คุณสมบัติของคอนกรีตกำลังสูงเสริมใยเหล็ก

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คุณสมบัติของคอนกรีตกำลังสูงเสริมใยเหล็ก
PERFORMANCE OF HIGH STRNEGTH FIBER REINFORCED CONCRETE

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บทคัดย่อ

โดยทั่วไป คอนกรีตกำลังสูงจะเปราะและยากต่อการผสมและเท จึงได้มีการปรับปรุงคุณสมบัติทั้งสองประการของคอนกรีตกำลังสูงนี้ให้มีค่าการยืดตัวสูงขึ้นกว่าเดิม เพื่อให้คอนกรีตชนิดนี้สามารถนำไปประยุกต์ใช้กับงานคอนกรีตได้มากขึ้น คุณสมบัติอื่นๆ ที่สำคัญของคอนกรีตกำลังสูงคือสามารถผสมและเทลงแบบได้โดยง่าย อย่างไรก็ตามถึงแม้ว่าได้มีการศึกษาค้นคว้าคอนกรีตชนิดนี้มาเป็นนาน ก็ยังคงมีคำถามต่างๆ เกี่ยวกับ มาตรฐาน คำจำกัดความ คุณภาพของคอนกรีต และวิธีทางการวิจัยเพื่อใช้คอนกรีตชนิดนี้ในงานภาคสนาม ในบทความวิจัยนี้ ได้ทำการศึกษาคุณสมบัติต่างๆของคอนกรีตกำลังสูงเสริมใยเหล็ก ซึ่งได้แก่ SIFCON (Slurry Infiltrated Fiber Reinforced Concrete) กับ คอนกรีตกำลังสูงเสริมใยเหล็กทั่วๆไป คุณสมบัติที่ทำการทดสอบประกอบด้วย คุณสมบัติทางด้านแรงอัด แรงดึง พลังงานสะสม และค่าโมดูลัสความยืดหยุ่น ในการศึกษาเกี่ยวกับ SIFCON นี้จะใช้เส้นใยเหล็กเสริมในปริมาณ 4 ถึง 10 เปอร์เซนต์ผสมกับน้ำปูนซีเมนต์ข้น สำหรับการศึกษาในกรณีของคอนกรีตกำลังสูงเสริมใยเหล็กแบบทั่วๆไปนั้น จะใช้ปริมาณของเส้นใยเหล็กเสริมเพียง 0.5 ถึง 1 เปอร์เซนต์เท่านั้น ผลการทดลองพบว่าใน SIFCON นั้นปริมาณเส้นใยเหล็กเสริม 8 เปอร์เซนต์ ให้ค่าผลการทดลองที่ดีที่สุด เมื่อใช้การผสมแบบธรรมดาทั่วๆไป เมื่อ SIFCON ได้รับแรงจนตัวอย่างแตกร้าวจะทำให้เส้นใยเหล็กเสริมตลอดแนวแตกร้าวประสานและยึดกันในคอนกรีต ซึ่งผลลัพธ์ที่ได้ก็คือค่ากำลังของคอนกรีต จะมีค่าคงที่ไม่ตกลงมาดังเช่นคอนกรีตที่ไม่มีเหล็กเสริม ปรากฏการณ์เช่นนี้เกิดขึ้นเช่นเดียวกับเหล็กเสริมทั่วๆไป การใช้เหล็กปลอกไม่ว่าจะเป็นเหล็กปลอกเกลียวหรือเหล็กปลอกเดี่ยวล้วนเพิ่มค่าการยืดตัวของคอนกรีต

SUMMARY

High strength cement-based matrices are often very brittle and difficult to mix and process. Improvement on these two aspects leads to new cement-based product commonly known as high performance concrete which is of interest to many investigators. Improved ductility of cement-based composites can lead to many potential new applications for the high performance high strength concrete. Other crucial properties of these concretes are the ease of production process as well as its workable condition. Although much is learned about these new materials during the last few years, many questions remain as to the standard, definition, quality assurance, and the direction of research in the field of high performance concrete. In this paper, the properties of high performance high strength fiber reinforced concrete were investigated. A type of high performance concrete so-called SIFCON (Slurry Infiltrated Fiber Reinforced Concrete) and a series of high strength fiber reinforced concrete were tested for its mechanical properties such as compressive strength, tensile strength, energy absorption, and the modulus of elasticity, etc. For SIFCON, steel fiber reinforcement of 4 to 10% was incorporated into the high strength slurry cement matrix. For conventional high strength fiber reinforced composites with normal fiber content of 0.5 to 1%, the effect of lateral reinforcement was investigated. The results from these studies reveal that the 8% fiber reinforcement of SIFCON shown to be the optimum percentage of these type of products when conventional mixing process was employed. A constant stress plateau exists after cracking as a result of fiber interlocking. This behavior is very much similar to traditional steel reinforcement. Confinement through stirrups or lateral reinforcement significantly enhances the ductility of the high performance brittle matrix.

