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Rate Sensitivity of Fracture Properties of HPC

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Abstract

The response of concrete for dynamic loading is of interest in a variety of civilian and military applications. Characterization of the behavior of concrete under dynamic loading is a prerequisite for the design and analysis of these structures. This paper present the results of a series of experiments conducted to investigate the rate sensitivity and the effectiveness of fiber inclusions in the improvements of fracture toughness of High Performance Concrete (HPC)beams. Single-edge notched beams (0.5 notch ratio) were loaded in three point bending over a wide range of displacement rates (Do).

Load-displacement curves show that their peak is higher as the Do increases, whereas the corresponding displacement is almost constant. Fracture energy, G f also increases but only under Do beyond a threshold value. The experimental finding of the present work addressed the positive roles of fibers (steel and polypropylene) in improving the performance of concrete under dynamic loading.

ملخص البحث:

يعد استخدام الخرسانة في التحميل الديناميكي أحد التطبيقات المهمة في الإنشاءات المدنية و العسكرية.لذا فإنه من المهم تحديد سلوك المنشأ الخرسانى تحت تأثير الأحمال الديناميكية كأحد المتطلبات الهامة في التصميم و التحليل لهذه المنشآت. يقدم هذا البحث نتائج سلسلة من الاختبارات المعملية أجريت لفحص تأثير معدل التحميل و تأثيره إضافات الألياف لتحسين متانة الانهيار للخرسانة عالية الأداءHPC ". ولتحقيق هذا الهدف اجريت الاختبارات على عتبات أحادية الحد في اختبارات الانحناء ثلاثي النقطة و على مدى واسع من معدلات الإزاحة و أظهرت منحنيات الإزاحة – الحمل زيادة قيم الحمل مع معدلات الإزاحة في الوقت الذي تثبت فيه قيم الإزاحة المصاحبة. كما ازدادت قيم طاقة الكسر " Gf " فقط عند تخطى معدل الإزاحة قيمة محددة " threshold " و أظهرت القياسات الحساسية العالية لطاقة الكسر بالشروخ الدقيقة مقارنة بقيمة أقصى حمل كما أوضحت النتائج المعملية الدور الايجابي لإدخال ألياف الصلب و البولي بروبلين في تحسين أداء الخرسانة تحت ظروف الأحمال الديناميكية كما أظهرت العينات المكسورة آليات متباينة للانهيار اعتمادا علي قيم الطاقة الممتصة أثناء الكسر و أوضحت ظروف الاختبار فقط ينبغي ضمان الارتباط الدقيق بين الألياف و البطانة الخرسانية.

***Keywords**: Fracture mechanics; High performance concrete (HPC); Volume fraction, bending test.*

1- Introduction

The term high-performance concrete (HPC) is generally associated with high strength, but in reality the term refers to an enhanced level of performance of any desired property of the concrete material. However, the definition of HPC is more controversial.Mehta and Aitcin [1] used the term HPC for concrete mixtures possessing high workability, high durability and high ultimate strength. An ACI committee on HPC [2] defined HPC as a concrete meeting special combinations of performance and uniformity requirements that can always be achieved routinely using convential constituents and normal mixing, placing, and curing practice. This definition has been used by the construction industry to develop high-early strength concrete mixtures and designate them as HPC. High-early strength concrete is often made with a high cement content, a very low water/cement ratio, a highly reactive pozzolan such as silica fume and is called HPC. Typically, HPC will have water cementations material ratio of 0.4 or less. Achievements of these low W/C concretes often depends on the effective use of admixtures to achieve high workability, another common characteristic of HPC mixes. HPC uses dense particle packing technique and selective material components to enhance the strength of concrete as well as the inclusion of HP-fibers to bridge cracks and consume energy while the fracture proceeds , thereby toughening the material. The fracture properties and autogenously shrinkage of HPC reinforced with highly dispersed nano-fibers such as carbon nanotubes and carbon-nano fibers were addressed [3].The results suggest that nano-fibers not only improve the fracture properties of cement matrix, by the controlling of the matrix cracks at the nano-scale level . They also improve the early age strain capacity of the cementations matrix producing a HP-nano concrete.HPC are advanced materials used in advances applications such as tunnels or nuclear power plant in which they can be accidently submitted to severe stress or thermal conditions . Fracture toughness of HPC on three-point bending of notched beams at elevated temperatures (25-900C^o)was performed [4]. The max.appliedload was found to be max. At 300C^{o}and then to decrease sharply at higher temperatures.The fracture energy of HPC at high temperature up to 450C^o: the effects of heating temperatures and testing conditions (hot& cold) were examined [5]. It was found that the fracture energy sustained a decrease-increase tendency with the increase of heating temperature. The effect of moisture on the fracture characterization of concrete/epoxy interface was declared [6]. The experimental results had shown a significant decrease, up to about 50%, in the interface fracture toughness of concrete /epoxy bond with selected levels of moisture and temperature conditioning of the specimens for both mode I and mixed mode conditions. HPC, referred to as concrete of low water/cement ratio, is stronger and stiffer than conventional concrete but it is generally more brittle. The micro-cracks developed and propagation determine the stress-strain curve of HPC under uni –axial compression [7].These micro-cracks already exist in the transition zone(the interfacial region between the cement paste and the aggregate as a result of shrinkage and thermal stresses before the application of external stresses. Nowadays, HSC is very often used in modern complicated structures of considerable height and span, such as sky scrapers, high towers and large bridges. These are more vulnerable to damages caused by earthquakes, wind and blast loading owing to the fact that HPC is more brittle than NSC.

