Effect of Vibration Time on Some Mechanical Properties of High Strength Steel Fiber Reinforced Concrete

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ABSTRACT

Concrete is a widely used construction material which has a low tensile strength and a low strain capacity at fracture. To improve such ambiguities, reinforcement is used with reinforcing bars or steel fibers. While reinforcing steel bar is continuous and is particularly located in the structure to optimize performance, fibers are discontinuous and are generally distributed randomly throughout the concrete matrix.

Based on previous researches, compaction of fresh concrete containing steel fibers is one of the most influential factors on mechanical properties. This study investigates effect of vibration time on mechanical properties of steel fiber reinforced concrete (SFRC). Considering the compressive strength above 55MPa, this study focuses on high strength concrete including three different percentages of steel fibers and control mix with no steel fiber tested that were vibrated at fresh state at four different vibration times.

The compressive strength, flexural strength (load-deformation relations) and splitting tensile strength tests were performed on cubes, beams and cylinders and optimum vibration duration tried to be obtained for each property among all test results.

Keywords: vibration time, steel fiber reinforced concrete, flexural strength, compressive strength, splitting tensile strength, flexural toughness, post-peak performance.

ÖZ

Beton yüksek basınç mukavemetine rağmen düşük çekme dayanımı ve düşük şekil değiştirme kapasitesi olan bir malzemedir. Bu olumsuz durumu ortadan kaldırmak için kullanılan iki metod vardır. Bunlardan birisi sürekli demir donatı kullanmak diğeri ise betona kısa kesilmiş çelik lif katmaktır. Demir donatılar sürekli olmalarına rağmen lifler kısa ve süreksiz olan malzemelerdir.

Taze betonun sıkıştırılma zamanı betonun özelliklerini etkileyen çok önemli bir uygulamadır. Bundan dolayı bu araştırmada çelik lifli beton farklı zamanlarında sıkıştırılarak basınç mukavemeti, yarmada çekme mukavemeti ve eğilme dayanımı (gerilme-şekil değiştirme davranışı) özelliklerine bakılmıştır. Basınç mukavemeti 55 MPa üzerinde olduğu için yüksek mukavemetli beton sınıfında olan betonların içerisine değişik oranlarda kısa kesilmiş çelik lifler katılıp taze halde 1.0 dakika, 1.5 dakika, 2.0 dakika ve 2.5 dakika sürelerde sıkıştırılmışlardır. Belirli yaşlarda yapılan bu deneyler neticesinde her bir özellik için farklı optimum sıkıştırma zamanları bulunmuştur.

Anahtar Kelimeler: sıkıştırma süresi, çelik lifli beton, eğilme dayanımı, basınç mukavemeti, yarmada çekme dayanımı, gerilme-şekil değiştirme davranışı.

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To my parents, treasures in my life, who have always stood by me

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LIST OF ABBREVIATIONS

HSC: High Strength Concrete

HSSFRC: High Strength Steel Fiber Reinforced Concrete

SFRC: Steel Fiber Reinforced Concrete

GGBS: Ground Granulated Blastfurnace Slag

D: diameter

l/d: Length over diameter

MPa: Mega Pascal

N: Newton

f_{cf}: Flexural strength

F: The maximum load

I: The distance

SSD: Saturated surface dry

BRE: Building Research Establishment

Chapter 1

INTRODUCTION

1.1 General

Concrete is a construction material which is used in different fields and has been extensively increasing to grow due to some special features such as being easily shaped, having resistance against physical and chemical external effects, economical reasons and its convenience in production. While concrete is widespread and more common than other materials, improvement of concrete properties by new techniques or new materials could be lead to more effective than the expected classical quality of concrete. For meeting the requirement of various effects which exist in places where concrete is used, different techniques are being developed such as incorporating admixture or additive, different curing conditions or any new methods that one of these techniques is using fibers to reinforce concrete against its brittleness. (Yilmaz et al. , 2010)

Concrete which is not reinforced has a low tensile strength and a low strain capacity at fracture. These defects are conquered by adding reinforcing bars, prestressing steel or steel fibers. In comparison between bars and fibers it should be noted that reinforcing steel is continuous and is particularly located in the structure to optimize performance while fibers are discontinuous and are generally distributed randomly throughout the concrete matrix. So the fiber reinforced concrete can be an economical and more useful construction material due to the flexibility in methods of fabrication (ACI committee544 , 2002).

