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An Investigation on Toughness of Steel Fiber Reinforced Heavy Concrete

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ABSTRACT

This paper presents an experimental study dealing with the toughness of heavy concrete based on the ASTM C1018. Mixtures including 0%, 0.5%, 1.0% and 1.5% of steel fiber content by volume are designated, which are all developed according to a mixture used in Kuosheng nuclear power plant in Taiwan· Metallic aggregates of iron shots and iron ore take 48.8% by volume in that mixture. Test results revealed that the tensile strength, rupture modulus and bond strengths appeared increasing with the increase of steel fiber content, while the compressive strength and modulus of elasticity turned out a bit decreasing. Flexural toughness tests showed that the toughness of heavy concrete grew with the steel fiber fraction.

KEY WORDS: heavy concrete, steel fiber, toughness index, crack.

INTRODUCTION

Degradation of radiation shielding structure, which may lead to radiation leakage is one of the most crucial issue to nuclear engineering since more mechanism of concrete has been figured out and more concrete technology has been innovated. Cracks always take place prior to deterioration or failure of a concrete structure. The area of studying cracking of concrete is referred to as fracture mechanics of concrete [1,2]. It is thought that concrete initiates its crack as the fracture toughness that is always defined quantitatively in terms of critical stress intensity factor K_C or fracture energy G_C has been reached [3,4]. From the aspect of fracture mechanics, there is a fracture process zone in front of the crack tip of concrete as crack propagates. Recently, there has been a number of proposals being suggested to RILEM, such as Hillerburg's work of fracture model [5], Bazant's size effect model [6], Jenq and Shah's two-parameter model [7] and Karihaloo and Nallathambi's effective crack model [8], which all provide methods to determine fracture properties of concrete.

Plenty of research efforts have been conducted in studying the fracture toughness and flexural toughness of normal concrete with various mixtures [9-15]; while few researches have been performed concerning with heavy concrete for its strengths as well as fracture property. ACI Manual of Concrete Practice [16] provides thorough procedures for measuring, mixing, transporting and placing. Few researches dealing with the fracture property of heavy concrete has been reported. Kan and Pei [17] found that the compressive and tensile strengths of heavy concrete did not differ from those of regular mortar at the same water to cement ratio; but, the modulus of elasticity increases with the heavy aggregate content.

As far as toughness strengthening and radiation protection are concerned, the inclusion of steel fibers could promote the performance of shielding structures. The objective of this research work attempts to investigate the mixture, fabrication and many basic engineering properties of heavy concrete which include strengths and flexural toughness under the influences of various contents of steel fibers. The testing results have also been compared with those of regular concrete.

TESTING PROGRAM

Material Preparations

Cement

Type I Portland cement is the only kind used for the entire experiment following the ASTM C150 or ASTM C595 for conventional concrete; the cement performance is suitable for use in heavy concrete. It is advisable not to use Type III cement or accelerators for heavy concrete in order to avoid high and rapid hydration heat that may result cracking**.** [18]

Aggregate

Unlike normal concrete, the main feature of heavy concrete is the inclusion of metallic fillers, which are usually ilmenite, limonite-goethite, serpentine, magnetite, barite, ferrophosphorous, steel aggregate and iron shot. In this study, iron ore and iron shot are adopted as concrete aggregates. The iron ore is from Brazil and has a maximum particle size of 9.5 mm and a fineness modulus of 3.04, according to ASTM C136-96a; its specific gravity is 4.8, as measured in the test. Iron ore with a little ferrophosphorous is chosen since ASTM reported that ferrophosphorous, when used in Portland cement, generates flammable and possibly toxic gases. Two types of iron shots manufactured locally are used; they have a specific gravity of 7.4 and maximum particle sizes of 1.75 mm and 2.0 mm. It appears that smaller particles are less likely to segregate, even though their densities are higher. And, regular coarse aggregate with maximum particle size of 3/4" and a fineness modulus of 4.22 is also used to fabricate mortar specimens for comparison with normal concrete.

Steel Fiber

The steel fiber adopted in this research is hooked-end type. It has a density of 7850 g /cm^3 and is 30 mm long with a diameter of 0.5 mm. The aspect ratio of length-to-diameter is 60. All fibers are in separate form such that they can be uniformly distributed in the matrix of concrete.

