ERJ
Engineering Research Journal
Faculty of Engineering
Minoufiya University

MODE II FRACTURE TOUGHNESS ESTIMATES FOR FIBER REINFORCED CONCRETES USING A VARIETY OF TESTING GEOMETRIES

A.S. Sherbini
Civil Engineering Dept., Suez Canal University, Ismailia, Egypt,

ABSTRACT

On the shadow of the ongoing debate on attempting to estimate mode II fracture toughness (K_{IIc}), the role of fibers and, or pozolan addition arises to importance. In this paper an experimental investigation of plain concrete, high strength concrete, and fiber reinforced concretes is reported. Three different types of fibers, namely steel, glass, and polypropylene fibers with a constant volume fraction v_f of 1.5%, are added to high strength concrete specimens. In an attempt to estimate a fairly accepted value of fracture toughness K_{IIc}, four testing geometries and loading types are employed in this investigation. Four points shear, Brazilian notched disc, double notched cube, and double edge notched specimens are investigated in a trial to avoid the limitations and sensitivity of each test regarding geometry, size effect, constraint condition, and the crack length to specimen width ratio a/w. The addition of pozolan enhanced both the compressive strength and mode II fracture toughness of concrete for almost all test geometries, while the addition of different types of fiber reduced the compressive strength and increased mode II fracture toughness in pure mode II tests. Mode II fracture toughness of concrete K_{IIc} decreased with the increment of a/w ratio for all concretes and test geometries. An element of mode mixity was traced in four points shear, and notched disc specimen tests. Double edge notched specimen test was found to be inconvenient for the current study due to its sensitivity to brittleness and anisotropity of concrete. Mode II fracture toughness K_{IIc} reported from double notched cube test showed higher values than all other tests due to the crack propagation miss alignment opposing sliding of crack surfaces.

تم اجراء هذا البحث في ظل الاختلاف حول محاولة تقدير متانة الكسر لشروخ النسق الثاني (KIIc)، وتأثير اضافة الألياف و ، أو البوزولان. حيث تم تقديم دراسة معملية على عينات من الخرسانة العادية ، والخرسانة عالية المقاومة ، بالاضافة الى الخرسانة المسلحة بالألياف.و قد تم استخدام ثلاثة أنواع مختلفة من الألياف، وهي الفولاذ والزجاج ، و ألياف البولي بروبلين حيث اضيفت الالياف المختلفة الى الخرسانة عالية المقاومة بنسبة حجمية ثابتة (١,٥٪). وقد تم حساب متانة الكسر لشروخ النسق الثاني (KIIc) باستخدام اربعة اختبارات مختلفة و هي الكمرة المعرضة لنقاط القص الاربعة ، القرص البرازيلي ذي الشق المركزي ، المكعب ذي الشقين ، والمنشور ذي الشقين المتقابلين.كما تم دراسة تأثير نسبة طول الشرخ الى عرض العينة لكل من الاختبارات و المواد المختلفة. و قد خلصت الدراسة الى تحسين اضافة البوزولان لكل من مقاومة الضغط و متانة كسر النسق الثاني المحسوبة للاختبارات المختلفة، في حين أن تأثيرإضافة أنواع مختلفة من الألياف خفض قوة الضغط بينما زاد من متانة كسر النسق الثاني المحسوبة للاختبارات التي امكن فيها التأثير على العينة بحمل قص خالص.كما أظهرت الدراسة انخفاض قيمة متانة كسر النسق الثاني المحسوبة بزيادة نسبة طول الشرخ الى عرض العينة و ذلك لجميع المواد و للاختبارات المختلفة. كما اظهرت الدراسة اختلاف قيم متانة كسر النسق الثاني المحسوبة للاختبارات المختلفة بسبب الاختلاف في ظروف التحميل و شكل العينة مما يوجد خليط من النسقين الاول و الثاني لا يمكن تجنبهما و يؤثر في نتائج الاختبارات المختلفة.

***KEYWORDS*:** High strength concrete; Fiber reinforced concrete; Mode II fracture toughness; Beam specimens; Compacted specimens.

INTRODUCTION

Concrete is a quasi-brittle material with a low strain capacity. Reinforcement of concrete with short randomly distributed fibers can address some of the concerns related to concrete brittleness and poor resistance to crack growth. Fibers, used as reinforcement, can be effective in arresting cracks at both micro- and macro-levels. At the micro-level, fibers inhibit the initiation and growth of cracks, and after the micro-cracks coalesce into macro-cracks, fibers provide mechanisms that abate their unstable propagation, provide effective bridging, and impart sources of strength gain, toughness and ductility [1, 2].

