an early age, concrete in which belite is used exhibits a relatively high fracture energy in comparison with the low strength developed. This behavior can be explained by the fact that a transition zone rarely exists on the aggregate surface in this concrete. On the other hand, concrete in which high-early-strength cement is used has a smaller fracture energy because a transition zone is present. Based on the relationship between interface strength and fracture energy, this phenomenon has been explained qualitatively.

Key words: *transition zone, belite cement, high-early-strength cement, ordinary Portland cement, fracture energy, tension softening curve, fracture mechanics*

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1. INTRODUCTION

Investigations aimed at understanding the mechanical properties of concrete through the parameters of fracture mechanics have been carried out in many places, possibly because it is widely known that the process of cracking from crack generation up to the fracture of concrete structures can be explained by the phenomena of micro crack generation, agglomeration, and crack development. Further, the fact that the fracture energy G_F and the tension softening curve, which are macroscopic parameters of the crack development process and are considered material properties of concrete, can also be used to simulate the size effect of concrete structures has given the fracture mechanics approach even wider appeal.

The fracture energy G_F is defined as the energy required to form a crack surface which transmits absolutely no tensile stress per unit area. From this definition, fracture energy is calculated as the area enclosed by the tension softening curve, which is the macroscopic relationship between the softening tensile stress applied to the crack surface and the width of the crack observed once a macroscopic crack is generated. The fracture energy is one of the most important parameters in the fracture mechanics of concrete, and it makes possible the numerical evaluation of crack development in concrete structures.

Generally, the fracture energy is considered to be peculiar to each concrete; that is, it is a property of the concrete itself. A variety of equations have been proposed for evaluation of fracture energy. However, of the current design standards, only the CEB-FIP Model Code 90 [1] provides a design equation for the fracture energy. This code gives the following equation for fracture energy, defining it as a function of compressive strength and maximum size of the coarse aggregate.

$$G_F = G_{Fo}\left(\frac{f_c'}{f_{co}'}\right)^{0.7} \tag{1}$$

In this equation, G_F is the fracture energy (N/mm); G_{Fo} is a basic value of fracture energy depending on the maximum size of coarse aggregate; f_c' is the compressive strength of the concrete (N/mm^2); and f_{co}' is 10 (N/mm^2). The code also states that, as a result of various factors not taken into account in Eq. (1), the accuracy of fracture energy evaluations using Eq. (1) is insufficient.

Although fracture energy is considered unique to each concrete, as already mentioned, it is not clear why evaluations of fracture energy vary so widely. Shinohara et al. have carried out various experiments to clarify the influence of the notch depth of notched beam specimens, loading rate, maximum size of coarse aggregate, water-cement (W/C) ratio, curing method, and age on the fracture energy and tension softening curves of concrete [2]. This experimental research also helped to clarify the wide variation in fracture energy itself.

Further, Nomura et al. examined tension softening curves by tracing backward the internal structure of the concrete. Their study indicated that the degree of hydration of the hardened cement paste has an influence on the tension softening behavior of concrete [3]. This research is very suggestive; it appears that, even if the fracture energy can be handled as a material property, the accuracy with which it can be evaluated is insufficient when only macroscopic measures such as compressive strength and maximum size of coarse aggregate are used. In order to accurately evaluate the fracture energy, it is necessary to trace the internal structure of the concrete back to the cement hydrate level.

The above is easily surmised by considering the origin of micro cracks in concrete: points of bonding between aggregate and mortar, weak portions in the hardened cement paste, etc. To date, however, there has been little research carried out on the fracture mechanics of concrete in which the internal structure is traced back to the cement hydrate level. The authors have earlier attempted to analyze the mechanical behavior of concrete made with belite cement from the point of view of fracture mechanics. In the process, it was found that the type of cement -- belite cement with a high C_2S content, high-early-strength cement with a high C_3S content, or ordinary cement -- has a great influence on the fracture mechanics properties of hardened concrete [4].