Mixture of Concrete

To investigate the effect of steel fibers on the mechanical properties of heavy concrete, the mixtures of both heavy concrete and normal concrete are designated with a unique water-to-cement ratio of 0.48, and with 0%, 0.5%, 1.0% and 1.5% of steel fibers in volume in the testing program. The normal concretes were made for comparison purpose. The mixture design is shown in Table 1. It is noted that the total amount of metallic aggregates is 40 % in volume -- 9.2 % for iron shot and 30.8% for iron ore. The normal concrete has the same fraction of regular coarse aggregate as metallic aggregates in heavy concrete. Slumps and air contents of fresh concrete of all mixtures conformed to the needs of workability.

Table 1 Mixtures of steel-fiber reinforced concrete

Mixture	FHC- Ⅰ	FHC- Ⅱ	FHC-Ⅲ	FHC-Ⅳ	FNC- Ⅰ	FNC - Ⅱ	FNC - Ⅲ	FNC -Ⅳ
Fiber	0%	0.5%	1.0%	1.5%	0%	0.5%	1%	1.5%
Water	308	308	308	308	308	308	308	308
Cement	643	643	643	643	643	643	643	643
Sand	227	214	201	188	226	213	200	187
Aggregate	-	-	-	-	1048	1048	1048	1048
Iron ore	1330	1330	1330	1330	-	-	-	-
Iron shot 550	341	341	341	341	-	-	-	-
Iron shot 660	327	327	327	327	-	-	-	-

Note: FHC and FNC stand for heavy concrete and normal concrete, respectively. All units are kg except for fiber.

Mixing and Curing

The procedure for mixing heavy concrete is similar to conventional concrete. In a typical mixing procedure, the iron ore, iron shot and steel fibers are mixed first, followed by cement and then water, as same as mixing of regular concrete. However, due to higher specific gravities of both iron ore and iron shot, too much compacting vibration that can lead to segregation has to be avoided. In addition, the absorption of aggregates obtained from laboratory are 1.19% for iron ore and negligible for iron shot. Trial mix for each mixture has been engaged until a good workability and a sufficient strength gain are achieved. In the mean time, air content is also measured from fresh concrete for each mix, which could provide useful data to figure out the amount of voids. All concrete specimens were cast in molds for one day and then placed in water for 28 days prior to testing.

Testing Specimens

Four types of specimens made from the above four mixtures were fabricated in this testing program. The Φ15 x 30 cm cylinders were used to determine the physical properties of concrete including modulus of elasticity and wave velocity. The Φ10x 20 cm cylinders were mainly tested for compressive strength and tensile strength. The cubic specimens of 15 x 15 x 15cm in dimension with an additional No. 6 steel bar being planted into the specimens, which also follows the ASTM, was used for pullout test in order to determine the pullout strength of concrete. Three-point bending beam specimen of 10 x 10 x 35cm in dimension was employed for flexural test. This was used to determine the modulus of rupture and flexural toughness of concrete.

Testing Procedure

Testing procedures of all fundamental mechanical properties conform to the ASTM Specifications [19-23]. Flexural toughness of steel-fiber reinforced heavy concrete complies ASTM C1018 [24], in terms of toughness indices I_5, I_{10} and I_{30}. In this method, the beams were tested in three-point bending on a hydraulic testing system as shown in Figure 1. Load and displacement data are recorded simultaneously before ultimate load is reached.

Wave velocity is measured from a cylinder through impact-echo method [25]. The testing system comprises an impact device, a receiver and a computer with data acquisition interference. An impact source excites a compressive stress wave (P-wave) at a point of one side. The receiver is placed on the same side to record the time duration wave traveling to and back from the other side. The wave velocity is thus determined by dividing the path length by the time duration.