The use of silica fume in combination with various types of fibers has been studied by several researchers [3]. The main point of research is the bonding characteristics of the paste to the fibers, and the influence of a combination of fibers and silica fume on the characteristics of concrete .The improved bond strength of silica fume concrete to various types of fiber reinforcement is reported in numerous papers in the review by Sellevold and Nilsen [3]. Ezeldin and Balaguru [4] looked at the bond to reinforcing steel behavior of normal strength and high strength steel fiber reinforced concrete using a pullout test method. They found that silica fume increased bond strength but resulted in brittle bond failure. Use of the steel fibers increased ductility and then enhanced the fracture toughness of concrete. Various studies have shown that addition of silica fume to glass fiber reinforced concrete (GFRC) made with alkali resistant glass fibers and sometimes high alumina cement can reduce or eliminate the loss of ductility and strength associated with increasing age [5].

In the belief that, mode II fracture properties distinction from mode I should exist, various approaches have attempted to define testing geometries where self-similar crack propagation occurs with only mode II deformations. Although there is a violent debate around the validity of such a test in driving cracks under pure mode II, these types of setups are considered the most important techniques in isolating shear parameters. Fig. (1.a) shows double-edge notched prism (DENP) which proposed by Hans-Wolf Reinhardt, Shilang Xu [6]. Double notched cube (DNC) as seen in Fig. (1.b) has been proposed by J. Watkins [7] and also used by G. Prokopski [8]. The Brazilian disc specimen with inclined centered notch (BND) of an angle β equal to 30º as shown in Fig (2.5c) has been proposed by Irobe and Pen [9] and also used by Jia *et al* [10]. The four-point shear beam(4PS) shown in Fig. (1d) goes to Iosipescu [11]; it looks very attractive and has been used by several researchers on concrete either with a single notch specimen or a double notch cubic specimen [6].

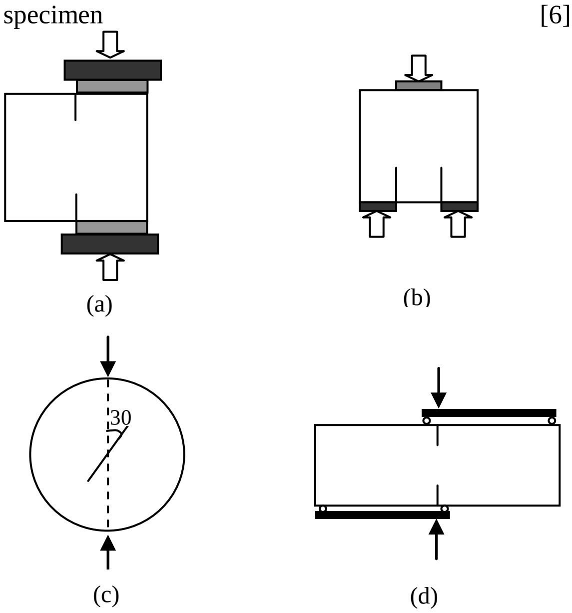

Fig. 1 Mode II fracture toughness test geometries

EXPERIMENTAL WORK

In this paper an attempt is made to establish the influence of pozolan, and or fiber addition on mode II fracture toughness of concrete. The experimental program included five groups, 1st group for plain concrete (PC), 2nd group for high strength concrete (HSC) and three groups of fiber reinforced concrete with constant volume fraction (V_f) of 1.5% steel fiber reinforced concrete (SRC), glass fiber reinforced concrete (GRC), polypropylene fiber reinforced concrete (PRC). Each group contains, cube, cylinder and four different mode II fracture toughness test specimens as will be subsequently detailed. Five specimens per sample were used for each tested parameter.