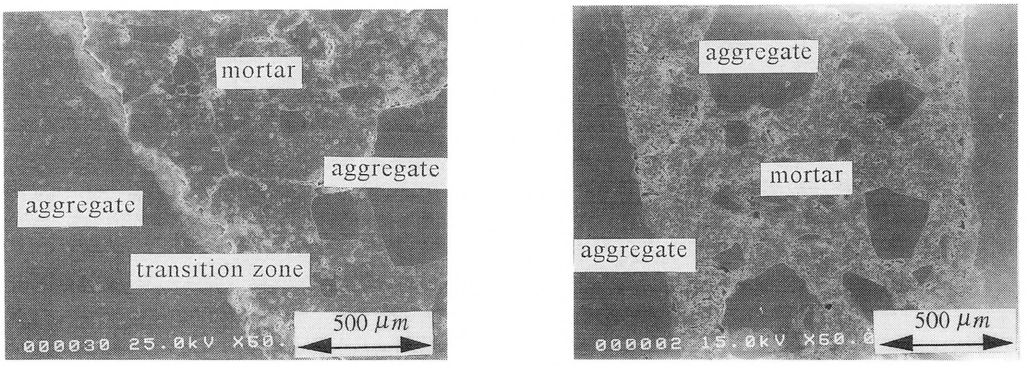
In this study, we use the experimental knowledge obtained in the previous experiments as the basis for examining why cement type has such a great influence on the fracture properties. Based on the results of previous tests with mortar and concrete, we clarify the relationship between the type of cement and the fracture properties of the hardened concrete.

2. SEM EXAMINATION OF HARDENED CONCRETE

Among the cement clinker minerals, C_3S and C_2S hydrate to form calcium silicate hydrate (C-S-H) and calcium hydroxide. However, C_3S produces more calcium hydroxide than C_2S, so high-early-strength cement containing a large amount of C_3S produces more calcium hydroxide than belite cement, which contains more C_2S. When calcium hydroxide precipitates at the interface between aggregate and cement paste, a so-called transition zone is formed [5]. A transition zone containing much calcium hydroxide has a relatively loose structure and is not continuous with other portions of the cement paste. Further, it has been reported that the transition zone becomes thicker as aggregate size, water-cement ratio, and unit water volume of the concrete increase.

The above understanding is obtained from research into cement chemistry. However, since fracture mechanics entails paying particular attention to the generation of micro cracks at the interface between aggregate and cement mortar, this information cannot be ignored. In other words, it can be hypothesized that concrete containing belite cement is relatively superior in fracture properties to concrete containing high-early-strength cement since the weak transition zone layer formed at the interface between aggregate and mortar is thinner in concrete containing belite cement [6].

Photos 1(a) and (b) are examples of scanning electron microscope (SEM) images of the aggregate - mortar interface in hardened concrete; (a) shows concrete containing high-early-strength cement and (b) shows concrete containing belite cement. In both cases, the W/C ratio is 45%. Properties of the materials used for the tests are shown in Table 1; the mix proportion for the concrete is given in Table 2.



(a) Concrete containing high-early-strength cement

(b) Concrete containing belite cement

Photo 1. SEM Images of Aggregate Boundary

Table 1. Properties of Materials Used

Type of material	Source	Specific gravity	Remarks
High-early-strength cement	N Company	3.14	C_2S=9.3%; C_3S=65.2%, Specific surface area = 4450 cm^2/g
Ordinary cement	N Company	3.16	C_2S=28.7%; C_3S=45.5%, Specific surface area = 3210 cm^2/g
Belite cement	N Company	3.22	C_2S=58.6%; C_3S=23.0%, Specific surface area = 3360 cm^2/g
Fine aggreagte	Mountain sand from Toyoda	2.51	FM=2.80, Absorption ratio = 1.47%
Coarse aggregate	Gravel from Kasugai	2.62	FM=6.62, Absorption ratio = 0.86%
High-performance AE agent	T Company	---	Polycarboxylic acid type

Table 2. Mix Proportion of Concrete (SEM Examination)

Max. aggregate size (mm)	Type of cement	W/C (%)	s/a (%)	Unit weight (kg/m^3)				
				W	C	S	G	AE agent C x %
13	High-early-strength	45	49.5	171	381	838	896	0.6
13	Belite	45	49.5	173	385	838	896	1.2

In Photo 1(a), the light-colored (relatively whitish) area seen at the interface between aggregate and mortar is the transition zone (a layer of calcium hydroxide). In concrete containing high-early-strength cement, the presence of this area is clearly visible. On the other hand, it is barely recognizable in the concrete containing belite cement (Photo 1(b)). This coincides with the findings by Hanehara [5] and Uchikawa [6].

These SEM photos of the aggregate and mortar interface, combined with an understanding of the relationship between type of cement and transition zone volume, indicate that concrete containing belite cement has better fracture properties than concrete containing high-early-strength cement.

3. EVALUATION OF BOND BEHAVIOR AT AGGREGATE - MORTAR INTERFACE USING SPLITTING TEST

3.1 Bond Behavior at the Aggregate - Mortar Interface

As already noted, it appears that the volume of the transition zone formed at the aggregate - mortar interface has a great influence on bonding behavior at the interface. From the observations made in Chapter 2, it is considered likely that bonding behavior at the aggregate - mortar interface in concrete containing belite cement is superior to that in concrete containing high-early-strength cement. In order to directly confirm this, it is sufficient to examine the bond strength itself at the aggregate - mortar interface. However, there is no established test method for evaluating bond strength at the aggregate - mortar interface.