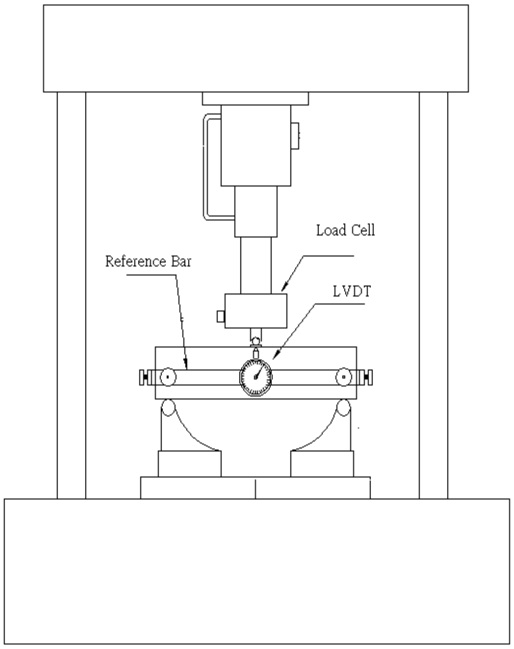

Fig. 1 Configuration setup of flexural test

RESULTS AND DISCUSSIONS

Mechanical Properties

The testing program investigated several mechanical properties of steel-fiber reinforced heavy concrete, such as compressive strength, splitting tensile strength, modulus of rupture, bond strength and flexural toughness which all conform to ASTM. The test results are presented and discussed as follows:

Compressive Strength

The compressive strengths of both heavy concrete and normal concrete with steel fibers in their matrix are lower than those without as shown in Figure 2. It can also be observed that the heavy concrete with 1% steel fiber content in volume has higher compressive strength than the others. And, for the same water-to-cement ratio and steel fiber content, the compressive strength for heavy concrete are all higher than those of normal concrete. This can attribute to the higher toughness and strength of heavy aggregate than regular aggregate.

Splitting Tensile Strength

The splitting tensile test following ASTM C496 was used to determine the tensile strengths of concrete with various amounts of steel fiber inclusions. Figure 3 shows that the tensile strength increases with the steel fiber fraction for both heavy concrete and normal concrete. An inclusion of 1.5 % steel fiber in concrete by volume can raise the tensile strength from 2.38 MPa to 5.51 MPa for heavy concrete and from 2.48 MPa to 5.63 MPa for normal concrete. This is attributed to the existence of fibers in matrix, which are across the potential cracking faces and enhance the crack resistance.

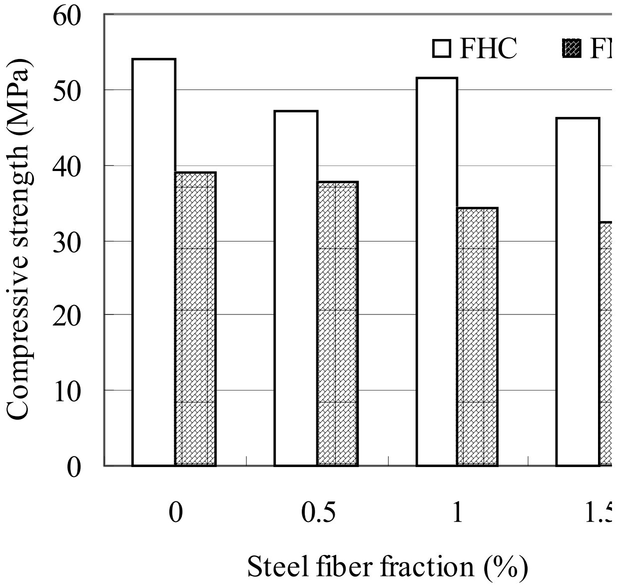

Fig. 2 Compressive strength versus steel fiber fraction

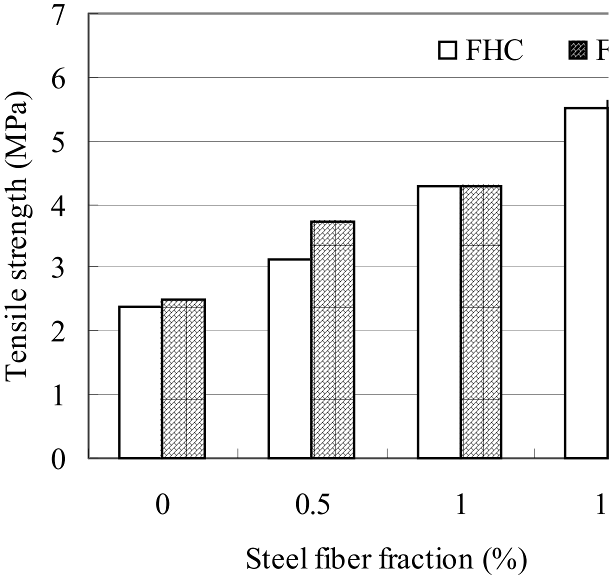

Fig. 3 Tensile strength versus steel fiber fraction

Modulus of Rupture

The three-point bending flexural test complying ASTM C293is adopted to estimate the modulus of rupture of heavy concrete. This provides a mean to estimate the flexural strength of concrete. It is shown in Figure 4 that modulus of rupture of heavy concrete also increase with the steel fiber fraction. A 1.5 % of steel fiber fraction raises the tensile strength from 6.66 MPa to 11.3 MPa for heavy concrete and from 6.61 MPa to 9.47 MPa for normal concrete. It makes heavy concrete a higher flexural strength than that of normal concrete. This could be explained by the above results that heavy concrete has a higher compressive strength than that of normal concrete, which leads to a higher flexural strength.