As a result, the dynamic fracture properties of HPC are important than these of NSC with regard to a safety assessment and the design of modern structures. Compared with the extensive research into static fracture behavior of HPC [8,9,10,11,12], much less information is available on its dynamic behavior .Mueller [13] has published a state of the art report on properties of HSC. Schuler and Hansson [14] measured the tensile strength and fracture energy of HPC with spalling testes, and Bentur and Mindess [15] obtained the dynamic mechanical properties of HSC and NSC using drop weight impact machine. Nevertheless, experimental data on the rate sensitivity of the fracture properties of HSC are very scare. Tai and Wang [16] investigated the mechanical behavior of ultra HSC under repeated impact loading by split Hopkinson pressure bar device. The results indicated the superior response of HSC. The present work has two main aims : the first was to design a HPC mix through innovative application of particle selection and distribution, advanced fiber selection in multiple magnitudes of scale and modified curing techniques to increase the strength and toughness of the HPC beyond current state of art performance. The second aim was to examine the sensitivity of the fracture energy and peak load and to provide formulations for such dependency. Such formulations seem to be helpful when simulating such rate dependency numerically.

2. Experimental Details

2.l Material Characterization & Mix design

HPC uses dense particle packing technique and selective material components to enhance the strength of concrete as well as the inclusion of HP fibers to bridge cracks and consume energy while the fracture proceeds ,there by toughening the material.

There are a number of strategies followed in the present work to achieve high strength and low porosity of the investigated concretes. Here is abrief description of the main points to be undertaken:

First and foremost, it is critical to avoid including flaws in the matrix. Flaws can be caused by any condition that interrupts the homogeneity of the matrix, such as capillary pores, entrained air bubbles, or poor quality paste at the paste aggregate interface. These flaws are initiation sites for the development andgrowth ofmicrocracksand act as stress concentrators. As the applied stress increases the microcracks grow into mesocracks, the mesocrocracks coalesce into macrocracks, and the concrete finally fails. Particle packing theory is used to minimize sites for flaws and maximize solid material volume in HPC. So, we have to choose the volume of a material to fit in the void space formed by the next larger size particles. Sand is the largest size material used in HPC. Its particle diameter generally ranges between 150 and 600 μm.The next largest particleis cement with an average diameterof about 15 µm. Of similar sizeis crushed quartz with an average diameter of 10 µm. The smallest particle, the silica fume has a diameter small enough to fill the interstitial voids between the cement and the crushed quartz particles. Silica fume plays a very important role in the hydration process and is used in quantities that are much higher than in NSC. Improved material homogeneity also strengtheness the matrix. Since calcium silicate hydrate (C-S-H) is the main hydration product in cement paste, it is beneficial that the paste components be composed of as much silica based material as possible to maximize creation of (C-S-H).Choosing a cement with a high silica cement and incorporating silica floor , silica fume , and silica sand into the mixture maximize the silica value and minimize differential strain under strain from component materials with different moduli of elasticity .Additional strength in HPC is achieved by using a very low water-to-cement ratio (W/C). A ratio of 0.42 was found to be necessary to consume all water and create (C-S-H) [17]. In the present work, W/C of 0.25 was chosen to achieve the highest level of strength and still be mixable. However, the mixes are stiff and unworkable. The use of high-range water-reducing admixture (HRWA) alleviaces stiffness and limited workability by assisting in deflocculating the cement grains .The HRWA was Glenium 3000NS and the accelerometer used in this study was Rheocrete CNI. The types of fibers included in HPC were non-deformed cylindrical steel fibers(12.5 mm long and 0.2 mm diameter)at a concentration of 6.2% of concrete weight .The mechanical properties of the used steel fibers, as given by the supplier are : Yield stress :3150 MPa, Ultimate stress 3250 MPa and modulus of elasticity 205 GPa .These data show that this type of steel is of high strength and has little reserve strength capacity beyond yield. The mixproportions used throughout the present work was given in Table [1]. A 0.0085m^3 capacitypan mixer was used. It was able toimpart enough energy into the mix to obtain sufficient rheology for the casting of specimens. The casting of all specimens used in this material characterization study was completed within 20 minutes after the completion of mixing. All specimens were cast on a vibrating table and allowed to remain on the table for approximately 30 sec.after filling. In beam specimens for flexure tests, the HPC was always placed in one end of the mold and allowed to flow to the other end to complete the filling. Two hours after casting, the cast surface was trowelled and the specimens were covered by polyethylene sheets for 24 hrs. and then wet mats for additional 72hrs .The specimens were then demolded and stored in the fog room (20 C^o,100%RH)until for 28 days. All the control specimens were cured along with HPC specimens. There was a strict control of the specimen-making process, to minimize scattering in test results. Compressive tests were conducted according to ASTM C39 on 75mm dia. x150mm height cylinders under four different rates of stress, namely : 0.24,0.35,1.00 and 1.75 MPa/s. This test was made to ensure that consistent batching, mixing,and curing of HPC had occurred.