For the purpose of making such measurements, we made specimens in which aggregate and mortar were serially arranged so they would bond with each other. We attempted to apply a direct tensile strength test to these specimens, but the experiment was difficult to implement and the data obtained varied widely. On this basis, we judged that, with this type of specimen, a direct tensile strength test was not a suitable way to evaluate bond strength at the aggregate - mortar interface.

Consequently, for experimental ease and reproducibility, we decided on the splitting test described below in place of a direct tensile strength test.

3.2 Evaluation of Bond Behavior at the Interface Based on Splitting Test

Cylindrical specimens were made with high-strength concrete having a compressive strength of about 1000 kgf/cm^2. The height and diameter of the specimens were both 10 cm. After a predetermined strength was reached, the concrete was divided into two pieces using a concrete cutter. This high-strength concrete was then used as a model of the coarse aggregate. As shown in Figure 1, one-half of the high-strength specimen resulting from the cutting operation was placed in a mold; the other half of the mold was filled with new concrete. In this manner, an interface was obtained along a diameter of the cylindrical body.

This interface was formed with a concrete cutter. Thus, unlike the actual aggregate - mortar interface, it is smooth. Further, it must be clearly understood that there is both aggregate and mortar at the interface, so it is not actually coarse aggregate alone. However, the test was designed to evaluate changes in bonding behavior at the interface with different types of cement, and it was thought possible to compare changes in bond behavior with high-strength concrete as a model of coarse aggregate.

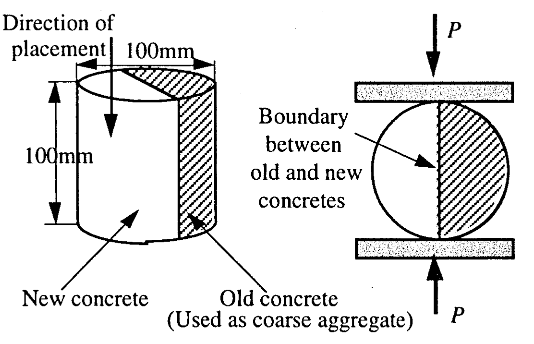


Figure 1. Specimen and Method of Loading for Evaluation of Bond Behavior

The above specimen was placed on the test apparatus in such a manner that the bond surface was vertical and the splitting tensile strength of the specimen was measured. The bond behavior at the interface was evaluated using the results of this test.

3.3 Experiment and Observations

The properties of the concrete materials used for the evaluation of bond behavior were as shown in Table 1; the mix proportion is shown in Table 5. Further, the properties of the materials for the high-strength concrete used to model the aggregate and the mix proportion are shown in Tables 3 and 4, respectively.

The high-strength concrete was cured in an autoclave. At the time of the test (when the concrete was more than four weeks of age), the average compressive strength of this concrete was 1,930 kgf/cm^2. The specimen used to evaluate bond behavior was removed from the mold one day after the new concrete was cast; the specimen was then cured in water. Test results confirmed that all cracks resulting from the splitting process were generated at the boundary between the new concrete and the high-strength concrete. Test results are shown in Table 6 and Figure 2.

Table 3. Properties of Materials Used for High-Strength Concrete

Type of material	Source	Specific gravity
Belite cement	C Company	3.22
Silica fume (SF)	E Company	2.21
Fine aggregate (S)	River sand from Ohi-gawa	2.63
Coarse aggregate (G)	Gravel from Mt. Dantoh	2.61
High-performance AE agent (SP)	T Company	---

Table 4. Mix Proportion for High-Strength Concrete

Max. aggregate size (mm)	Type of cement	W/(C+SF) (%)	Unit weight (kg/m^3)					
			W	C	SF	S	G	SP
15	Belite	15	90	522	78	631	1164	18

Table 5. Mix Proportion for Concrete (for Evaluation of Bond Behavior)

Max. aggregate size (mm)	Type of cement	W/C (%)	s/a (%)	Unit weight (kg/m^3)				
				W	C	S	G	AE agent C x %
13	High-early-strength	65	53.5	172	264	955	870	0.6
		45	49.5	171	381	838	896	
13	Belite	65	53.5	173	266	955	870	1.2
		45	49.5	173	385	838	896	

Table 6. Results of Bond Behavior Tests

Type of cement	W/C (%)	Tensile strength at boundary (kgf/cm^2)		Compressive strength of concrete (kgf/cm^2)	
		at 7 days	at 28 days	at 7 days	at 28 days
High-early-strength cement	65	6.9	12.8	235	263
	45	11.0	13.2	356	428
Belite cement	65	11.8	12.9	165	310
	45	12.7	13.1	196	506

Test results at the age of seven days indicate that concrete containing belite cement had a higher tensile strength and better bonding properties at the interface than concrete containing high-early-strength cement. On the other hand, concrete containing high-early-strength cement had a considerably lower tensile strength at the interface and bonding properties were poor, especially when the W/C ratio was 65%. At this age, the compressive strength of concrete containing high-early-strength cement and with a W/C ratio of 65% was about 40% greater than that of the corresponding concrete containing belite cement.