The cement used in all concrete mixes was ordinary Portland cement_of 450 kgs/m^3. Light gray silica fume with specific surface area of 18 m^2/gm supplied from the Ferro silicon alloys plant in Edfo zone, Egypt, was used with 10% added percentage to the cement content to produce HSC. The sand used was local natural siliceous sand with specific gravity of 2.55, fineness modulus "F.M." of 2.51, and specific surface area "S.S.A." of 50.47 cm^2/gm. The coarse aggregate was dolomite with nominal maximum size of 10 mm, specific gravity of 2.6, F.M. of 6.69, and S.S.A. of 6.54 cm^2/gm. A super plasticizer called Adecrete PVF (naphthalene sulphonated compound) was added to the mixing water to improve the workability and to keep the slump almost constant. The mixing sequences

ACI Committee 544 [12] was adopted in the present work to mix all mixes. Plain mild steel, high zirconia alkali resistance glass (NEG ARG) fibers, amd MC polypropylene fiber were used in this investigation. In the case of steel fiber, fiber aspect ratio was 50, and the modulus of elasticity and the yield strength were 200 GPa and 265 MPa, respectively. In the case of glass fiber, the fiber was supplied in chopped strads of 25 mm length, the modulus of elasticity and the ultimate tensile strength were 74 GPa and 1.4 GPa, respectively. The used MC polypropylene fiber meets the requirements of ASTEM C1116, and C1399 with a fiber length of 15 mm and thickness of 0.0965±10% The modulus of elasticity and the ultimate tensile strength were 3.9 GPa and 0.6 GPa, respectively. All fibers were added to the HSC matrix to produce high strength fiber reinforced concretes used in the present study. The mix proportion by weight for all mixes was 1:1.92:2.0:0.38 (cement: sand: dolomite: water/[cementitious materials]).

A vertical mixer of revolving blades type was used in mixing. Materials of the specified mix were weighed first and then mixed in a dry state for about one minute. The required amount of water and superplasticizer was then added during the next two minutes. The contents were left to agitate in the mixer until a homogenous mix was obtained. The fiber was then added in small increments by sprinkling them onto the surface of the mix until all the fibers were absorbed into the matrix .This technique was performed to prevent balling or interlocking of the fibers. The freshly mixed concrete was tested for slump as a quality control test, the result was about (100 mm). The mixed materials were then placed in the molds, compacted using external vibration, leveled, and cured in water for 28 days before testing.

Cubes of 150x150x150mm dimensions were prepared to be tested under static compression. Cylinders of 150mm diameter and 300mm height were prepared to be tested under indirect tension. The mean values of compressive and tensile strengths are presented in Table 1.

Table 1: Compressive and Tensile Strengths in MPa.

	PC	HSC	SRC	GRC	PRC
Compressive	39.5	54.2	49.7	50.3	51.8
Tensile	3.7	5.1	5.4	5.2	5.1

Mode II Fracture Toughness Test Specimens:

Concerning mode II of fracture (sliding mode), four test methods have been adopted in this study which aim at a pure state of shear stress. Looking closer at these methods, it turned out that most of them produce a mixed state of normal and shear stress mainly due to unavoidable load eccentricities, and hence bending moments which occur either from the beginning or after some deformation of the specimen. The four tests; double-edge notched prism, double notched cube, Four point shear, and the Brazilian notched disc specimen will be discussed as follow:

Double-Edge Notched Prism (DENP)

Five prism specimens of 200 mm width, 200 mm depth, and 100 mm thickness for each type of concrete were used, as shown in Fig.1. The notches depth were taken 30, 40, and 50 mm. To calculate mode II fracture toughness Tada's solution [13] would directly apply

If h ≥ 2a, w ≥ πa.

$$K_{II\,c} = \frac{\sigma}{4}(\pi a)^{1/2} \qquad (1)$$

If h ≥ 2a, w ≤ πa

$$K_{IIc} = \frac{\sigma}{4} w^{1/2} \qquad (2)$$

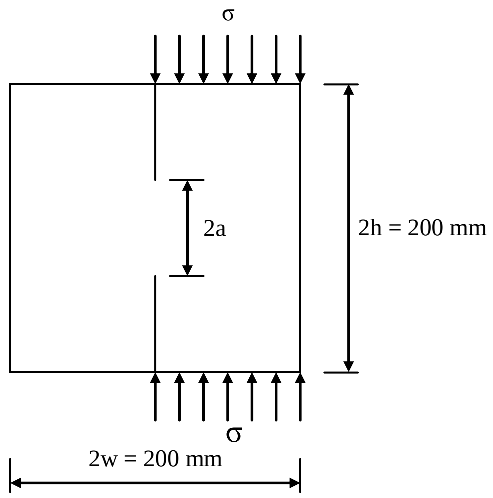

Fig.2 Double-edge notched prism geometry.