Concrete having a compressive strength above 55 MPa is introduced as high strength concrete (HSC) (Commitee363, 2002). One of the most significant features of HSC is low water/cement ratio which should be compensating with superplasticizer and adequate compaction and curing. In other words, HSC is a more brittle material in comparison to plain concrete which can be improved by addition of steel fiber to reduce brittleness (Eren & Marar, 2010).

Steel, glass, synthetic, and natural fibers are the basic fiber categories. The steel fibers are different than the others with their aspect ratio as described by length over diameter. For conventionally mixed steel fiber reinforced concrete (SFRC), high aspect ratio improves the post-peak performance more than the lower aspect ratio fibers and this is due to their high resistance to supplement from the matrix (ACI committee544 , 2002).

Over recent years, steel fibers have been used extensively for floor slabs, shotcrete and prefabricated concrete products as the major reinforcing and also structural purposes in reinforcement of cage for tunnel segments, concrete cellars, foundation slabs and in prestressed elements (Ross, 2009).

The improved flexural toughness (such as the ability to absorb energy after cracking), impact resistance, and flexural fatigue endurance are the most significant properties of SFRC (ACI committee544 , 2002).

Steel fiber reinforced concrete (SFRC) comprise of hydraulic cements containing fine or fine and coarse aggregates and discontinuous discrete steel fibers. SFRC fails only after the steel fiber breaks or is pulled out of the cement matrix in terms of tension (ACI committee544 , 2002).

SFRC is a composite material whose properties can be associated to the fiber properties (volume percentage, strength, elastic modulus, and a fiber bonding parameter of the fibers), the concrete properties (strength and elastic modulus), and the properties of the interface between the fiber and the matrix.

Fiber strength, stiffness and the capability of the fibers to bond with the concrete are the significant characteristics of fiber reinforcement and the aspect ratio of the fiber is important factor for linking fibers with matrix. The aspect ratio range is between 20 to 100 and the length dimension range changes from 6.4 to 76 mm (ACI committee544 , 2002). Moreover, the curing procedure, matrix composition and fiber size, fiber content, fiber spacing and arrangement, fiber direction versus testing direction can influence mechanical properties of fiber-reinforced concrete (Toutanj & Bayasi, 1998)

Design procedures for SFRC should be followed as the strength design methodology described in ACI 544.4R. Furthermore, equipment currently used for conventional concrete construction does not need to be modified for mixing, placing, and finishing SFRC (ACI committee544 , 2002).

Moreover, additions of fibers will result in a loss of slump for identical concrete mixtures. This loss is increased as the aspect ratio of the fiber or the amount of fibers added increases. On the other hand, decrease of slump does not essentially denote that there is a corresponding loss of workability, especially when vibration is used during placement (ACI committee544 , 2002).

In steel fiber reinforced concrete, fibers tend to settle towards the bottom of the beam concerning movement and compaction. Also, relative location of testing direction as compared to casting (replacement and compaction) direction because of fiber settlement might be effective on properties of SFRC (See Figure 1.1).