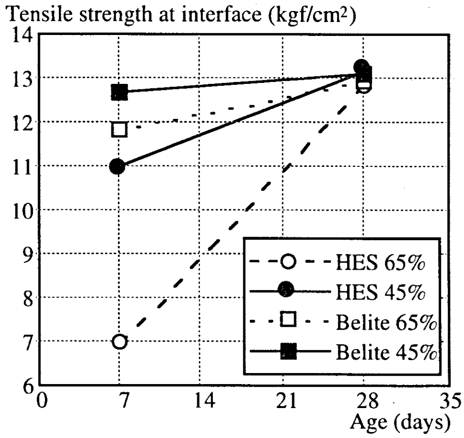


Figure 2. Changes in Tensile Strength at the Interface with Age

In contrast, the bond strength at the interface was about 40% weaker for concrete containing high-early-strength cement than for concrete containing belite cement. In the case of a 45% W/C ratio, although there was little difference in tensile strength between the two, concrete containing high-early-strength cement was slightly weaker than concrete containing belite cement.

At 28 days, the type of cement has little influence on tensile strength at the interface. At this age, although the compressive strength of concrete containing belite cement is higher than that of concrete containing high-early-strength cement, the tensile strength at the interface is little different despite the variation in compressive strength.

In summary, concrete containing high-early-strength cement has weaker bonding at the aggregate - mortar interface at the age of seven days than concrete containing belite cement, especially when the W/C ratio is high. Further, it was clarified that bonding behavior varies as time passes. Moreover, it seems that the mechanism of changes in bond strength has no relation to the development of compressive strength.

Research in the field of cement chemistry has shown that the transition zone at the aggregate interface changes in thickness as time passes, reaching a maximum at 7 days; after that, it decreases gradually [5], [6]. Although it is very difficult to directly explain the change in bond

Table 7. Summary of Mortar Specimen

Type of cement	High-early-strength cement		Belite cement	
W/C (%)	50		50	
C : S	1 : 3		1 : 3	
Fine aggregate diameter (mm)	0.85 ~1.19 (Fine sand)	1.19 ~2.38 (Coarse sand)	0.85 ~1.19 (Fine sand)	1.19 ~2.38 (Coarse sand)

behavior at the interface by the existence of the transition zone alone, it is clear that for both types of concrete a difference in hydration products at the transition zone has a great influence on bonding and that the existence of the transition zone plays an important role in this mechanical behavior.

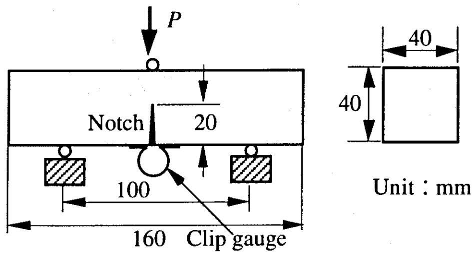


Figure 3. Three-Point Bending Test on Notched Beam (Mortar)

4. MEASUREMENT OF FRACTURE PROPERTIES USING MORTAR SPECIMEN

4.1 Outline of Experiments

It has been reported that the transition zone becomes thicker as the aggregate size is increased. In order to study this, specimens were made with fine aggregates of different maximum diameters and the fracture properties of the hardened mortar were measured. This provides information on the influence of type of cement on fracture properties. Two types of fine aggregate, classified by the ratio of particles passing through a sieve, were prepared. For convenience, they are called coarse sand and fine sand (See Table 7).

A three-point bending test was carried out on notched beam specimens as shown in Figure 3. The specimens had cross-sectional dimensions of 4 cm × 4 cm and was 16 cm long; the loaded span of the simply supported beams was 10 cm. A 2 cm notch was made in the specimens immediately below the loading point in the middle of the span to localize cracking; the notch was made with a diamond rock cutter before loading. In addition to the relationship between load and displacement, the crack mouth opening was also measured. All specimens in this test were 28 days old.