INTRODUCTION

Development of high strength concrete has been widely explored for the last fifteen years. It is obvious that two of the main difficulties facing high strength concrete users and producers are the brittle nature and the poor workability of these high strength concretes. The improvement of these deficiency has led to the new product so-called high performance concrete. However, the differences on the definition of high performance concrete among researchers around the world remain the topic of discussion [1]. The variation on the definition of high performance concrete varies from high strength high ductility cement composites [2] to flowable medium and high strength concrete. The former is the concept generally adopted in North America and in Europe while the latter is widely studied in Japan.

The applications of high performance concrete then vary widely depending on the original concept used in developing such high performance concrete. In North America and Europe, most of the high performance concretes were developed by providing a better ductility to the brittle concrete. Such an improvement was done through the addition of steel fibers into the high strength matrices. The added fibers were commonly in the range of less than 2%. This limitation was controlled by the balling effect which tends to take place under conventional mixing process if the fiber content exceeds the 2% limit. Attempt to increase the fiber content in concrete was successfully developed by Lankard and Newell [3] using a high strength cement slurry infiltrated into the mold fully packed with fibers. This process allows the addition of fibers up to 24% which tends to significantly strengthen the energy absorption of the high strength brittle matrices. Although many investigations have been carried out to study the properties of these materials such as compressive strength [4], flexural behavior [5], and tensile characteristics [6] for the past few years, there is still a need to further understand how the presence of fibers enhances the properties of concrete. Of particular interest are the failure mechanism, the energy absorption, the predictability of these properties for engineering design and applications. Some of these parameters will be investigated here.

Another type of high performance concrete studied here is the properties of normal high strength concrete with the addition of steel fibers. The presence of fibers in brittle high strength concrete helps improve the ductility and post-cracking characteristics of concrete. While many different types of high strength concrete are presently being used in actual construction, the extremely brittle nature of these concretes associated with its abrupt failure were not clearly understood. Many designers select to provide additional lateral reinforcement to ensure safety against brittle failure. Such a practice although is widely accepted still needs to be properly understood as to the performance and characteristics of these additional reinforcements. The present study also covers the effect of lateral reinforcement and fiber content on the behavior of high strength concrete.

In this study, the concrete used can be divided into two categories as: 1) SIFCON with fiber volume fraction varied from 4 to 10%, and 2) a high strength fiber reinforced concrete with conventional fiber volume fraction of 0.5 to 2%. The properties of these concrete were studied to evaluate for its mechanical properties such as compressive strength, tensile strength, energy absorption, fracture energy, and the elastic modulus, etc. The effect of lateral confinement and fiber content were also investigated.

SIFCON

Slurry infiltrated fiber concrete (SIFCON) was first developed by Lankard [3]. SIFCON consists of high volume percentage of fibers and therefore cannot be mixed as conventional fiber reinforced concrete. To make SIFCON, fibers are first placed in the mold and vibrated, if necessary, then high strength slurry which consists of cement paste, silica fume, and high dosage of water reducing agent, is poured on to the mold and vibrated until the mold is filled.

The addition of fibers to cement-based matrices is commonly known to improve the post-cracking tensile strength of concrete. With increasing fiber volume fraction beyond the traditional limit of 2% to a high percentage of 15 to 20%, Shah [7] reported the presence of high fiber volume fraction not only enhanced the post-cracking load carrying capacity but also increased the tensile strength of the composites. This conclusion may lead to many applications of high volume fiber reinforced concrete. The tensile properties of concrete and other cementitious composites are often believed to be insignificant and therefore ignored in the design and analysis. This practice was partly due to the difficulties involved in conducting the direct tensile test. However, tensile characteristics play the crucial role in all cracking phenomena of concrete structures. It is therefore important to thoroughly understand the tensile characteristics of concrete and other cement-based composites, especially the high performance concrete such as SIFCON.

Properties of SIFCON under compression, bending, and impact have been previously studied by several investigators [4,5,6]. In this investigation, emphasis will be given to the property of SIFCON under direct tension. Attempt was also made to predict the tensile response of SIFCON using a normalized stress-displacement concept.