2.2 Three Points Bending Fracture Tests

In order to study the effect of displacement rate on the fracture behavior of the HPC, 3 PB tests were conducted on single-edge notched beams over a wide range of displacement rate from 10^{-4} to 10^{3} mm/s.A Servo Electrical Testing Machine manufactured in GM. R&D center NAO-30500 Mounted Road, Warren,MI 48090-9055-USA was used to perform the flexure tests. It is a computer controlled machine with data acquisition system that is capable of performing flexural tests in either load or displacement control.Three point bending was applied on beam with cross section 60x60 mm and 280mm span length Notches in beams were made using a diamond saw prior to conducting the fracture tests. The width of the notch was kept constant at about 2 mm.The crack tip had a rounded profile and was not sharpened by any means. The crack was cut into the tension flange to a distance of approximately 30mm which corresponds to a value of 0.5 for the initial notch to beam width (notch ratio).Bending tests were performed immediately after the notch was cut based on ASTME 1820 standard test method for measurement of fracture toughness.

Set-up of flexural tests arrangements is shown in Fig.1.A close view of the three point bending test is declared in Fig.2. Central deflections and loads measurements were recorded at each load increment. The area under the load-deflection was calculated using a computer program and the fracture energy Gf (N/m) was determined.Fracture tests were performed under three displacement rates :5x10-4, 0.8,and 12mm/s is following the procedures devised by Zhang et al. [18] In position control. The first rate 5x10 4 mm/s was considered to represent the quasi-static level and three specimens were tested at each rate. Higher displacement rates, 1000mm/s and 2500mm/swere reached by impact tests using the instrumented drop-weight impact apparatus, Fig.3. An impact hammer weighing 100kg was used and two drop heights were adapted , 250 and 400 mm respectively. The hammer was hoisted mechanically to the required drop height and released by an electronic quick release system.The impact force wasmeasured by a piezoelectric force sensor.The reaction force between the support and the specimen was determined by a further two force sensors. An accelerometer attached tothe hammer wasused to measure acceleration and displacement duringimpact process. The velocity of the hammer U (t) can be obtained by:

The velocity of the hammer $\dot{U}_n(t)$can be determined by:

$$\dot{U}_h(t) = \dot{U}_h(0) + \int_0^t \ddot{U}_h(t)\,dt(3)$$

Where:

$\dot{U}_h$ (0) – initial impact velocity (m/s) = √2aH

$\ddot{U}_h$ (t) – acceleration recorded by the accelerometer attached to the hammer (m/s^2)

a- gravitational acceleration (9.71± 0.14 m/s^2)

H – Hammer drop height (m)

The displacement of the hummer $U_h(t)$is calculated by:

$$U_h(t) = \int_0^t \left[\dot{U}_h(0) + \int_0^t \ddot{U}_h(t)\,dt \right] \quad (1)$$

3. Results and Discussions

Table 2 declares the flexural strength of the precracked beams. A hand of the data shown, one can deduce the following observations:-

Mix design with different constituents gave wide range of strength properties. Specimen ID2038 with and without fibers have the highest tensile strength (max. and first cracking) compared with the other specimens. So, 2038 can be safely considered as HPC specimens.

The ratio of tensile first cracking strength to tensile ultimate remains almost unchanged at a value of two third. First cracking was defined as the discontinuity in the load displacement curve caused by instantaneous decrease in load. The strength and toughness results and analysis are highly dependent on the correct identification of first cracking in each beam test. The HPC may begin to behave nonlinearly due to primarily to internal micro-cracking before the first overall cracking of the beam, therefore, determining first cracking can be somewhat subjective. The beam response is linear until first cracking when a clearly defined decrease in load-carrying capacity occurs.Soon thereafter the load again begins to increase. The saw tooth pattern, shown in Fig.4, is indicative of additional individual cracks forming throughout the highly stressed face of the beam.

The strength values increase almost linearly with fiber volume fraction. The (2038+F) ID sample gives the highest ductility, (as expressed by maximum displacement :8mm) as shown in Fig.4, compared with 1.2mm for 2w sample. Concrete with incorporation of both well aimed weak spots like the polypropylene fibers in order to create micro-cracks and the use of steel fibers in order to bridge these finely dispersed cracks could help to increase ductility. This was actually the case for (2038 +F) sample.

Table.3 shows the stress rate effect on compression testing results for (2038+F) cylinders. It is normally accepted that higher stress rates will result in higher compression strength and modulus of elasticity values. For this reason, using ASTM C39 stress rate of 0.24+0.01 MPa/s is recommended for any standardized compression testing of concrete.