4.2 Results of Experiment

According to the RILEM method, fracture energy G_F was calculated using Eq. (2).

$$G_F = \frac{W_o + m \cdot \delta_o}{A_{lig}} \qquad (2)$$

Table 8. Fracture Energy and A_o of Mortar at 28 Days

Type of cement	Type of aggregate	Compressive strength (kgf/cm^2)	G_F kgf/cm	Constant A_O x 10^3	
High-early-strength cement	Fine sand	447	0.0562	0.785	Average 0.685
	Coarse sand	458	0.0426	0.580	
Belite cement	Fine sand	216	0.0280	0.650	Average 0.720
	Coarse sand	249	0.0375	0.790	

Where, W_o: area below load-displacement curve,
m: weight of specimen between supports,
δ_o: displacement at fracture,
A_{lig}: area of fracture portion of specimen above notch (ligament area) projected onto a plane perpendicular to the beam axis.

In general, fracture energy increases as the tensile strength or compressive strength becomes higher. Therefore, it is considered improper to compare absolute values of fracture energy themselves under considerably different levels of tensile and compressive strength.

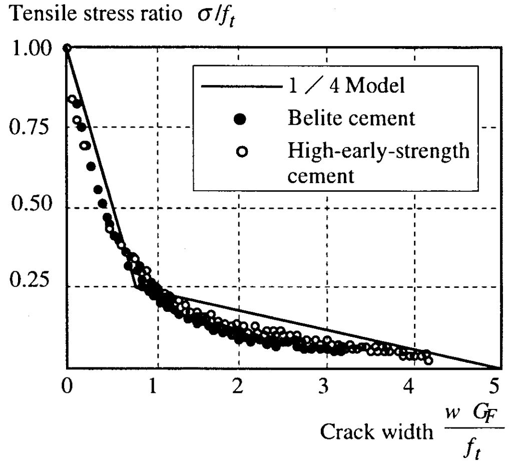


Figure 4. Tension Softening Curve of Mortar (Fine Sand)

So, after referring to Eq. (1), which is the design equation for the fracture energy of concrete in CEB-FIP Model Code 90, we decided to examine a constant A_o (Eq. (3)) obtained by measuring the fracture energy and compressive strength of the mortar.

$$A_o = \frac{G_F}{f_c'^{\,0.7}} \tag{3}$$

Further, with the new J-integral based method proposed by Uchida et al. [7], the tension softening curve can be obtained based on the relationship between load and displacement, and the relationship between load and crack width. Obtained test results for hardened mortar are shown in Table 8 and Figure 4.

4.3 Consideration of Fracture Property Values

According to Table 8, the value of fracture energy at 28 days was larger in mortar containing high-early-strength cement than in mortar containing belite cement. However, no close relationship between fine aggregate size and fracture energy was recognized. Here, in consideration of the degree of strength development of mortar containing belite cement, the compressive strength of the mortar was corrected using Eq. (3) to compare the constants A_o.

As shown in Table 8, A_o of mortar containing belite cement was larger in the case of coarse sand and slightly smaller for the same mortar in the case of fine sand. Further, the average A_o of the mortar containing belite cement was larger than that of the other mortar. In other words, the fracture energy of mortar containing belite cement is almost the same as, or larger than, that of mortar containing high-early-strength cement when corrected by the compressive strength in consideration of the influence of strength development.

This result indicates the same tendency as the qualitative relationship between the existence of the transition zone described in Chapter 2 and the fracture energy. However, as described above, the influence of fine aggregate size and the transition zone cannot be clarified; it seems that the influence of this slight difference in size on the existence of the transition zone may be relatively small.

Figure 4 shows the obtained tension softening curves for the mortar together with the one-fourth tension softening model. It is clear that the tension softening curves of the mortar coincides with the one-fourth tension softening model regardless of cement type. After the bend point, the value given by the one-fourth tension softening model is slightly larger than the actual test results. This is because external energy is absorbed at positions other than the cross-section of the ligament (that is, the notched cross-section) in the test; however, the difference is very small and the one-fourth tension softening model is sufficiently applicable as a typical tension softening curve for mortar as well as concrete.

5. MEASUREMENT OF FRACTURE ENERGY USING CONCRETE SPECIMEN

5.1 Outline of Experiment

For mortar, the influence of the type of cement on fracture energy was confirmed by applying a correction based on compressive strength. In the next step, the effect of the type of cement on concrete fracture properties was examined based on the measurement of fracture energy. The experiment was carried out as shown in Figure 5. The 40-cm long notched concrete specimens had a cross-section of 10 cm × 10 cm and a loaded span of 30 cm. A 5-cm deep notch was cut immediately under the loading point using a concrete cutter.