The condition h > 2a ensures the uniform distribution of stress on the loaded end of the strip. If there were other means to guarantee a uniform stress distribution, the condition h> 2a could be relaxed. The dimensions of the specimens were such that w < πa and h is mostly < 2a, which means that neither equation (1) nor (2) apply rigorously but are only an approximation [6].

Double Notched Cubic Specimen (DNC)

Five cube specimens of (150 x 150 x 150 mm) for each type of concrete were taken. The crack depth factor K_{IIc} was determined according to the formula of Watkins [7]. The notch depth was taken 50, 60, and 75 mm. The notches were made by the saw with 4mm thickness. The stress intensity factor:

$$K_{IIc} = \frac{5.11 P_Q}{2BW}(\pi a)^{1/2} \qquad (3)$$

Where P_Q is the force initiating cracking (growth); B is the height above crack tip, W is the total height, and a is the depth of the crack as shown in Fig.3 [8].

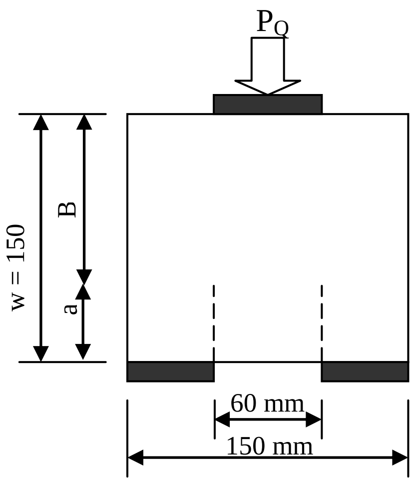

Fig.3 Double notch cubic specimen

Four-Point Shear Beam (4PS)

Five beams specimens of (100 x 100 x 500 mm) for each type of concrete were cast; the notch depth was 30, 40, and 50 mm. The notches were made by the saw with 4mm thickness. The stress intensity factor K_{IIc} was determined according to the LEFM formula:

$$K_{II\,c} = Y_{II}\,\sigma(\pi a)^{1/2} \qquad (4)$$

Where Y_{II}; the geometry correction factor was adopted from the work of Tada *et al* [13]. The test setup is shown in Fig. 4.

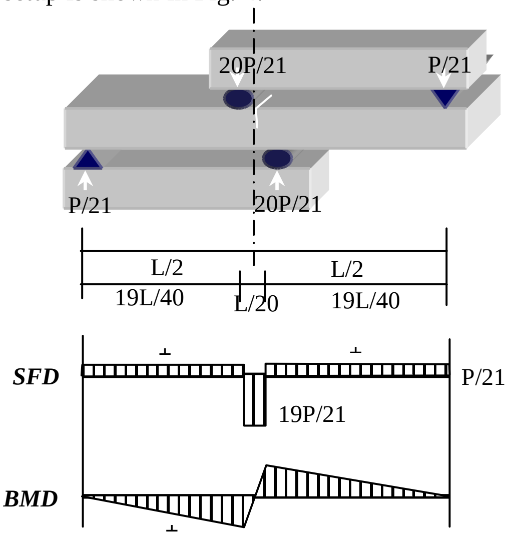

Fig.4 Four-points shear test setup

The basic problem in measuring mode II fracture parameters for any material is the necessity of achieving a pure-shear state of stress and propagating a crack with $K_{IIc} >> K_{Ic}$. In a practical sense this means developing a test specimen for which the region surrounding a flaw is in a state of stress such that propagation will occur in a sliding action and the opening, or mode I action, will be negligibly small. Such a specimen and testing arrangement has been proposed by Iosipescu for metals [11]. This test specimen has been adopted for cementitious materials by Swartz *et al* [14] and then by Bazant and Pfeifer[15].

The Brazilian Notched Disc Specimen (BND)

Five disc specimens of 150 mm diameter and 60 mm thickness for each type of concrete were taken. It is possible to change the mode of fracture from (tension-shear for β approximately less than 30º and compression-shear for β approximately greater than 30º (depending on a/R)) by rotating the notch inclination angle with respect to the loading direction. The ratios of notch length, 2a, to disc diameter, 2R, i.e 2a/2R, used are 0.3, 0.4, and 0.5, as shown in Fig.5 According to Yarema *et al.* [16] mode II fracture toughness can be calculated applying the following formula:

$$K_{IIc} = -\frac{2P}{t}\sqrt{\frac{\lambda}{\pi R}}\left\{\begin{array}{l} B_0 - \lambda^2(B_0 + \frac{1}{2}B_2) + \lambda^4(-\frac{1}{8}B_0 + \frac{1}{4}B_2 + \frac{3}{8}B_4) \\ + \lambda^6\,(B_0 - \frac{1}{16}B_2 + \frac{1}{8}B_4 + \frac{5}{16}B_6) + \\ \lambda^8(-\frac{17}{64}B_0 + \frac{3}{8}B_2 - \frac{5}{128}B_4 + \frac{5}{64}B_6 + \frac{35}{128}B_8) \end{array}\right\}$$