High Strength Fiber Reinforced Concrete

High strength fiber reinforced concrete used in this study was a product of high strength concrete made from silica fume with 0.5 to 1% of steel fiber as reinforcement. The amount of water to cement ratio was kept at around 0.28 to 0.30. Extra dosage of superplasticizer was added to improve the workability of the high strength concrete. The strength of the matrix is in the range of approximately 12,000 to 14,000 psi or 850 to 1000 ksc. Fibers and other concrete materials were mixed in the mixer in a conventional manner. Lateral confinement was provided at different intervals in the concrete samples to study its effect on the compressive properties of these cementitious composites.

EXPERIMENTAL PROGRAM

Direct Tension Test

Series of uniaxial tension test were conducted on SIFCON using an end-tapered specimen. The middle section of the specimen has a thickness of 25 mm (1 in.) and a width of 75 mm (3 in.). The specimen has a net cross section of 1935 mm^2 (3 in^2). Details and schematic diagram of the specimen and the test setup were discussed in Ref.[8] and therefore will not be repeated here. The tapered specimen was so designed that both ends can easily fit into the self-interlocked grips. This setup eliminates any difficulties involved with glueing and alignment as required in other direct tension tests. Two side notches were saw-cut at the middle of the specimen to ensure that cracks occur at the critical section where two clip gages are attached to provide the feedback control signals. All data collected through a PC data acquisition system were automated. The loading rate for the direct tension test was 0.0001 in./sec for axial tension.

Compression Test

Series of fiber reinforced high strength concrete cylinders were prepared using silica fume and low water-cement ratio mixes. Conventional 3"x 6" cylinders were prepared for compression test which is used to observed the ultimate compressive strength, the modulus of elasticity, the energy absorption, and the post-peak response of these cementitious composites. The test setup was presented in details in Ref.[9]. The test was controlled by the two clip gages mounted on top of the cylinder to measure the axial deformation. The feedback provides the means of measuring post-peak response of these brittle concretes. The applied rate of loading in compression was 0.05 in./min. of axial deformation. Depending on the loading rate and the type of reinforcement in the test specimen, occasionally explosive type of failure occurs in conventional testing machine. In the closed-loop testing system used in this study, the feedback system controls the loading rate and provides stable type of failure for these high strength concrete samples even for plain high strength concrete with no steel fiber nor lateral reinforcements.

Material Composition and Mix Proportions

The SIFCON in this study was made from hooked-end steel fibers with volume fraction of 4 to 10%. Cement-silica fume slurry with water to cement ratio of 0.35 was used to infiltrate into the fiber-filled molds. The amount of silica fume used in the mix was 10% with 4% of superplasticizer to improve the workability of the mixes. No fine aggregate nor fly ash was added in the selected mixes. The mix provides an average compressive strength of 11,000 psi or about 750 ksc. Casting SIFCON was generally done with first filling the mold with fibers. Depending on the volume fraction of the mix, vibration may be needed. For low percentage of fiber volume fraction such as 4 and 6%, the amount of fibers is less than the size of the mold. For this case, fibers will be added simultaneously with the slurry to ensure proper fiber distribution. The mold was usually filled with about 8% of fiber volume fraction. Vibration during placement of slurry is needed to minimize air void in the SIFCON specimens. The distribution and orientation of fibers and the shape of the test specimen, the thickness in particular, play an important role on the properties of SIFCON.

For high strength fiber reinforced concrete, the steel fiber volume fraction used in the mix was 0.5, 0.75, and 1%. Hooked-end steel fibers with an aspect ratio of 60 were added in the high strength concrete mix. The mix proportion of the high strength matrix was listed in Table I. Confinement in the form of circular hoops was constructed from steel wire of 12 gage and with f_y= 66 ksi. The spacing of the hoops was set at 1, 2 and 3 in. apart. The 3"x 6" high strength concrete cylinders were cast and cured in lime-saturated water until the day before testing. The age of test specimen varied from 2 to 56 days. The strength of these high strength concrete is around 12,000 to 14,000 psi (850-1000 ksc).

Table I Mix Proportion of High Strength Fiber Reinforced Concrete

Mixing Proportions		
Materials	Weight Ratio	Weight (lb/yd^3)
Water	0.28	244
Cement	1.00	870
Sand	1.40	1218
Aggregate	2.20	1914
Silica Fume	0.05	44
SP (fl.oz)	40 fl.oz/100 lb of cement	348