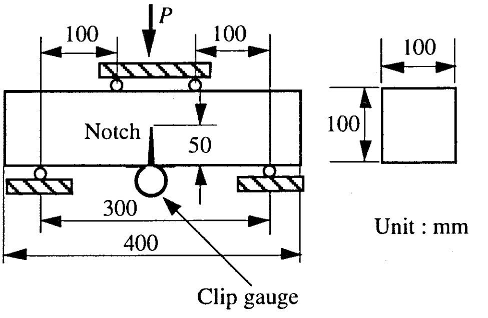
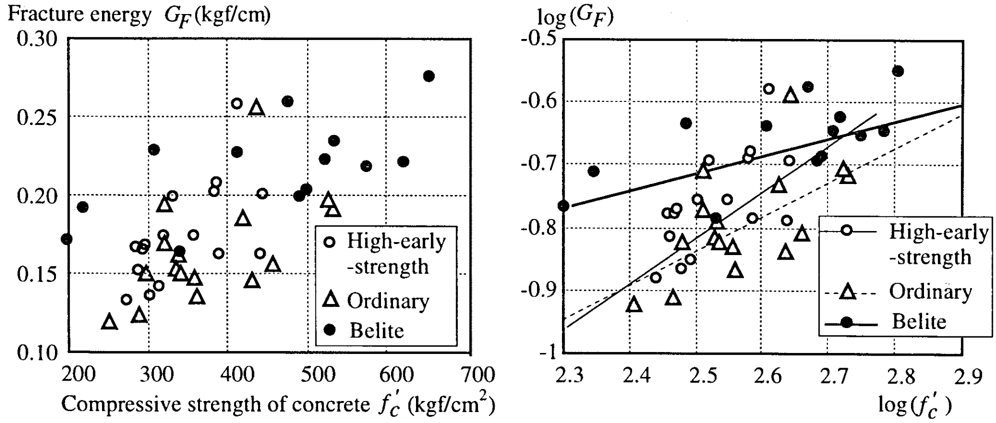


Figure 5. Three-Point Bending Test of Notched Beam (Concrete)

With the mix proportion shown in Table 9, concrete specimens were made for each type of cement (high-early-strength cement, ordinary cement, belite cement) with different W/C ratios.

Table 9. Mix Proportion for Concrete

Max. aggregate size (mm)	Type of cement	W/C (%)	s/a (%)	Unit weight (kg/m^3)				
				W	C	S	G	AE agent C x %
13	High-early-strength	55	51.5	172	312	900	888	1.2
		45	49.5	171	381	838	896	
13	Ordinary	55	51.5	172	313	900	888	0.8
		45	49.5	172	382	838	896	
13	Belite	55	51.5	173	315	955	888	0.6
		45	49.5	173	385	838	896	



(a) Relationship between G_F and f'_c (b) Relationship between log(G_F) and log (f'_c)

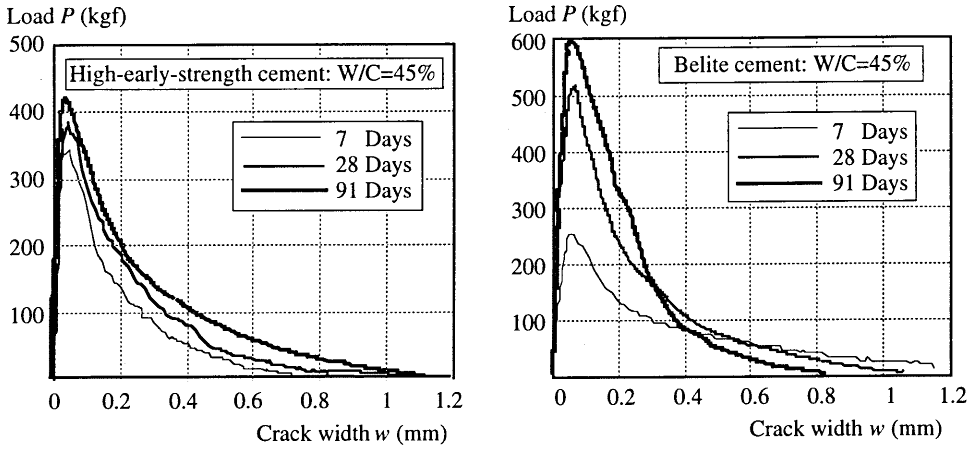
Figure 6. Relationship between Compressive Strength and Fracture Energy

Bending tests were carried out on these specimens at ages of seven days, 28 days, and 91 days to measure the relationship between load and displacement, and the relationship between load and crack width. Materials used for the concrete were the same as those shown in Table 1; the maximum size of coarse aggregate was constant at 13 mm.