However, the data of compression tests performed at different stress rates ranging from 0.24 to 1.7 MPa/s do not clearly indicate a change in behavior caused by increasing stress rate. The compressive strength remained around 190 MPa which is three times higher than NSC. Fig.5, exhibits the test specimens after compression test at a loading rate of 0.24

MPa/s for (2038+F) and plain cylinders . The (2038+F) with polypropylene fibers as defective spots is shown. The failed test specimen possesses much more finely ramified cracks compared to the plain specimen without fibers that exhibits only a few vertical surfaces of a fracture Fig.5-b Crack closure, though incomplete, was observed on unloading, suggesting that the fibers bridge the cracks, without catastrophic fiber rupture. The load-displacement relationships of 2038+F notched (notch ratio) =0.5 beams under different displacement rates are given in Fig.6.

It is clear that peak loads increases in line with increases in displacement rates. However, the stiffness of the beam does not show a similar tendency which is due to the sensitivity of the elastic flexibility of the beam boundary conditions during the application of the concentrated load [19].

Considerably, the concrete material behaves in a more brittle manner, and increases in strength, toughness, and modulus of elasticity were found as the rate of loading increased. This is because the impact cracks tend to propagates through rather than around aggregate granular, resulting in an increase in strength and toughness.

Table.4 reveals the experimental results of peak load , Pmax (KN) and fracture energy, Gf (N/M) at different displacement rates. The data in the parenthesis are standard deviation. The dynamic increase fracture (DIF), is defined by the ratios of peak load and of fracture energy to their corresponding quasi-static values . In this regard, the displacement rate of 5x10 mm/s is considered as a quasi- static loading condition. Fig.7, declares the dependence of DIF for fracture energy on displacement rate. Beyond a certain threshold (800mm/s), the rate effect becomes more pronounced and significant increase is observed.

The following equation was derived from the experimental data of Fig 7.

DIF $G_{max} = - 13.707\ X^3 + 211.77\ X^2 – 468.51\ X + 270.9$

This equation may be helpful when performing numerical simulations. Now, let us discuss the dependence of the Gf on D^o as follows: The slight rate effect may be attributed to the viscous effect mainly originated by the presence of free water in voids and porous structures. The fact that dry concrete exhibits very little rate sensitivity provides further justification for our explanation of this dependency [18]. However, under high D^o values over the threshold, the rate sensitivity is remarkable due to the inertia effect [19]. The mechanism of failure at high D^o is characterized by the propagation of many microcracks at the same time.These microcracks do not have sufficient time to search for the minimum energy paths. So they are forced to propagate along the shortest path even with higher resistance. This leads to the result that the fracture energy should increase with displacement rate. It is believed that the response of a structure to impact loading depends on an interaction between impacting body and structure by many factors, including relative masses, velocities, contact zone stiffness, frequency of loading and locally energy absorbed area. Fig.8 shows the rate sensitivity of the peak load which has similar trend to that of fracture energy. However,it might be possible to express the dependency of Pmax on D^o by one exponential functions.

DIF $P_{max=}\quad -0.528X^3 + 32.08X^2 - 67.123X + 36.014$

The maximum .DIF for P maximum is 10 compared with 41.78 for G_f. It could be concluded the fracture energy is more sensitive to microcracks than the peak load.

4. Conclusions

The emphasis of this paper is placed on the rate sensitivity of fracture of HPC. Single-edge notched beams were loaded in three-points bending over a wide range of displacement rates. The experimental findings of the present work indicate that:

1- The investigated HPC is a load rate sensitivity material, it resists high load and absorbs more energy under dynamic loading than under static loading.

2- Polypropylene fibers are particularly effective in improving the performance of concrete under dynamic loading. This is attributed to their higher strain capacity and loading bearing capacity in the post cracking zone. The low modulus of elasticity of Polypropylene fibers combined with the considerable adhesion in the matrix improved its capacity to stretch during dynamic loading.

3-Polypropylene fibers fibrillation became more and more dominant failure modes with increasing displacement rate.

4- Different modes of failure are associated with quite different amounts of energy absorption during fracture as well as with different test conditions.