COMPRESSIVE STRESS-STRAIN CURVES OF SIFCON

The compressive stress-strain curves of SIFCON with different fiber volume fractions are shown in Fig. 1. It can be seen that there is no significant effect due to fiber volume fraction on the ultimate compressive strength, peak strain, and the modulus of elasticity of the composites. Of particular interest from the observed experimental results is the existence of the post-peak stress plateau which is similar to the phenomena observed in steel. Regardless of the fiber volume fraction, the stress plateau seems to be constant at approximately about 7000-8000 psi (490-560 ksc). The stress plateau is likely a result of the shear interlock among fibers in the vicinity of the crack plane. The fiber interlocking stabilizes the failure mechanism and therefore provides ductility to the brittle matrix. Fig. 2 shows the comparison of the compressive stress-strain curves of SIFCON observed from this study with the one reported by Naaman [4]. Although both curves were derived from a 10% SIFCON mix, the results were rather different both in terms of the Young 's modulus of elasticity and the ultimate compressive strength. These variations can be attributable to the effect of specimen configuration which affects the fiber orientation. In any case, there is one common behavior which can be observed from these two responses which is the trend of an existing stress plateau after the ultimate load. Table II summaries various observed properties of SIFCON under compression. The fiber content varies from 4 to 10% in this study while those reported by Naaman [4] were in the range of 10 to 12%. In this study, the results indicate that the Young 's modulus of elasticity decreases when fiber volume fraction increases. This may be explained that the presence of fibers tends to create discontinuity of the high strength matrix. Depending on the interfacial bond between the fiber-matrix interface, the overall stiffness of the composite system may thus be reduced. While peak stress does not seem to be affected by the amount of fibers, the peak strain behaves otherwise, i.e. the higher the fiber volume fraction, the larger the peak strain. These results may be due to the plasticity of steel fibers bridging over the crack plane. The interlocking of fibers yields an enormous resistance to fracture along the failure plane which results to stable large deformation of the composites. Fig. 3 shows two tested SIFCON cylinders under compression with large stable failure deformation of up to half an inch. Fiber interlocking can also be clearly observed in this same figure.

TENSILE BEHAVIOR OF SIFCON

One of the major problems of high strength concrete is its brittle nature of the composite which often tends to fail in an abrupt and catastrophic manner. To prevent this phenomena in practice, extra confinement is provided to ensure sufficient post-cracking ductility. The addition of fibers into the brittle matrix can also enhance the ductility of high strength concrete. The use of fibers for this purpose was quite common as can be seen from many existing fiber reinforced concrete structures. However, in normal fiber reinforced concrete (FRC), the amount of fibers added into the composites is limited by the potential balling of fibers which tends to occur when the volume fraction of fibers exceeds two percent. Therefore, under conventional mixing process fiber reinforced concrete common contains less than 2% of fibers. The tensile load carrying capacity of normal FRC does not seem to be affected by the presence of fibers. However, in larger fiber volume fraction cement-based materials, the presence of fibers was reported to increase the tensile strength of concrete [7]. In this study, direct tension test was carried out on the SIFCON specimen. The results confirm the increase of tensile strength as the fiber volume fraction increases.

Fig. 4 shows the stress-displacement relationships of SIFCON for four different fiber volume fraction of 4, 6, 8, and 10% SIFCON. Each of these curves seems to indicate the same pull-out behavior of fibers as can be seen from the stress variation after the peak load. Each of these stress variation represents the pull-out of fibers. While those specimens with 4, 6, and 10% show a similar pattern on the post-peak responses the 8% one behaves different with a longer stress plateau. Such a finding can be viewed in two different aspects as follows: 1) the 8% fiber volume fraction may represent the optimum mix since the amount of fibers contains in this mix just fills up the mold perfectly while others may be less than or more than the capacity of the mold. This will result to an uneven fiber distribution in the concrete specimen, and 2) the difference of the 8% fiber volume fraction from others may be a result of the rotation of the test specimen induced by the uneven distribution of fibers. Based on the observation in this study, the former seems more likely to be the reason. Fig. 4 also shows that the ultimate tensile strength of SIFCON increases with the fiber volume fraction. Nonlinearity prior to the ultimate load for these SIFCON specimens are rather significant citing multiple cracking at the critical section. There is also no doubt on the ductility improvement of SIFCON as compared to the high strength matrix.

Table II Properties oF SIFCON under Compression

	Fiber Orientation	Volume Fraction	E x10^6 (psi)	Peak Strain	Peak Stress (ksi)	Stress Plateau (ksi)
Present Study	Random	4	-	0.010	12.00	7.7
		6	1.705	0.0088	11.4	6.25
		7	2.161	0.007	10.01	5.7
			2.220	0.007	11.36	4.8
		8.5	1.690	0.011	11.50	6.4
		9.48	1.924	0.016	12.03	5.2
			1.743	0.013	11.85	7.4
		10	1.565	0.012	11.27	7.0
Naaman	2P	12.0	1.43	0.010	8.7	6.3
	B	11.6	1.05	0.019	13.1	10.0
	M	10.1	1.13	0.019	11.5	7.3
	3P	11.9	0.87	0.015	10.6	7.0
	B	11.8	-	-	-	-
	M	10.1	1.13	0.018	12.2	5.8