5.2 Results of Experiment

Figures 6(a) and 6(b) show the relationship between measured fracture energy and concrete compressive strength; normal coordinates are used in (a) and logarithmic coordinates in (b). If the fracture energy of concrete were a function of the concrete's compressive strength and, as in the CEB-FIP Model Code 90 for instance, it is expressed as an exponential function, the gradients of regression lines for concretes made from a variety of cements must be the same in logarithmic coordinates. However, the test results and regression lines shown in Figure 6(b) show smaller gradients for the fracture energy of concretes containing belite cement than those of concrete containing ordinary or high-early-strength cement.

As shown in Figure 6(b), the influence of type of cement on the fracture energy of concrete



(a) Relationship between load and crack width with time for concrete beam containing high-early-strength cement

(b) Relationship between load and crack width with time for concrete beam containing belite cement

Figure 7. Measured Tension Softening Curves

decreases gradually with the development of compressive strength as the concrete ages. However, when compressive strength is low at early ages, the fracture energy of concrete containing belite cement is clearly larger than that of concrete containing high-early-strength or ordinary cement.

As seen from the small gradient of the regression line, the rate of fracture energy increase in concrete containing belite cement, which results from the rising compressive strength, tends to fall gradually as time passes. However, since belite cement is superior in long-term strength development, the fracture energy of concrete containing belite cement always tends to be larger than that of concrete containing other types of cement.

Figures 7(a) and 7(b) show the relationship between load and crack width obtained from a notched beam bending test. As shown in Figure 7(a), in the case of concrete containing high-early-strength cement, it is clear that the relationship between load and crack width increases in a similar manner as the concrete ages. On the other hand, in the case of concrete containing belite cement, as shown in Figure 7(b), the tail portion of the curve at an early age does not decrease rapidly regardless of the increase in crack width, but crosses the curves at the longer ages indicating larger fracture energy. As described above, higher fracture energy at an early age is a characteristic of concrete containing belite cement.

5.3 Flexural Strength of Concrete

An increase in the fracture energy of concrete means that the flexural strength of plain concrete, or the diagonal tensile strength of a reinforced concrete member, increases because of the influence of the tension softening curve. Figure 8 shows the relationship between compressive strength and flexural strength for a variety of cement types; the W/C ratio is 0.45. In Figure 8, the flexural strength obtained from $f_b = 1.017 f_c'^{2/3}$ is also shown for reference.

As expected, the flexural strength of concrete containing belite cement is always higher at a particular compressive strength than that of concrete in which another type of cement is used; this substantiates the idea that concrete containing belite cement has a higher fracture energy. It also indicates that the flexural strength of concrete containing belite cement is the closest to that of the evaluation equation.

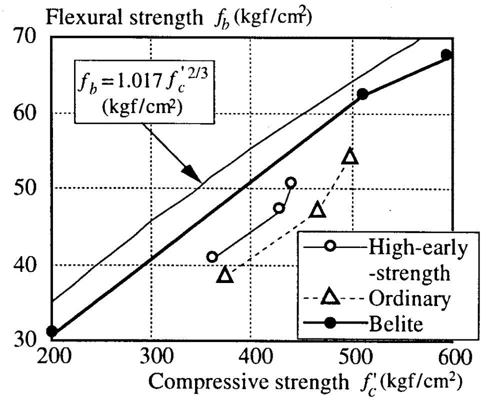


Figure 8. Relationship between Compressive Strength and Flexural Strength

6. CONSIDERATION OF INTERFACE STRENGTH AND FRACTURE ENERGY

Tests using various types of cement have made clear that the magnitude of concrete fracture energy is influenced by the bonding at the interface between aggregate and mortar, as well as by macroscopic factors such as compressive strength and the maximum coarse aggregate size. Here, we consider the relationship between this interface strength and fracture energy.

In general, micro cracks in concrete originate at the interface between aggregate and mortar, which is weak zone, or in voids in the mortar. Cracks that occur at the aggregate interface are generally called "bond cracks." These cracks grow to form matrix cracks in the mortar. In this process, when a matrix crack intersects an aggregate particle, conditions at the time determine whether the crack bypasses the aggregate or penetrates it.

It is assumed that the strength of the aggregate interface is influenced by the size of the transition zone which forms at the interface, as well as by the strength of the concrete itself. On the other hand, it is assumed that the size of the transition zone has little influence on mortar strength. Considering the strength of the aggregate itself as well as the above factors, a conceptual relationship between concrete strength and W/C ratio is shown in Figure 9.