Bond Strength

The nominal bond strengths of various mixtures of concrete were determined using the pullout test, following the ASTM C900. Fig. 5 shows the testing results, which reveal the tendency that bond strengths of concrete grow with the inclusion of steel fiber, which is similar to that of splitting tensile strength or modulus of rupture. The inclusion of steel fiber raises the tensile strength from 6.65 MPa to 16.1 MPa for heavy concrete and from 6.14 MPa to 14.7 MPa for normal concrete. Obviously, steel fiber could provide the confinement of concrete around the steel bar. Also, it makes heavy concrete higher bond strength than that of normal concrete. Furthermore, the type of cracking observed from the fractured surface of all specimens showed that splitting failure is a typical for those concretes without fibers and become less clear as more steel fibers were included.

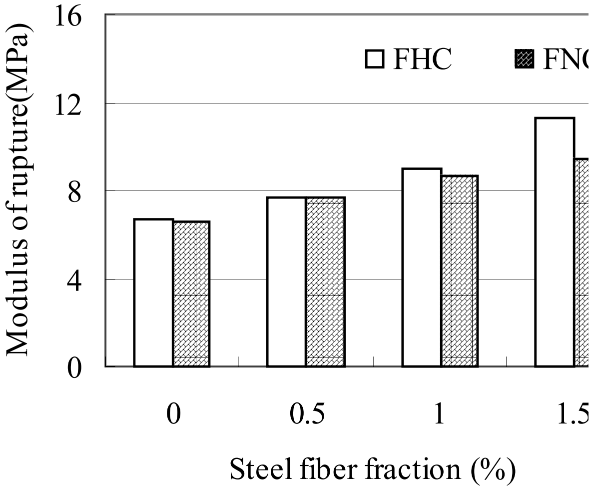

Fig. 4 Modulus of rupture versus steel fiber fraction

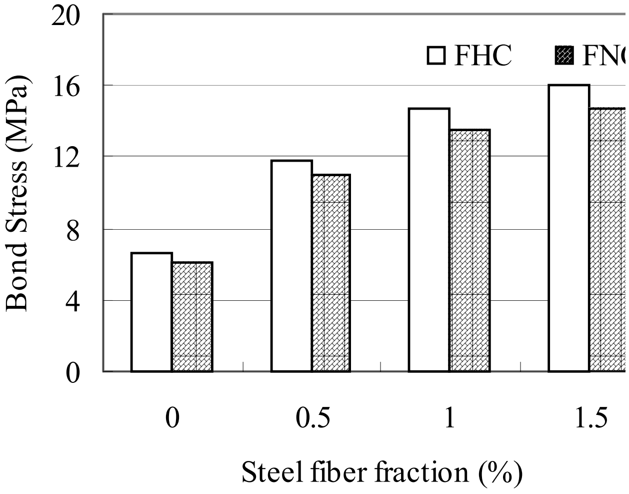

Fig. 5 Bond strength versus steel fiber fraction

Elastic Modulus

The elastic moduli are investigated in the tests in accordance with ASTM C469 and a four-point beam test. Test results revealed that the elastic modulus of both heavy concrete is higher than normal concrete. They are all decreasing with the increase of steel fiber. As is shown in Fig.6, it can be seen that a 1.5% inclusion of steel fiber in concrete makes the elastic modulus of concrete decline from 41.4 GPa to 33.6 GPa for heavy concrete and from 26.7 GPa to 19.1 GPa for normal concrete, based on the cylinder test. The tensile elastic modulus and compressive elastic modulus investigated through a four-point bending test showed that the former increases with the steel fiber fraction but the later decreases. And, the compressive elastic moduli are similar to those determined from the cylinder test. The declination of compressive elastic modulus can be attributed to the increase of steel fibers which lead to increase of air content as mixing in fresh concrete.