References

1. Mehta, p. and Aitci, P."Cement, Concrete, and Aggregate" J. ASTM, v.12, No.2, pp.70-78, 1990.
2. Russell, H., ACI Define High Performance Concrete, ACIconcrete TNT, Feb, pp.56-57, 1999.
3. Metaxa,Z,Konsta-Gdouts,M.,and Shah,S.,"Crack Free Concrete with Nanofiber Reinforcement", Proceedings of the Third Int. Symposium on Nanotechnology in Construction,eds.Bittnar,Z. et al.,Springer pp125-130,2009.
4. Djaknovn,S,Ouedraogo,E.and Benyahia,A.,"Fracture Toughness of HPC on Three-point Bending of Notched Beam at Elevated Temperatures, Adv.Materials Research,v 89-91,pp. 159-167,2010.
5. Zhang,B.andBicanic,N.,"Fracture Energy of HPC at High Temperature Up to 450Co",Magazine of Concerete Research,v.58(5),pp.277-288,2008.
6. Lan,D.and Buyukozturk,O."Fracture Characterization of Concrete/epoxy Interface Affected by Moisture", Mechanics of Materials, V.42, pp.1031-1042, 2010.
7. Graybeal,B.,"Material Property Characterization of Ultra-High Performance Concrete",Report No. FHWA-HRT-06-103, pp.70-75, 2006.
8.Einsfeld,R. and Velasco,M.,"Fracture Properties for HPC",Cement and Concrete Research,v.36,pp.576-583,2006.
9.Sagar,R.,Dinesh,S.and Antosh,A.,"Fracture Energy of Normal and HSC Beams",Indian Concrete J., V.79, pp.37-42,2005.
10. Chen,B. and Liu,J.,"Effect of Aggregate on the Fracture Behavior of HSC", Constr. and Building Materials",v.18,pp.585-590,2004.
11. Rao,G.and Prasad,B.,"Fracture Energy and Softening Behavior of HSC",Cement and Concrete Research,v.32,pp.247-252,2002.
12. Dong,Z. and Keru,W.,"Fracture Properties of Hsc",J.of Materials in Civil Eng.,V.13,pp.86-88,2001.
13. Mueller,H.,"Constitutive Modelling of HS/HPC-State of the Art Report",CEB FIP Bulletin,v.42,2008.
14.Schuler,H.and Hansson,H.,"Fracture Behavior of HPC Investigated with Hopkinson Bar",JP.8th Int. Conf. on Mech. and Physical Behavior of Materials Under Dynamic loading,pp.1145-1151,2006.
15.Bentur,A.andMindess,S.,"Fibre Reinforced Cementitious Composites "Moden Concrete Technology Series, puls.by Taylor and Francis Group, NY,USA ,2nd Edition,2007.
16. Tai,y.and Wang,I."Elucidaring the Mechanical Behavior of UHSC under Repeated Impact Loading", Structural Eng.and Mechanics,V.37,No.1,pp.1-15,2011.
17. Al-Amoudi,O.,Moslehuddin,M.and Abiola,O. "Effect of Super plasticizer on Plastic Shrinkage of Plain and Silica Fume Cement Concrete", Construction and Building Materials,v.20,pp.642-647,2006.
18. Zhang, X., Ruiz,G.and Yu,R.,"A New Drop Weight Impact Machine for Studying Fracture Process in Structural Concrete",Anales de Mecanica de la Fracttura,v.2,pp.655-659,2008.
19. Ruiz, G., Zhang, X., Yu, R.and Del Viso,J.,"Effect of Loading Rate on Fracture Energy of HSC",Strain,10 Jun.2010.