In Figure 9, Area A is where the strength of the concrete is affected by the strength of the mortar; in Area B the strength of the concrete is affected by interface strength; and in Area C it is affected by the strength of the aggregate.

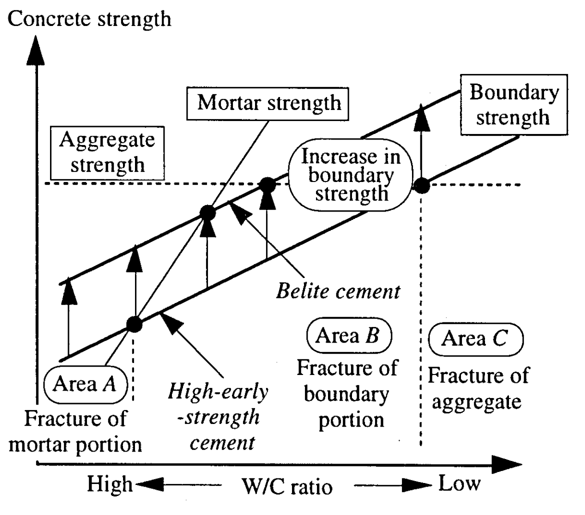


Figure 9. Relationship between Interface Strength and Fracture Mode

Area A represents the lowest strength; Areas B and C follow in order. However, in Area A, cracks occur in the mortar portion, and these cracks bypass the aggregate, so that the fracture energy absorbed per unit volume of concrete is large; considering that this area has low strength, the fracture energy per unit strength is relatively larger.

On the contrary, cracks in Area C are not dispersed, but rather are localized; moreover, the cracks penetrate the aggregate linearly, so the amount of fracture energy absorbed is small. Further, since this area has high strength, the fracture energy per unit strength is lower. Area B is between Areas A and C. Consequently, it is thought that Area A has the greatest fracture energy per unit strength, with B and C following in order.

Concrete containing belite cement yields a small transition zone at the aggregate interface, so the interface strength seems to be high. Therefore, as shown in Figure 9, the interface strength line rises to give a narrow Area B, especially at an early age when strength is low, and the strength of the concrete is influenced by Area A. As a result, it can be deduced that fracture energy per unit strength increases. On the contrary, in concrete containing high-early-strength cement, the existence of the transition zone causes the interface strength to decrease, so the interface strength line falls such that Area B becomes wider, and the strength of the concrete is influenced by Area B. Consequently, the fracture energy is comparatively smaller than that of concrete containing belite cement.

As described above, by considering the change in interface strength of the aggregate, which is affected by the presence of the transition zone, and the strength of the mortar which is largely unaffected by it, it is possible to explain the relationship between cement type and the concrete fracture energy.

7. CONCLUSIONS

In this study, the relationship between cement type and the fracture properties of concrete were examined from the viewpoint of mechanical conditions at the interface between aggregate and mortar. The following conclusions can be reached:

(1) Concrete containing high-early-strength cement, which contains relatively large amount of C_3S, has a porous portion with low bond strength, called a transition zone, at the aggregate interface. This was confirmed by using a scanning electronic microscope. Further, it was confirmed in splitting tests that the bond strength of aggregate and mortar is high in concrete containing belite cement high in C_2S, and the bond strength decreases in concrete containing high-early-strength cement with more C_3S.
(2) When corrected for compressive strength, the fracture energy of mortar containing belite cement is equivalent to or larger than that of mortar containing high-early-strength cement.
(3) The fracture energy of concrete containing belite cement tends to be larger in comparison with that of concrete containing high-early-strength cement, especially when strength is low at an early age. As strength develops with aging, the rate of increase in fracture energy accompanying compressive strength tends to fall. However, concrete containing belite cement is superior in long-term strength development, so the absolute fracture energy of the concrete

always tends to be larger than that of concrete containing high-early-strength cement.
(4) In concrete containing belite cement, the presence of a transition zone at the aggregate interface is rare, so interface strength increases. As a result, it is thought that brittle fractures, arising from localized cracks which penetrate the aggregate, are prone to occur. However, when the strength of the concrete is low at an early age, fracturing of the mortar itself, rather than brittle fracture, is dominant because the bond strength at the interface is greater. In this type of fracturing, it is thought that the cracks are dispersed, and the fracture energy absorbed per unit concrete volume increases.
(5) On the other hand, the existence of a transition zone in concrete containing high-early-strength cement causes interface strength to decrease and fractures occur at the interface. Compared with fractures in the mortar, these cracks concentrate at the interface and less fracture energy tends to be absorbed. Thus, it is possible to conclude that concrete containing belite cement has greater fracture energy than concrete containing high-early-strength cement.

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