Table III Fracture Energy and Tensile Strength of SIFCON

SIFCON	V_f (%)	Max.Stress (ksi)	Max.Stress (MPa)	G_f (kip/in)	G_f (kN/m)
Naaman	12	2.81	19.4	0.45	78.8
	12.6	3.85	26.6	0.574	100.5
	12.8	3.85	26.6	0.574	100.5
Present Study	4	0.88	6.1	0.12	21.0
	6	1.25	8.6	0.18	31.5
	8	2.06	14.2	0.26	45.5
	10	2.42	16.7	0.32	56.0
Reinhardt	8.5	1.33	9.2	0.345	60.5
	13.5	2.06	14.2	0.766	134.1
Plain Concrete				0.0003	0.05

Fig.3 SIFCON Cylinders (3"x6") under Compression

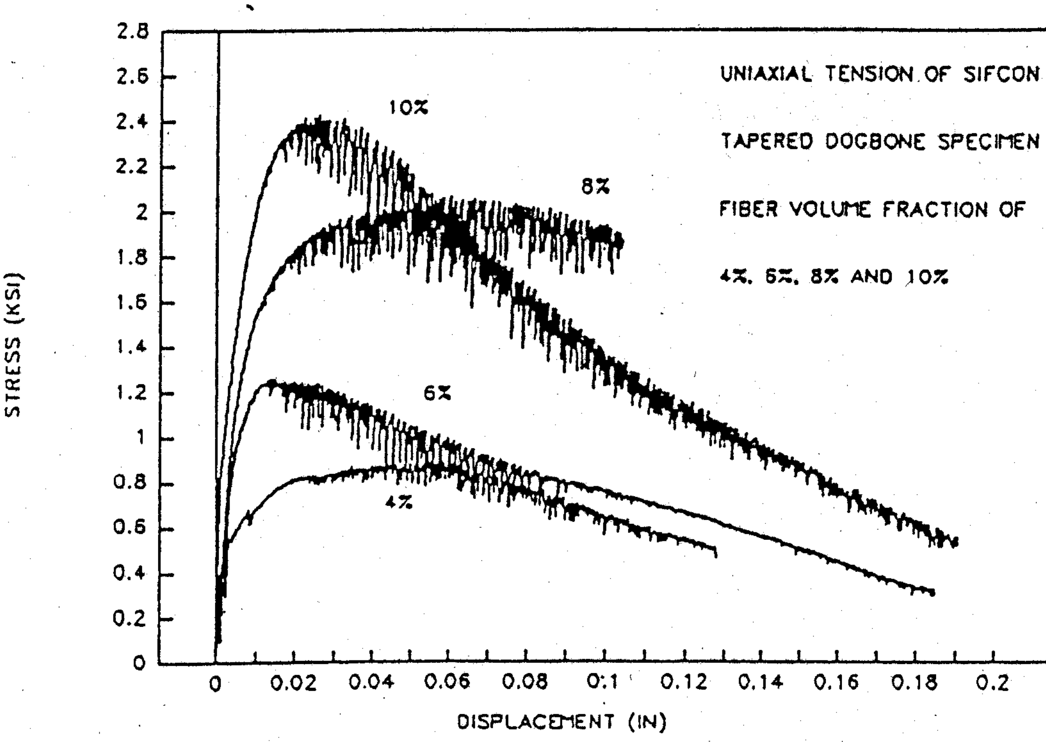

Fig.4 Tensile Stress-Displacement Relationship of SIFCON

Table III summaries the fracture energy and maximum tensile strength of SIFCON from this study and of those reported by other investigators [4,6]. The peak strength was found to increase with the amount of fibers added. Different setup tends to significantly influence the observed ultimate tensile strength of the composites. Fracture energy of SIFCON varies directly with the amount of fibers presented in the mix. Fracture energy of SIFCON was found to be much larger than (1000 times more than) those of plain concrete. The tensile strength and other tensile related characteristics of SIFCON seem to be strongly affected by the test setup, specimen configuration, and the volume fraction of fibers added. To predict the post-peak behavior of the SIFCON composites under direct tension, a normalized stress-displacement model was proposed [10]. The predicted results seem to agree well with the experiment data. For the sake of brevity. the details of these comparison can be found in Ref.[9] and therefore will not be presented here.