Where:

$B_0 = \sin 2\beta$

$B_2=2[\sin 4\beta - \sin 2\beta]$

$B_4=3\,[\sin 6\beta - 2\sin 4\beta]$

$B_6=4[\sin 8\beta - 3\sin 6\beta]$

$B_8=5[\sin 10\beta - 4\sin 8\beta]$

Where R and t are the radius and thickness of the specimen respectively, λ= a/R, and β: the notch inclination angle = 30º [17].

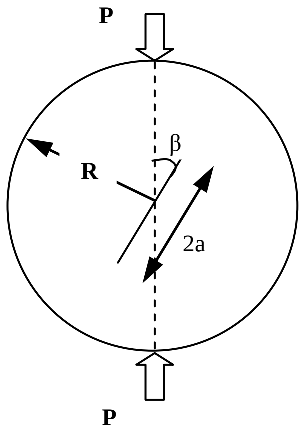

Fig.5 Cracked Brazilian disc specimen

RESULTS AND DISCUSSION

Our aim of this experimental investigation is to study the effect of adding pozolan and or fiber on the mode II fracture toughness K_{IIc} of concrete. A comparison between the estimated values of K_{IIc} of concrete according to four different test techniques was reported in this investigation attempting to find an answer for the confusing argument, "Is mode II fracture toughness a real material property?"

Figure (6) shows the relation between the notch depth to specimen width ratio (a/w) and mode II fracture toughness K_{IIc} for different test setups. Five types of concretes are presented in each sub-figure. It is clear that K_{IIc} is inversely proportional to (a/w) for all concretes and test configurations. The effect of adding both pozolan and different types of fibers is more significant with reduced values of a/w. This logical behavior is due to the fact that, by increasing a/w both length and severity of crack increase, while the defense zone represented in the crack forehead ligament decreases. It is obvious from figure that, the estimated value of K_{IIc} for HSC is greater than that of

PC for all test configurations except that revealed from (DENP) test setup. The monitored increment of K_{IIc} with incorporating silica fume to the mixture is addressed to the accompanied increment of compressive strength. This finding agrees with the data reported by Golewski and Sadwski [18].

Although, the compressive strength increased by about 35% with incorporating silica fume to the mixture, the corresponding increment of K_{IIc} didn't exceed 10%, which might be due to the increased brittleness resulting from adding the pozolan. Regarding(DENP) test setup, the effect of elevated brittleness surmounted the effect of compressive strength increment. This finding agrees with the data reported by Xu et al. that, the (DENP) test setup is sensitive to the brittleness of tested specimen [19].

The reported data of K_{IIc} with adding different types of fibers to the HSC matrix were truly perplexing. The integrated effects of mode mixity, specimen geometry, and anisotropity of FRC, made the interpretation of the results really confusing. Although, the values of K_{IIc} calculated from (DNC) test setup are markedly greater than those reported from (4PS) test setup, more than three folds, the behavior of K_{IIc} enhancement with addition of different types of fibers to HSC matrix is the same. The enhancement of K_{IIc} with addition of steel fiber is supreme to all other types (30%, 25%), then the effect of polypropylene addition comes next (25%, 18%), and the improvement of glass fiber addition comes last (13%, 8%) for (4PS) and (DNC) test setups respectively. The monitored increment of K_{IIc} with addition of fiber might be due to the fiber resistance to crack surfaces sliding, while the elevated values of K_{IIc} reported from (DNC) test setup could be due to the effect of misalignment of crack propagation producing a component of compressive stress perpendicular to crack surfaces and increasing the closure effect regarding sliding mode