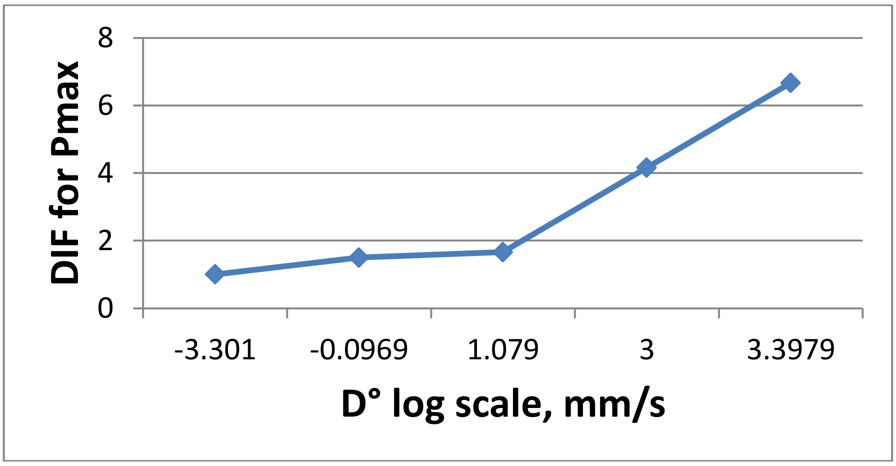


Fig.7 Dependence of DIF for fracture energy on displacement rate

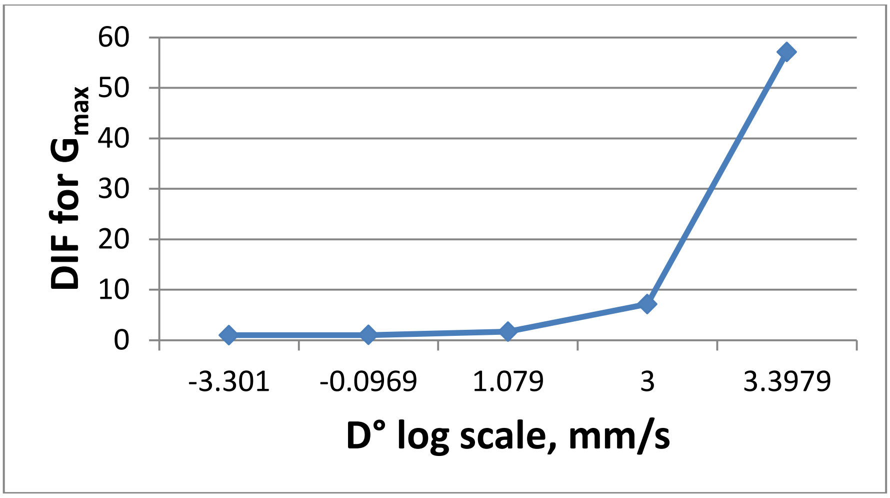


Fig.8 Dependence of DIF for fracture energy on displacement rate

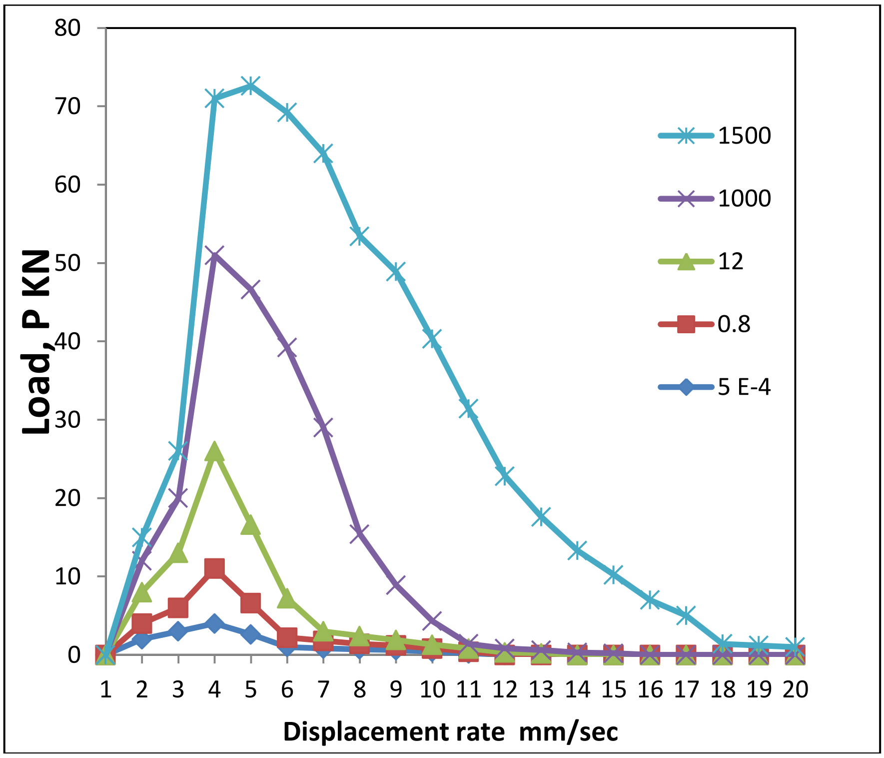


Fig.9 The relation between displacement rate and load

Table 1 Mix Proportions

Material	Amount (kg/m3)	Wt.%
Portland Cement	712	28.5
Fine Sand	1010	40.4
Silica Fume	230	9.3
Ground Quartz	210	8.4
Super plasticizer	30.7	1.2
Accelerator	30	1.2
Steel Fibers	156	6.2
Water	109	4.4
Polypropylene Fibers	10	0.4

Table 2 flexural strength of the precracked beams

specimen I.D.	Fiber vol. Fraction (%)	Specific Surface Area (cm^{-1})	σ_f (MPa)	σ_i (MPa)	(σ_i/σ_f)%
2w	2.43	1.294	8.87	5.61	63.3
2w+F	2.48	1.323	9.11	5.76	63.3
3w	3.70	1.973	12.10	7.56	63.3
3w+F	3.72	1.984	14.67	9.29	63.3
1538	5.2	1.223	28.13	17.80	63.3
1538+F	5.24	1.233	31.29	19.80	63.3
2038	6.00	1.576	37.74	23.88	63.3
2038+F	6.21	1.609	42.46	26.86	63.3

Table 4 experimental results of peak load P_{max} and fracture energy G_f at different displacement rates

	$H_{(mm)}$	D^{o}(mm/s)	P_{max}(kN)	DIF for P_{max}	G_f(N/m)	DIF for G_f
Hydraulic Servo-Controller		$5*10^{-4}$	6(0.3)	1	140(10)	1
		0.8	9(0.4)	1.5	145(13)	1.03
		12	10(0.8)	1.66	150(14)	1.70
Drop-wt. Impact	250	1000	25(4.2)	4.16	1000(24)	7.14
	400	2500	40(7.4)	6.67	8000(700)	57.10

*DIF: Dynamic Increase Factor

Table 3 stress rate effect on dynamic increase factor of (2038 +f)

Stress Rate (MPa/s)	Compressive Strength (MPa)	St.Dev.(MPa)
0.24	185	8.1
0.30	190	6.3
1.00	194	5.4
1.70	194	3.2