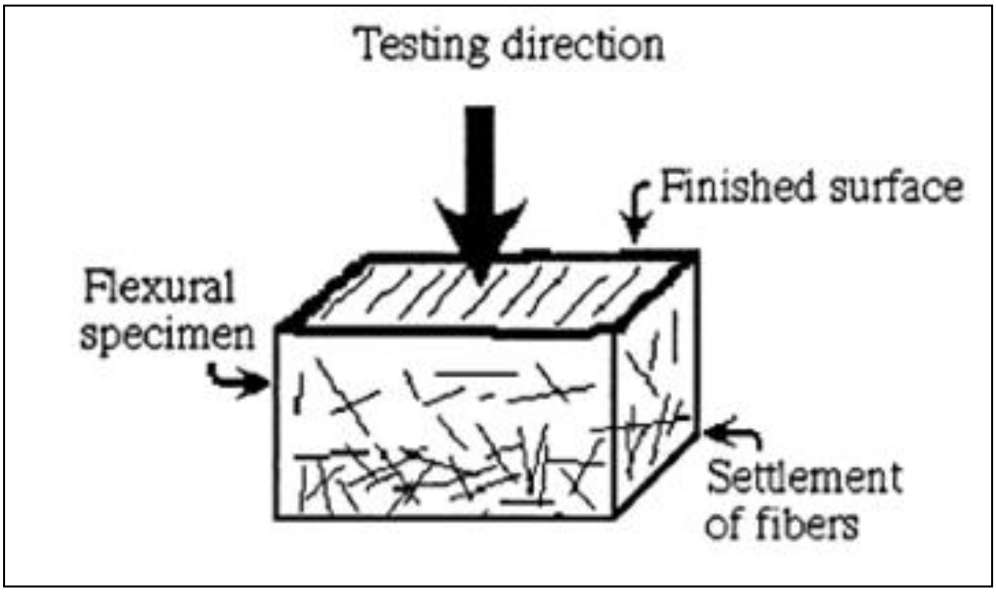

Figure 1.1: Free body diagram of fiber reinforced beam. (Toutanj & Bayasi, 1998)

Regarding the flowability of fibrous concrete mixture, fiber settlement may cause no homogeneous fiber dispersion in a way that more fibers can locate in the lower half of the beam. This attitude can improve the flexural behavior of steel fiber reinforced concrete in beams. (Toutanj & Bayasi, 1998)

Through the bending test, the post-peak behavior is associated to the fiber distribution in the cross section. However, the distribution of fibers can be uniform after the mixing process, the casting and compaction process with wall effects that can affect fiber orientation (Torrijos et al. , 2010).

Studies on steel fiber reinforced concrete carried out on the orientation of fiber which is a significant factor in steel fiber reinforced concrete. Also the compaction could be a significant factor in orientation of fiber; therefore vibration time also might be an effective factor. The aim of this study is to investigate about the effect of vibration time on mechanical properties of high strength steel fiber reinforced concrete.

1.2 Objectives and works done

The objective of this study is to investigate about the effect of different vibration times on high strength steel fiber reinforced concrete with different percentages of steel fiber. This study is based on experimental work and also analysis of results for four mixes with four different vibration times which were compared in terms of some mechanical properties.

Regarding to objective, experiments on sieve analysis, moisture content and trial mix designs were done. Related standards from BS-EN and ASTM were used and the samples of different mixes were casted and cured according to standards.

1.3 Works done and achievements

This study is based on experimental work, analyses of results obtained from experiments and conclusions. Below achievements were done:

1. Hardened density and compressive strength tests on cubic specimens, flexural strength test on beams and splitting tensile strength test on cylindrical samples were performed.

2. Relations between amount steel fibers and vibration times were obtained. Also, load-deformation behavior of beams was determined. The area under load deformation curves was determined for obtaining flexural toughness.

3. Considering four mixes with different volume fractions of steel fiber and also four different vibration times, results of experiments were compared among each other and discussed.

1.4 Thesis outline

In chapter 2 (literature review), the previous significant works on mechanical properties of steel fiber reinforced concrete with different subjects have been mentioned in brief.

Chapter 3 (experimental works) compromises inclusive details about materials, methods and the experiments in current study.

In chapter 4 (results and discussions) the results of experiments and related analysis were represented and discussed based on results of tests and previous achievements of researchers.

In chapter 5 (conclusions), based on discussions from results, conclusions of the study are listed.

Chapter 2

LITERATURE REVIEW

There have been many studies on steel fiber reinforced concrete about mechanical properties and durability. From 1972 till now many researches and experimental studies were done to determine the effects of different admixtures and conditions including curing, casting and testing with various accept ratios, fiber types and different volume fractions on the properties of fiber reinforced concrete.

The investigation done by Edgington and Hannant about the effect of fiber orientation by vibration concluded that SFRC is reinforced by fibers randomly in three dimensions. Due to the fact that fiber orientation during compaction can exhibit anisotropic behavior which could result in superior effect by arranging the compaction procedure so that the fibers are aligned in the most beneficial direction relative to the stress field. On the other hand, if the effects of vibration on fiber alignment are not fully respected, the strength of steel fiber reinforced concrete could be much lower than predictions based on laboratory tests using different compaction procedures (Edgington & Hannant, 1972).