Wave Velocity

The testing results show that the wave velocities of both heavy concrete and normal concrete generally decreases as steel fibers increasing, as shown in Fig. 7, which implies that more steel fibers introduce more voids in heavy concrete. However, the mixture of heavy concrete with 1% steel fiber fraction turns out a higher wave velocity than others. This is consistent with an inspection on the test results of compressive strength.

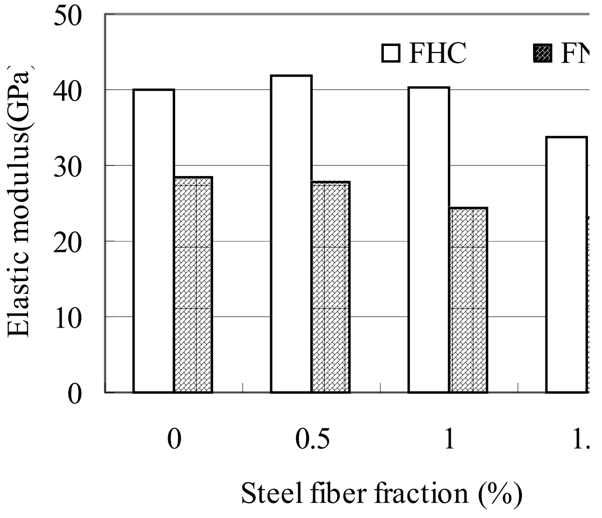

Fig. 6 Elastic modulus versus steel fiber fraction

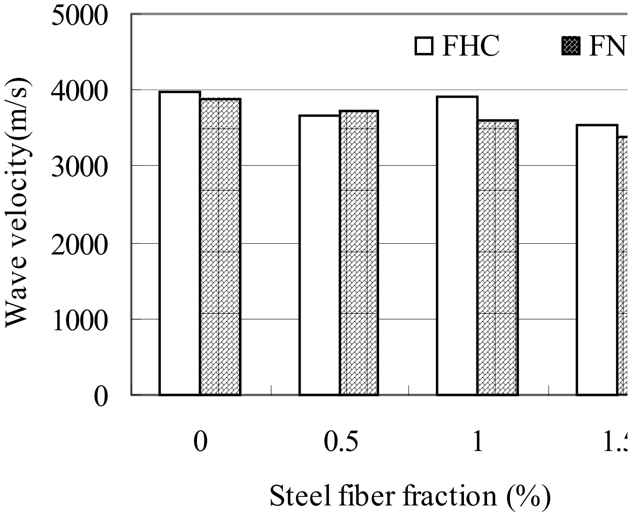

Fig. 7 Wave velocity versus steel fiber fraction

Toughness Indices

Flexural toughness of steel-fiber reinforced concrete complies ASTM C1018 [24], in terms of toughness indices I_5, I_{10} and I_{30}. Test results, shown in Table 2, display that the toughness indices of I_5, I_{10} and I_{30} grow with the inclusion of steel fibers. It also reveal that the toughness indices of heavy concretes with a given steel fiber fraction are all lower than those of normal concretes. The reason for this could be partly due to the aggregate feature that the iron shots in heavy concrete have round and smooth surfaces than regular aggregates, which appear easier to de-bond from matrix and decrease the toughness of concrete. Typical load-displacement curves of normal concrete with steel fibers of 0.5%, 1.0% and 1.5% by volume are shown in Figure 8. Both of them show that the peak loads for all curves are similar but their post-peak curves are raised up as the steel fibers fraction is increased.

Table 2 Toughness indices of steel-fiber reinforced concrete

Mixture	FHC-Ⅱ	FHC-Ⅲ	FHC-Ⅳ	NC-Ⅱ	NC-Ⅲ	NC-Ⅳ
Toughness index I_5	3.74 (3, 3.0%)*	3.72 (3, 3.9%)	3.78 (3, 2.7%)	3.57 (3, 6.3%)	4.56 (4, 6.0%)	5.12 (3, 5.5%)
Toughness index I_{10}	5.34 (3, 5.1%)	5.66 (4, 4.4%)	6.67 (3, 5.8%)	6.12 (3, 5.9)	7.38 (4, 5.9)	10.5 (3, 11)
Toughness index I_{30}	12.4 (3, 32%)	14.8 (4, 17%)	17.0 (3, 11%)	15.0 (3, 15%)	21.3 (3, 11%)	31.7 (4, 15%)

* : (sample size, coefficient of variation).