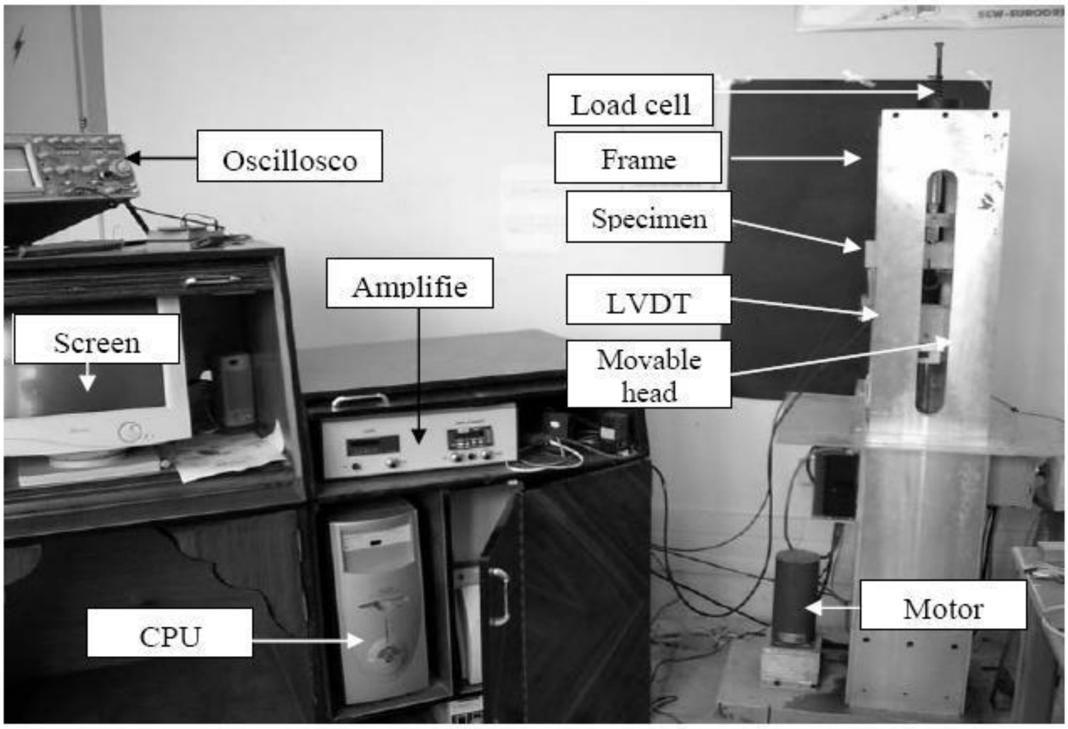


Fig.1 Set-up of flexural test arrangement

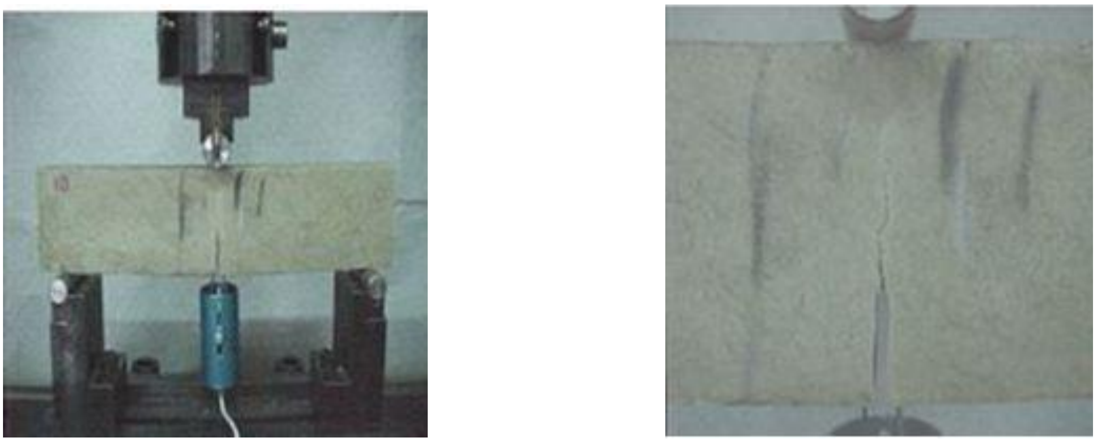


Fig.2 A close view of the three pinot bending test

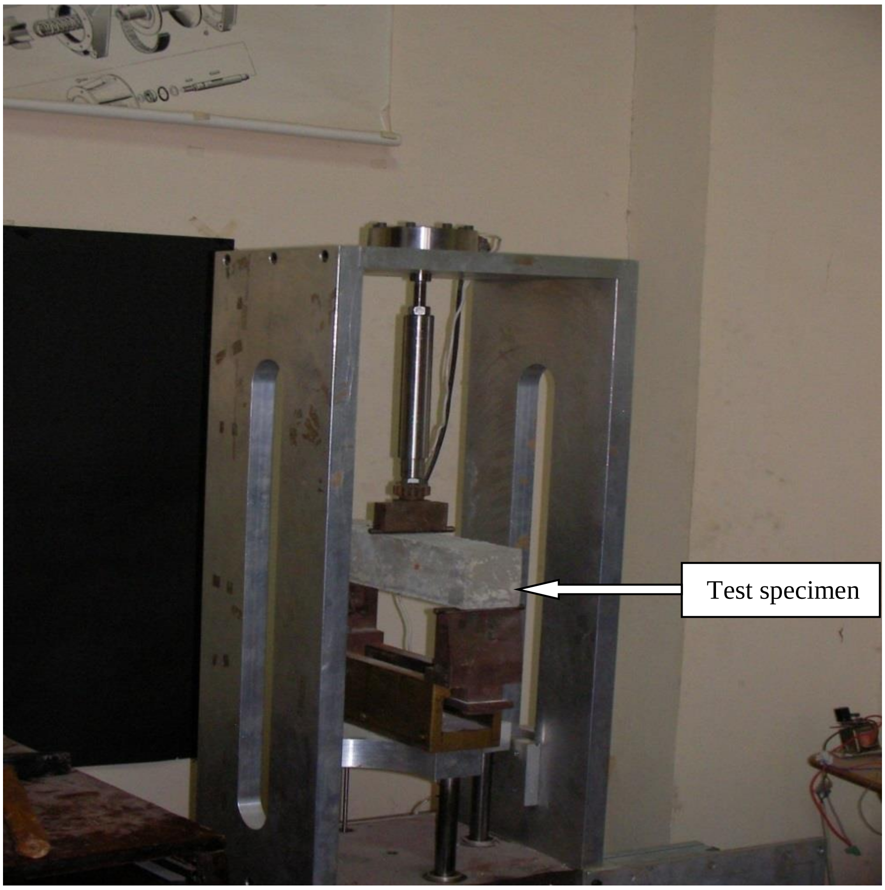


Fig.3 Drop weight impact apparatus