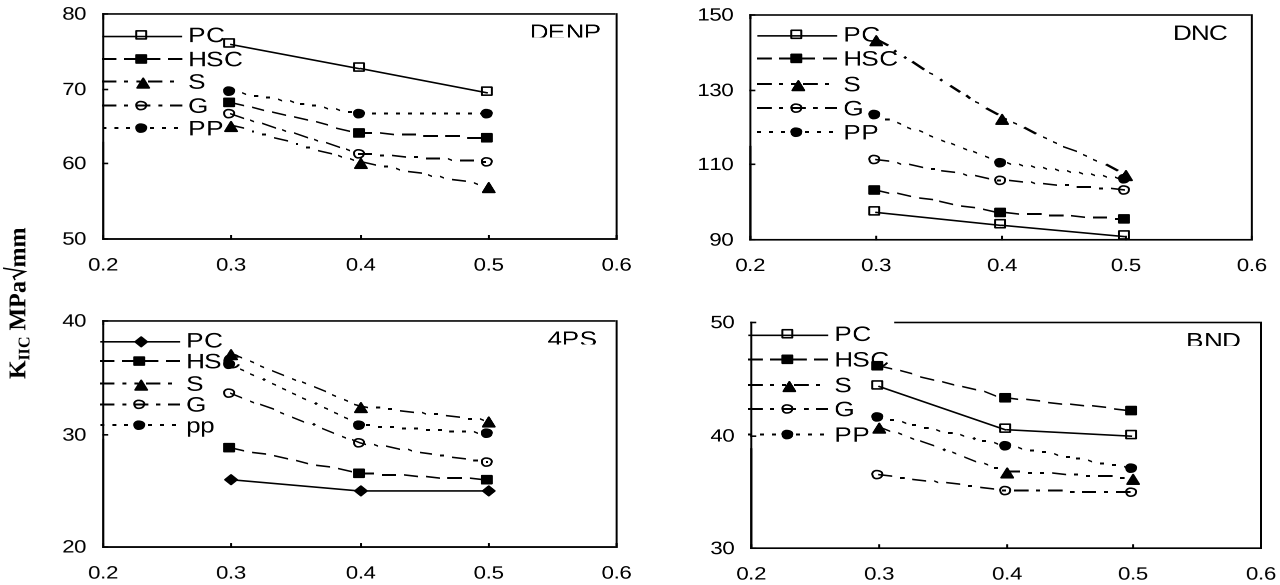

Fig.6 Notch depth to specimen width ratio (a/w) versus mode II fracture toughness K_{IIc} for various test setups.

In case of (DENP) test set up, the reported data shows a significant decrease of K_{IIc} with incorporating fibers to HSC mix. The behavior is different from previous test setups and the estimated values of K_{IIc} are misleading as in the case of adding silica fume to PC mix. The sensitivity of the test to brittleness affected the behavior when adding silica fume, while the anisotropity of SFRC due to the randomization of fibers affected the reported data of K_{IIc} with incorporating different fiber types. This finding agrees with the data reported by Xu *et al* [19], that, the (DENP) test setup is sensitive to the isotropity of tested specimen.

Regarding (BND) test setup, the addition of fibers decreased the calculated values of K_{IIc} for all fiber types. The reduction percents were (15%, 20%, and 12%) when adding Steel, glass, and polypropylene fibers respectively. The effect of compressive strength reduction with incorporating fibers to HSC mix, weakened the pre notch neighbored points and as a result decreased the calculated values of K_{IIc} in this test setup.

Figure (7) shows the relation between the notch depth to specimen width ratio (a/w) and mode II fracture toughness K_{IIc} for different types of concretes. Four test setups are presented in each sub- figure. It could be seen that, for all concretes types the measured values of K_{IIc} ascend with changing the test setup starting from (4PS) as a minimum value then, (BND), then(DNC), and finally (DENP) as a maximum value .The previous trend is not only valid for different concretes but, for different a/w in each concrete as well.

It can be seen that a common drawback of the present mode II testing methods is that in the direction perpendicular to crack plane a tensile stress can not be avoided. So, at the crack tip the tensile stress component certainly causes a mode I stress intensity. For the materials with low tensile strength like concrete a small mode I stress intensity could result in tensile failure prior to shear failure in those specimen geometries employed in mode II tests.

Therefore, attention in seeking a suitable mode II testing method should be focused on the choice of corresponding specimen geometry, in which in the direction perpendicular to the crack plane no existence of the tensile stress component would be possible so that the mode I stress intensity at the crack tip could be zero.