Gao et al. did research about the mechanical properties of steel fiber-reinforced, high-strength, lightweight concrete (SFRHLC) with compressive and flexural strengths up to 85.4 MPa and 11.8 MPa, respectively. The study was carried out the amount of modulus of elasticity depending on fiber volume, and aspect ratio for SFRHLC was lower than the steel fiber-reinforced for normal concrete. Although, the increasing trend of compressive strength of SFRHLC was insignificant, splitting tensile and flexural strength improved significantly with increases of fiber volume and aspect ratio. This resulted in improvement in flexural fracture toughness due to the fact that the fiber pull-out and de-bond increased the fracture energy (Gao et al. , 1997).

The study about effects of curing and testing direction relative to casting direction on the mechanical properties of steel fiber reinforced concrete was done by Toutanji and Bayasi. Three different environmental conditions: steam, moisture, and air curing were utilized for curing the specimens. The results derived from experiments were showing that first-crack or ultimate flexural strength did not increase by steam curing, however compressive strength was increasing and flexural toughness was decreasing. On the other hand, air curing was showing a reduction in the first-crack and ultimate flexural strength significantly and also a reduction in flexural toughness slightly. The results indicate that in the steam curing there was a brittle bond between steel fibers and mortar and there was slight improvement in flexural behavior in the air curing. The specimens with a relatively high flowability (workability) were tested in the direction perpendicular to casting direction exhibited reductions in flexural first-crack strength, flexural ultimate strength, and flexural toughness in comparison to specimens tested in the direction parallel to casting direction. Specimens with relatively moderate and low flowability exhibited insignificant reductions in flexural first-crack and ultimate strength in the same conditions. However, flexural toughness of mixtures with moderate and low flowability reduced significantly (Toutanj & Bayasi, 1998).

A study of the effects of silica fume and steel fibers on some mechanical properties of high-strength fiber-reinforced concrete by Eren et al. demonstrated that increasing the amount of fibers leads to an increase impact resistance. This increase is not proportional to silica fume content. The addition of silica fume and steel fibers to plain concrete increases the surface abrasion resistance. The maximum increase in surface abrasion resistance was observed with the addition of 2% steel fibers by volume with an aspect ratio of 83 and 10% silica fume. Also, the addition of silica fume to plain concrete increases compressive strength. On the other hand, compressive strength slightly reduces by addition of fibers due to poor compaction. Fiber-reinforced concrete can be an alternative for use in pavement, overlays, grades, sidewalks, and other such applications where surface abrasion resistance is especially important. These tests showed that, for such applications, the use of 10% silica fume and 2% steel fibers with an aspect ratio of 83 will give the maximum resistance for surface abrasion (Eren et al. , 1999).

Redon et al. studied on several applications of automatic image analysis methods on concrete reinforced by ribbon shaped amorphous cast iron fibers and demonstrated that concrete incorporating fiber produce the formation of large entrapped air voids which resulted in increase of compressive strength of the plain concrete as compared to FRC one, due to loss of compactness that then partially recovered by the use of 0.4% superplasticizer. Considering use of superplasticizer, three dimension arrangements of fibers were isotropic transverse. By the 2D Fourier image transform, the horizontal orientation of the fibers was evidenced. And also, axial microcrack anisotropy was apparent in the same direction of the compression. Consequently, with regard to fiber and microcracking orientation, the mechanical behavior could be related to morphological features (Redon et al. , 1999).

Rapoport et al. did research about permeability of cracked steel fiber-reinforced concrete and showed that the permeability of cracked concrete is reduced by steel reinforcing macrofibers at larger crack widths. This study illustrated that the permeability of reinforced concrete is more than that of unreinforced concrete even incorporating 0.5% steel fibers by volume, and also the higher steel volume of 1% reduces the permeability by more than 0.5%. Maybe this is due to the influence of crack stitching and multiple cracking of steel fiber reinforcement (Rapoport et al. , 2001).