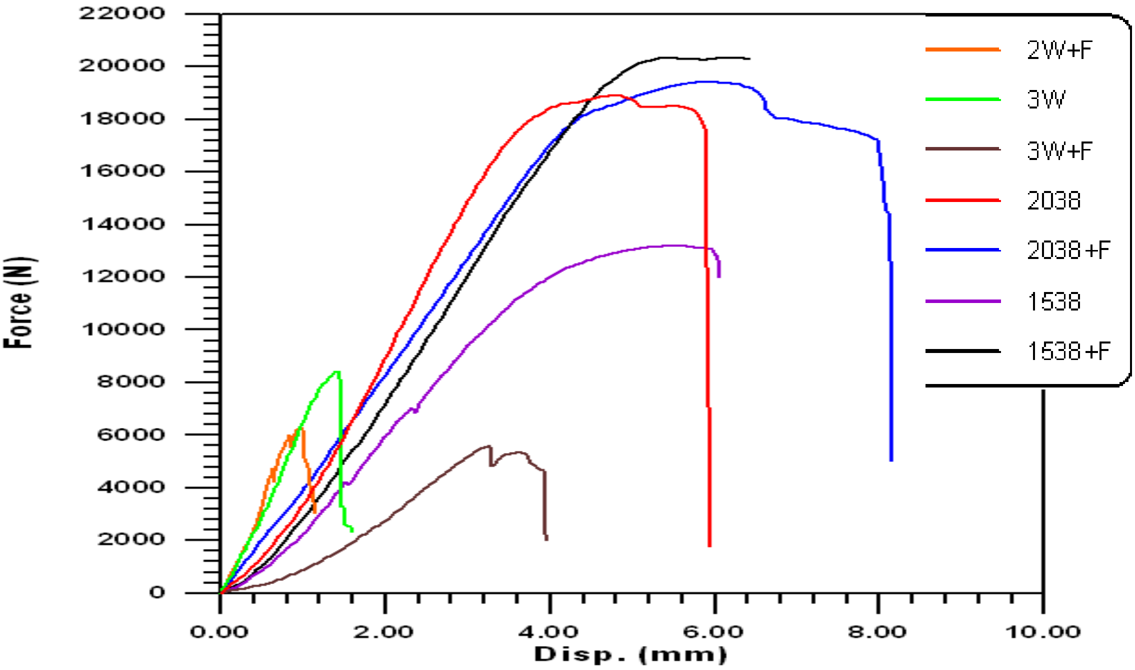
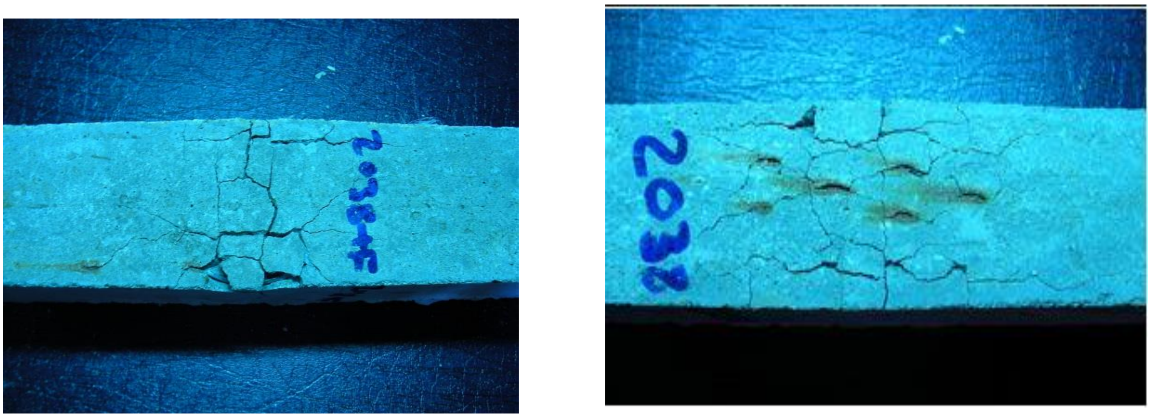


Fig. 4 Force-displacement curves for un cracked beams



(a) (b)

Fig.5 Test specimens after compression test at a loading rate of 0.24 MPa/s for (2038+f) a and plain b) cylinders