In other words, if shear failure occurred at the crack tip, it would be independent of the final failure of the specimen for the chosen specimen geometry under the corresponding loading condition. Thus, one would be confused by other unreal failure phenomena in the investigation for mode II fracture.[20]

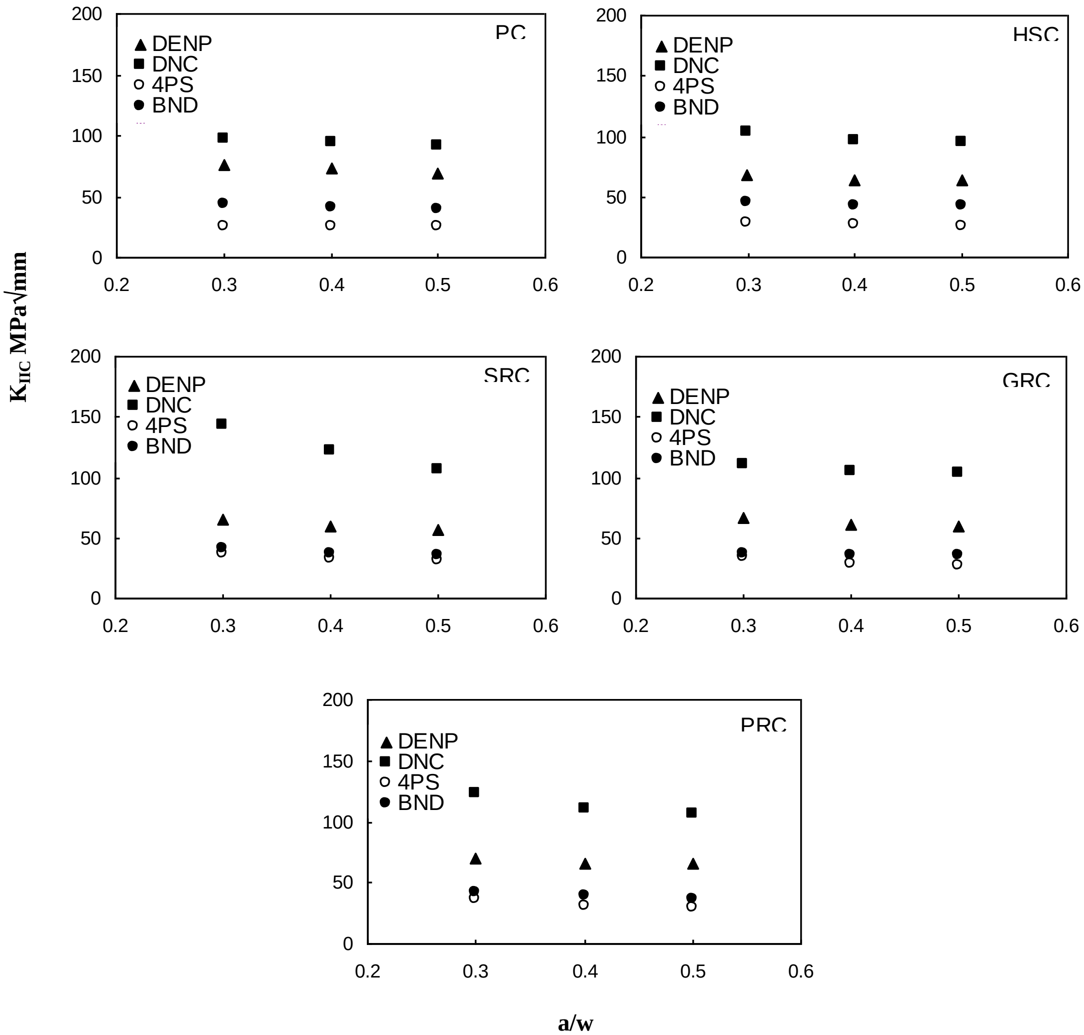

Fig.7 Notch depth to specimen width ratio (a/w) versus mode II fracture toughness K_{IIc} for different concretes.

CONCLUSIONS

The results of the present experimental work support the following conclusions:

1. The addition of pozolan enhanced the compressive strength and as a result, increased mode II fracture toughness of concrete for almost all test geometries.
2. The addition of different types of fibers reduced the compressive strength and increased mode II fracture toughness in pure mode II tests (4PS), and (DNC).
3. Mode II fracture toughness of concrete K_{IIc} decreased with increasing a/w ratio for all concretes and test geometries.
4. Double edge notched specimen test was found to be inconvenient for the current study due to its sensitivity to brittleness and anisotropity of concrete.
5. Mode II fracture toughness K_{IIc} reported from double notched cube (DNC) test setup showed higher values than all other tests due to the crack propagation miss alignment opposing sliding of crack surfaces.
6. Mode II fracture toughness K_{IIc} of concrete is found to be sensitive to a/w, geometry of test specimen, and loading condition.
7. Four points shear (4PS) test set up reflects the most reliable values of mode II fracture toughness K_{IIc} of concrete.
8. As an over all conclusion, mode II fracture toughness K_{IIc} of concrete couldn't be assumed as a real material property.