PROPERTIES OF HIGH STRENGTH FIBER REINFORCED CONCRETE

Stress-Strain Curves of High Strength Concrete

The stress-strain curves of high strength concrete are different from the normal strength concrete. Perhaps the major difference is at the Young 's modulus of elasticity and the nonlinearity of the stress-strain curves. The stress-strain curves of high strength concrete tend to be more linear for the reason that there is less microcracks in the tested specimen than the one of normal strength concrete. Failure mechanism of high strength concrete is usually abrupt with a straight vertical crack planes. Most specimens seem to fail under lateral tensile stress rather than the conventional compression failure. Due to excessive strain energy stored in the specimen prior to ultimate failure, the release of this applied energy generally cuts through the grain of aggregates. As a result, aggregate plays a major role in the development of high strength concrete. Fig. 5 shows the stress-strain curves of high strength concrete tested at different ages. As the specimen gets older, the ultimate compressive strength becomes higher. However, it also shows that the nonlinearity of the curve decreases as the sample gets stronger. Although the post-peak responses shown in this figure of these specimens are not so distinct from each other, it is commonly found that the higher the strength of concrete the more brittle the matrix becomes. In other words, low strength concrete behaves more ductile than higher strength concrete.

Modulus of Elasticity

The modulus of elasticity of concrete is one of the very important parameters needed for the calculation of deflection. In general, designers depend on the formulation provided by the ACI Building Code in estimating the modulus of elasticity of concrete in his design. However, for high strength concrete, this parameter varies widely depending upon the type of high strength concrete used. Table IV compares the observed values of modulus of elasticity of high strength concrete from this study with those reported by Carrasquillo et al. [11] and the corresponding values predicted from the conventional ACI code. The ACI recommended equation for normal strength concrete always gives a higher value than the actual experimental one. The type of coarse aggregate used in the high strength concrete also affects the modulus of elasticity of that high strength concrete. It can also be concluded that the higher the strength of concrete the higher the E value becomes.

Table IV Modulus of Elasticity of High Strength Concrete

Investigator	Coarse Aggregate	f'_c (psi)	ε_o (in./in.)	E_c (10^6 psi)	E_c* (10^6 psi)
Carrasquillo (1981)	Crushed Limestone	10,670 11,050 11,100	0.0029 0.0030 0.0029	5.01 5.30 5.33	5.89 5.99 6.00
	Gravel	9,290 9,520 9,500 10,570	0.0028 0.0031 0.0030 0 0036	4.05 3.66 3.70 3.72	5.49 5.56 5.55 5.86
Present Study	Basalt	9,549 10,945 11,660 12,154 13,258	0.003038 0.003023 0.003144 0.003310 0.003326	4.497 4.770 4.840 4.735 4.781	5.57 5.96 6.15 6.28 6.56
	Crushed Stone	11,493 11,673 12,060	0.003250 0.003417 0.003583	3.876 3.759 3.667	6.11 6.16 6.26