Another study on the effect of silica fume on the bond characteristics of steel fiber in matrix of reactive powder concrete, done by Chan and Chu verified that the addition of silica fume enhances the steel fiber–matrix bond characteristics due to the interfacial-toughening effect upon fiber slip. Based on this research the optimal value of silica fume–cement ratio was found to be in between 20% and 30% (Chan and Chu, 2004).

Another study on mechanical properties of steel fiber-reinforced concrete by Thomas and Ramaswamy demonstrated the maximum increase in the compressive strength, modulus of elasticity, and Poisson's ratio to be quite small (less than 10%) by incorporating steel fibers in various grades of concrete. The maximum increase in the tensile strength, namely, split tensile strength and modulus of rupture was obtained to be about 40% for various grades of SFRC. In different concrete grades with increasing fiber dosages, the post-cracking response was significantly enhanced. Also 30% improvement was observed in the strain related to the peak compressive strength which is another noteworthy advantage resulting from the use of fibers (Thomas and Ramaswamy, 2007).

Another research done by Mohammadi et al. on properties of steel fibrous concrete containing mixed fibers in fresh and hardened state showed that maximum increase in compressive strength of SFRC containing shorter fibers at fiber volume fraction of 2.0% is 25% over plain concrete. Also, 59% increase in split tensile strength of fibrous concrete was observed compared to plain concrete with a fiber mix ratio of 65% long fibers, 35% short fibers (2.0% volume fraction). Regarding to results, a maximum increase in static flexural strength and toughness were obtained for fibrous concrete with 100% long fibers (2.0% volume fraction) and the maximum increase in first crack load and first crack toughness were obtained in a concrete with short fibers (2.0% volume fraction). According to observations, a fiber combination of 65% long fiber + 35% short one can be added as a suitable combination for best mechanical properties (Mohammadi et al. , 2008).

Torrijos et al. evaluated the influence of the casting/placing procedure on the post-peak behavior of fiber reinforced self-compacting concrete, and its relationship with the type, distribution and orientation of fibers. Two types of steel fibers of different lengths (50 mm and 30 mm) and a structural type polymer fiber used for making three concrete mixes with three different methods of casting: filling the molds from the concrete, pouring concrete from one end of the mold, and filling the molds vertically. A result of this study showed a preferential orientation (mainly in horizontal planes) was found in FR-SCC incorporating steel and polymer fibers in conventional vibrated FRC. The fiber reinforcement was particularly less efficient when casting beams were vertical and tested horizontally, for all three mixes. Specimens incorporating the longer steel fibers and cast from one end of the mold illustrated a higher post-peak response than beams cast from the centre of the mould while the same result was not observed in specimens with shorter steel fibers or polymer fibers which could be explained by mesostructural characteristics of the concrete (type, distribution and orientation of fibers). In addition to the ratios between the dimensions of the mould and the length of the fibers, the significant differences were found in terms of fiber orientation between beams cast following the standard procedure in the case of mixes with long fibers. However this effect was not evident in the case of short fibers. Consequently, it appears that the mesostructural characteristics of FR-SCC and the comprehension of the fiber distribution/orientation can be taken as a useful tool to make more advantage out of fiber reinforcement, i.e. by defining convenient casting conditions (Torrijos et al. , 2010).

The effect of steel fibers on plastic shrinkage cracking and some other properties of normal and high strength concretes were investigated by Eren and Marar on two different compressive strength concrete levels namely 56 and 73 MPa. Concrete was casted by adding three different volumes of steel fibers having three different aspect ratios. The study showed that VeBe time and wet density of fresh concrete increased by accumulation of fibers. It was also observed a significant decline in water bleeding for high strength concrete compared to normal strength concrete for all mixes. The first crack initiation time for high strength plain concrete was observed to be two times higher than that of normal strength plain concrete. Moreover, the investigation carried out that fiber aspect ratio and fiber volume has no obvious effect on water evaporation rate and first crack initiation time (Eren & Marar, 2010).