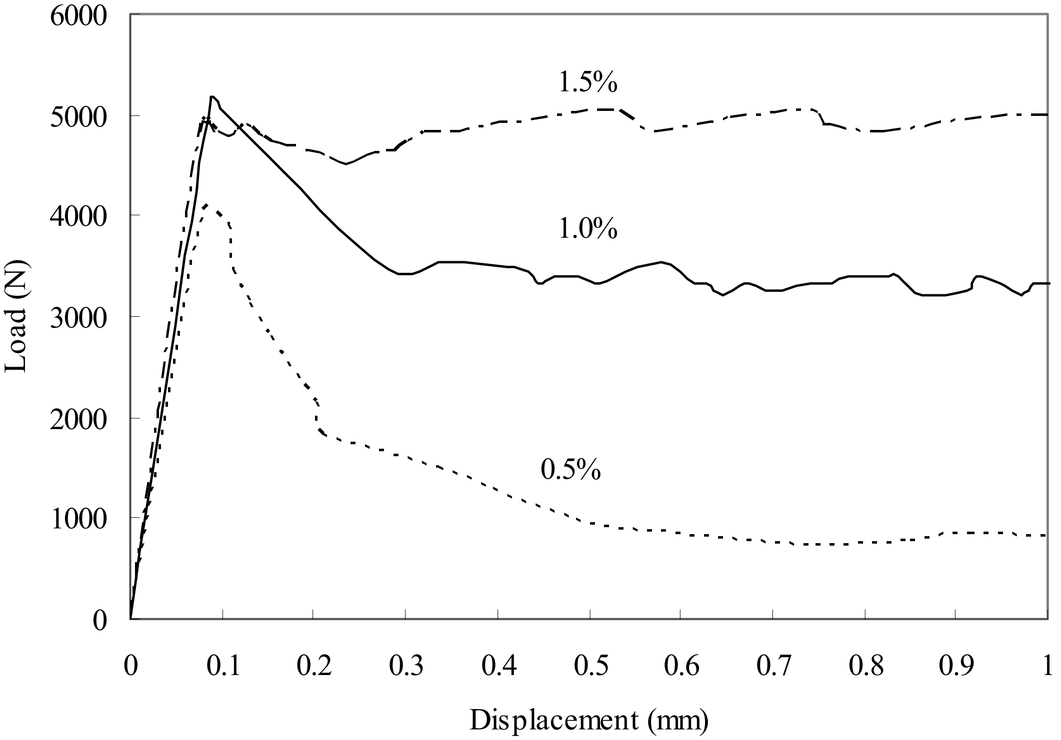

Fig. 8 Typical load-displacement curves of concretes with various steel fiber fractions

CONCLUSIONS

From the testing results, some conclusions can be drawn and summarized as follows:

1. The compressive strengths and elastic modulus of both heavy concrete and normal concrete with steel fibers in their matrix were lower than those without. But, it was observed that the heavy concrete with 1% steel fiber fraction has higher compressive strength and elastic modulus than the others. And, for the same water-to-cement ratio and steel fiber content, these properties of heavy concrete were all higher than those of normal concrete.
2. For a given fiber content, the compressive elastic moduli determined from the cylinder test and the beam test turned out very close to each other, both of which appears decreasing with the increase of steel fiber fraction; while the tensile elastic modulus displayed increase with the steel fiber fraction.
3. Wave velocity measured from heavy concrete was found decreasing with the increase of steel fiber. This phenomenon appeared consistent with the trend that air content increase with the increase of steel fiber in the stage of fresh concrete.
4. The flexural toughness of heavy concrete displayed increasing with the increase of steel fiber fraction. But, all of their toughness indices I_5, I_{10} and I_{30} appeared lower than those of normal concrete. The reason for this could be partly due to the aggregate feature that the iron shots in heavy concrete have round and smooth surfaces than regular aggregates.