* ACI 318-77

$$E_c = 57000\sqrt{f'_c}\,\text{psi}$$

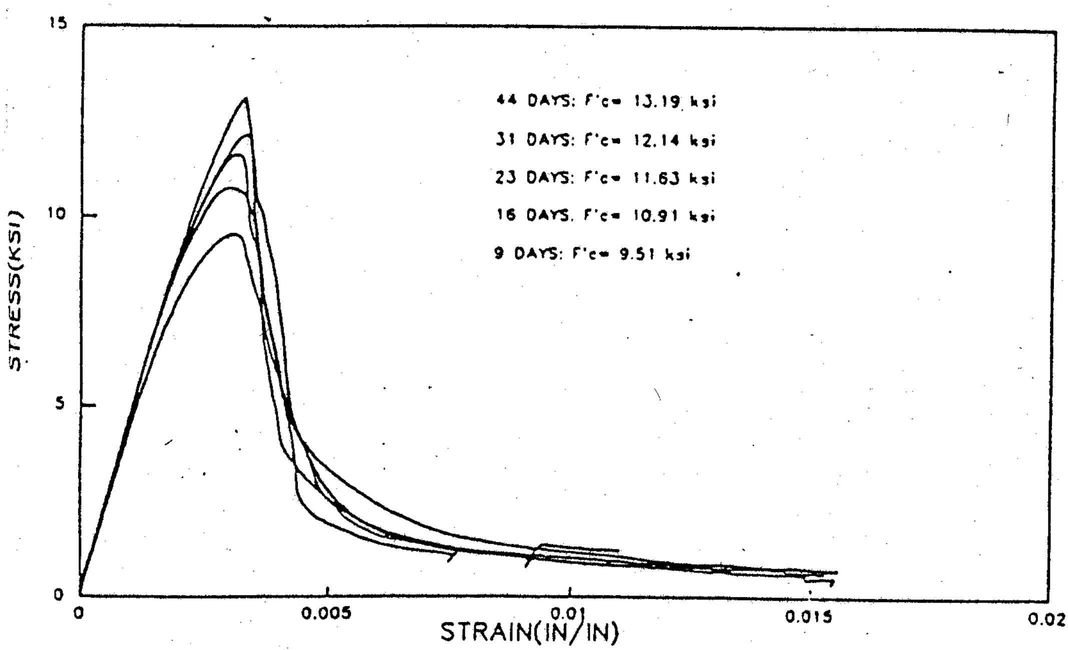

Fig. 5 Stress-Strain Curves of High Strength Concrete

Effect of Fiber Reinforcement

The presence of fibers in the brittle high strength cement-based matrices helps improve the ductility and energy absorption of the composites. Fibers bridge the cracks which were induced by the applied load. Depending on the type of fiber, the enhancement varies. Fig. 6 shows the influence of fiber volume fraction on the compressive stress-strain relationship of high strength concrete. The ascending portion of the curves was hardly affected by the fibers. However, post-cracking behavior of the high strength concrete is strongly influenced by the presence of fibers. The larger the amount of fibers added, the tougher the composites. Of course, when the fiber volume fraction exceeds the 2% limit, one needs to be concerned with the fiber balling effect and hence special processing technique must be taken into account.

Effect of Lateral Confinement

The brittle nature of high strength concrete was often taken care of by the addition of extra lateral confinement. Fig. 7 shows the effect of lateral confinement on the stress-strain behavior of plain high strength concrete. The more lateral confinement provided, the tougher the materials become. For high strength fiber reinforced concrete, the effect of lateral confinement further toughens the overall ductility of the composites (Fig. 8). Undoubtedly, such a material will be extremely suitable for structures in the earthquake prone region.

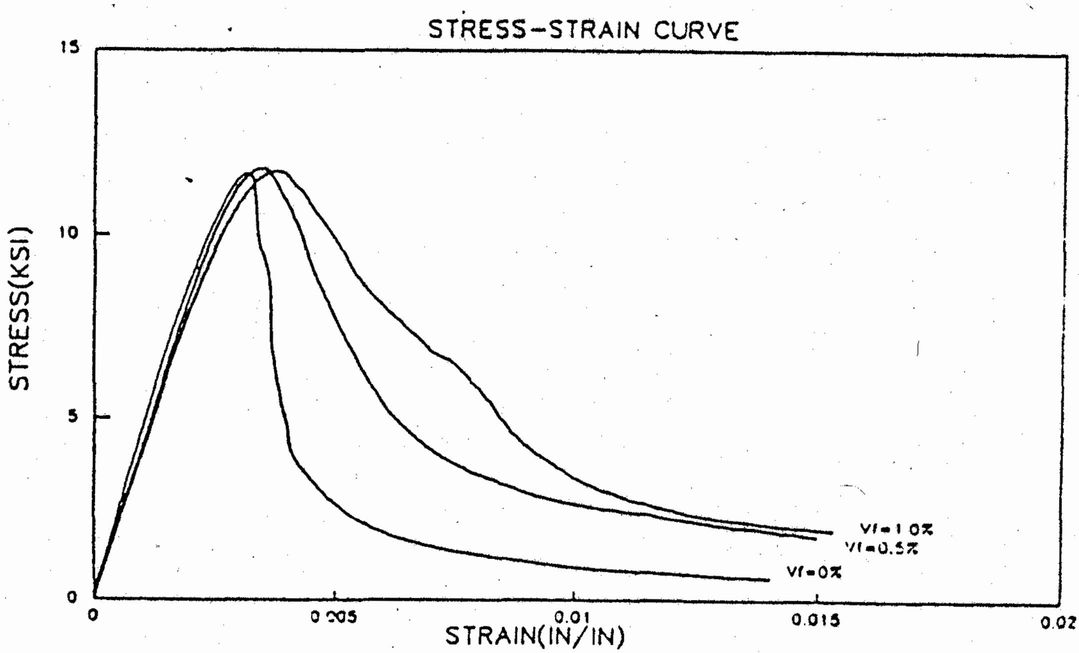

Fig. 6 Influence of Fibers on the Stress-Strain Relationship of High Strength Concrete