REFERENCES

1. Bentur A. and Mindess S., "Fiber Reinforced Cementitious Composites", Elsevier Applied Science, London, (1990).

2. Balaguru P.N., and Shah S.P., "Fiber Reinforced Cement Composites", McGraw-Hill, Inc., New York, (1992), pp. 530

3. Sellevold E.J., and Nilsen T., 1987, "Condensed Silica Fume in Concrete: A World Review", Supplementary Cementing Materials for Concrete, ed. V. M. Malhotra, CAN- MET, Ottawa, Canada, pp. 165-243.

4. Ezeldin A., and Balaguru P., 1989, "Bond Behavior of Normal and High-Strength Fiber Reinforced Concrete", ACI Materials Journal, V. 86, No. 5, pp. 515-524.

5. Bentur A., and Diamond S., 1985, "Effects of Direct Incorporation of Microsilica into GFRC Composites on Retention of Mechanical Properties After Aging", Proceedings, Durability of Glass Fiber Reinforced Concrete Symposium, Chicago, ed. S. Diamond, Prestressed Concrete Institute, Chicago, Illinois, pp. 337-351.

6. Hans W., Reinhardt, Josko O., Shilang X., and Abebe D., "Shear of Structural Concrete Members and Pure Mode II Testing", Elsevier Science Ltd. Advanced Cement Based Materials, 1997, 5, 75-85.

7. Watkins J., "Fracture Toughness Test for Soil-Cement Samples in Mode II", Journal of Fracture 23, RI35-RI38, (1983).

8. Prokopski G., "Influence of water-cement ratio on micro-cracking of ordinary concrete", journal of materials science, 26, 6352-6356, 1991.

9. Irobe M., Pen S.Y., "In Fracture Mechanics of Concrete Structures", Bazant, Z.P., Ed. Elsevier Science: London and New York, 719-726, 1992.

10. Jia Z., Castro M.A., and Shah S.P., "Observation of Mixed Mode Fracture with Center Notched Disk Specimens", Cement and Concrete Research, Vol. 26, No. 1, pp. 125 137, 1996.

11. Iosipescu N., "New accurate procedure for single shear testing of metals", Journal of Materials, 537-566, 1967.

12. ACI committee 544, "Fiber Reinforced Concrete", American Concrete Institute, Detroit, MI, 66pp., 2011

13. Tada H., Paris P., Irwin G., "The Stress Analysis of Cracks Handbook", 2nd ed. Paris Productions Incorporated: St. Louis, 1985.

14. Swartz S.E., Lu L.W., Tang L.D., and Refai T.M.E., "Mode II fracture-parameter estimates for concrete from beam specimens", Exper. Mech., Vol. 28, pp 146-153, 1988.

15. Bazant Z.P. and Pfeiffer P.A., "Shear fracture tests of concrete", Materials and Structures 19, 111–121, 1986.

16. Yarema S.Ya., Ivanitskaya G.S., Maistrenko A.L. and Zboromirskii A.I., "Crack development in a sintered carbide in combined deformation of types I and II", Problemy Prochnosti 8 (1984) 51-56.

17. Atahan H.N., Tasdemir M.A., "Mode I and mixed mode fracture studies in brittle materials using the Brazilian disc specimen", Materials and Structures, Vol. 38. pp. 305-312, (April 2005).

18. Golewski G.L., and Sadowski T., "An Analysis of shear Fracture Toughness K_{IIc} and Microstructure in Concretes Containing Fly-ash" Construction and Building Materials, Vol. 51, pp. 207- 214, (2014).

19. Shilang Xu, Reinhardt H.W. and Gappoev, Murat, "Mode II fracture testing method for highly orthotropic materials like wood", *IJF*. 75 (1996) 185-214.

20. Hans W.R., Shilang Xu., "Experimental determination of K_{IIc} normal strength concrete", Materials and Structures, Vol. 31, June 1998, pp 296-302