NOMENCLATURE

I_5 = Toughness index obtained by dividing the area up to a deflection of 3.0 times the first-crack deflection by the area up to first crack

I_{10} = Toughness index obtained by dividing the area up to a deflection of 5.5 times the first-crack deflection by the area up to first crack

I_{30} = Toughness index obtained by dividing the area up to a deflection of 15.5 times the first-crack deflection by the area up to first crack

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REFERENCES

1. ACI Committee 446, “Fracture Mechanics of Concrete: Concept, Models, and Determination of Materials Properties”, ACI 446.1R-91, American Concrete Institute, Detroit, MI., 1991.
2. Shah, S. P, Swartz, E. S. and Ouyang, C., *Fracture Mechanics of Concrete*, 1st ed., John Wiley & sons, Inc., 1995.
3. Broek, D., *Elementary Engineering Fracture Mechanics*, 4th ed., Martinus Nijhoff Publishers, Dordrecht, 1986.
4. Kaplan, M. F., “Crack Propagation and the Fracture of Concrete,” *Journal of the American Concrete Institute*, Vol. 58, No.5, 1961, pp. 591-610.
5. Hillerborg, A., Modeer, M., and Petersson, P.-E., “Analysis of Crack Formation and Crack Growth in Concrete by Means of Fracture Mechanics and Finite Elements”, *Cement and Concrete Research*, Vol. 6, No.6, 1976, pp. 773-782.
6. Bazant, Z. P. and Oh, B. H., “Crack Band Theory for Fracture of Concrete”, *Materials and Structures*, RILEM, Vol. 16, 1983, pp. 155-177.
7. Jenq, Y. S. and Shah, S. P., “Two Parameter Fracture Model for Concrete”, *Journal of Engineering Mechanics*, ASCE, Vol. 111, No. 10, 1985, pp. 1227-1241.
8. Karihaloo, B. L. and Nalathambi, P., “Notched Beam Test: Mode I Fracture Toughness,” in RILEM Report 5, Fracture Mechanics Test Methods for Concrete, Edited by Shah, S. P., and Carpineteri, A., Chapman & Hall, London, 1991, pp. 1-86.
9. Naus, D. J. and Lott, J. L., “Fracture Toughness of Portland Cement Concretes,” *ACI Journal*, Proceedings, Vol. 66, No. 6, 1969, pp. 481-489.
10. Nallathambi, P., Karihaloo, B. L., and Heaton, B. S., “Effect of Specimen and Crack Sizes, Water Cement Ratio and Coarse Aggregate Texture Upon Fracture Toughness of Concrete,” *Magazine of Concrete Research*, Vol. 36, No. 129, 1984, pp.227-236.
11. Hillerborg, A., “The theoretical Basis of a Method to Determine the Fracture Energy G_F of Concrete,” *Materials and Structures*, Vol. 18, No.106, July-August, 1985, pp. 291-296.
12. Petersson, P. E., “Crack Growth and Formation of Fracture Zones in Plain Concrete and Similar Materials,” Report TVBM-1006, Division of Building Materials, Lund Institution of Technology, Sweden, 1981.
13. Naaman, A. E., 1984, “Fiber Reinforcement for Concrete," Concrete International, pp.21-25.
14. Edgington, J., Hannant, D. J., and Williams, R. I. T., 1974, “Steel Fiber Reinforced Concrete”, Building Research Establishment Current Paper CP 69/74.
15 M. C. Nataraja, N. Dhang, and A. P. Gupta, “Toughness Characterization of Steel Fiber-Reinforced Concrete by JSCE Approach”, Cement and Concrete Research, vol. 30, pp.593-597 (2000)
16. ACI Manual of Concrete Practice, “Heavyweight Concrete – Measuring, Mixing, Transporting and Placing,” Part II, 304.3R, 1989.
17. Kan, Y.-C., K.-C. Pei and C.-L. Chang, "Strength and Fracture Toughness of Heavy Concrete with Various Iron Aggregate Inclusions," ***accepted by Journal of Nuclear Engineering & Design***.
18. ACI Manual of Concrete Practice, 1989. Heavyweight Concrete – Measuring, Mixing, Transporting and Placing. Part II, 304.3R.
19. ASTM Standards C39-86, Test Method for Compressive Strength of Cylindrical Concrete Specimens, 1986.
20. ASTM Standards C293-79, Test Method for Flexural Strength of Concrete (Using Simple Beam with Center-Point Loading), 1979.
21. ASTM Standards C469-87, Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression, 1987.
22. ASTM Standards C496-87, Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens, 1987.
23. ASTM Standards C900-87, Test Method for Pullout Strength of Hardened Concrete, 1987.
24 ASTM Designation: C 1018-97, “Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading)”, pp.528-535
25. Malhotra, V. M. and Carino, N. J., *CRC Handbook on Nondestructive Testing of Concrete*, CRC Press, Inc. 1991.