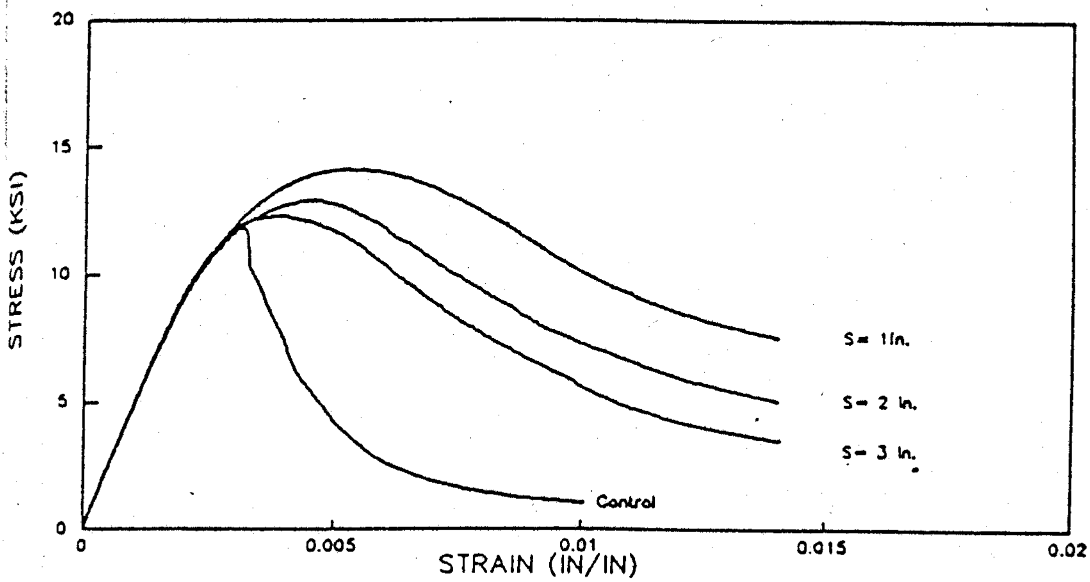

Fig. 7 Influence of Lateral Reinforcement on the Stress-Strain Relationship of High Strength Concrete

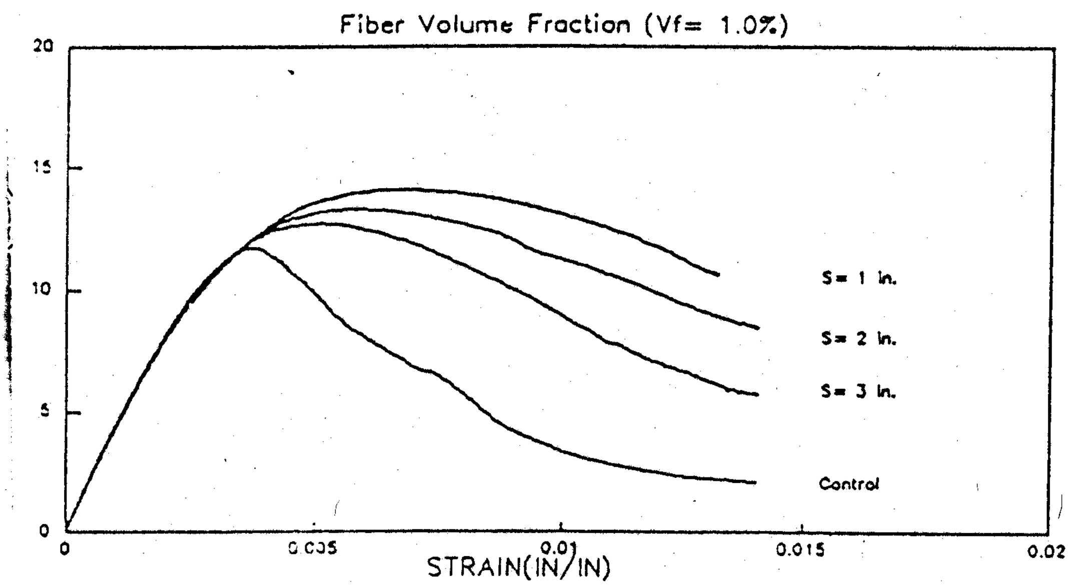

Fig. 8 Influence of Lateral Reinforcement on the Stress-Strain Relationship of High Strength Fiber Reinforced Concrete

CONCLUSIONS

Form this study, the following conclusions can be drawn:

1. SIFCON exhibits a post-peak stress plateau in compression. This stress plateau is believed to be due to the shear interlocking of fibers along the crack plane.

2. The larger the amount of fiber incorporated into the cement composites, the higher the tensile strength and fracture energy of SIFCON become. On the other hand, the presence of fibers does not have any significant effect on the compressive strength of cementitious matrices.

3. The addition of fibers into high strength concrete can significantly improve the ductility of the composites.

4. The addition of extra lateral confinement into high strength concrete matrix strongly influences the post-cracking toughness of the high strength composites.

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