Akcay and Tasdemir studied mechanical behavior and fiber dispersion of hybrid steel fiber reinforced self-compacting concrete. Based on tests consequences, it could be concluded that the addition of fibers resulted in an insignificant decrease on workability of SCC and the geometry of long fibers was the most important effective factor on flowability and workability in comparison to their strength. Although, addition of fibers led to a decline in rate of flowability, no noteworthy change in the final flowability was observed. Concerning the fracture energy test, the concretes with high strength long steel fibers exhibit improvement in toughness and ductility as compared to the concretes with normal strength steel fibers. Moreover, concretes with normal strength fibers have lower peak loads and steeper gradients of the softening branch than those with high strength fibers. The study demonstrated that the dispersion and alignment of fibers have effects on the mechanical properties of HSFRSCCs (Akcay and Tasdemir, 2011).

Park et al. investigated the effects of blending fibers on the tensile behavior of ultra high performance hybrid fiber reinforced concrete (UHP-HFRC). Four types of high strength steel macro-fibers, including long smooth (LS), two types of hooked (HA and HB) and twisted (T) fiber were used in the concrete mixes. In the study the combination of 1.0% macro-steel fiber and 0.0%, 0.5%, 1.0% and 1.5% micro steel fiber were used for casting UHP-HFRCs. Regarding the results, it was displayed that the shape of the tensile stress–strain curves of UHPHFRC was primarily reliant upon the type of macro-fiber rather than micro fiber, generally. The addition of micro fibers in hybrid systems resulted in an improvement on both the strain hardening and multiple cracking behavior of UHP-HFRC. As the amount of micro fibers increased, the tensile properties were drastically enhanced, while in the case of macro-fibers there was just a raise in the first cracking strength. In terms of tensile strain capacity and multiple cracking hardening behavior, concrete with T-fiber was the best performance. Concrete with HA-fiber showed superior improvement in elastic performance coefficient as compared the concrete with the fibers due to an increase of fiber content (Park et al. , 2011).

Sahin and Koksal performed a research on the effects of both steel fiber and matrix strengths on fracture energy of high strength concrete with three variables namely water/cement ratio, steel fiber strength and steel fiber volume fraction. Based on test results steel fiber volume and strength have no major effect on compressive strength and modulus of elasticity of concrete while splitting and flexural strengths improved significantly. It has been displayed that slighter descending branch of load‒deflection curves resulting in higher ductility and fracture energy of high-strength concrete produces by the higher fiber volume fraction. However, very considerable influences of matrix and fiber tensile strengths on the fracture energy and characteristic length should be noted. The softening part of load-deflection curve is important due to the bond strength between matrix and steel fiber which controls the behavior of fiber crossing the crack or both matrix and fiber strengths. Steel fibers may be broken into two parts or pulled-out from matrix and influence on the fracture toughness or energy absorption capacity of SFRCs. Considering the most possible fiber‒matrix interface which is very effective on preventing the complete fiber pull-out from matrix without rupture, increase the crack crossing of SFRCs. This relationship between fiber and matrix plays a significant role in improving ductility, first crack strength and flexural strength of SFRCs. Consequently concerning the test results they proved that matrix and fiber strengths are effective parameters for the mechanical properties and especially fracture energy. Therefore, water/cement ratio and fiber strength and volume as three important parameters in mix design must be taken (Sahin & Koksal, 2011).

Although there have been many studies in the case of steel fiber reinforced concrete in different subjects, there is not any research about the effect of vibration time on mechanical properties of concrete directly. Since the vibration time can be counted as an effective factor on orientation of steel fibers in matrix there, there should be investigated.

Chapter 3

EXPERIMENTAL WORK

3.1 Introduction

In this experimental study effect of different vibration times on mechanical properties of high strength steel fiber reinforced concrete (HSSFRC) is investigated. The concrete specimens were tested at four different vibration times namely, 1:00, 1:30, 2:00 and 2:30, with four different volume percentages of 0, 0.5, 1, 1.5 steel fibers with an aspect ratio of 80. The Ground Granulated Blastfurnace Slag cement, class of 42.5, crushed limestone aggregate from Beşparmak Mountains Cyprus (both fine and coarse), potable water and Glenium 27 superplastisizer were utilized for casting concrete specimens.

Three different types of samples were made for three different tests. Cubic samples of 150*150*150 mm were used for compressive strength, beams of 100*100*500 mm for flexural test and cylinder of 150*300 mm for splitting tensile test. The natural curing condition was accomplished for the samples and the tests were done at 7 days and 28 days.

3.2 Materials used

3.2.1 Cement

Ground Granulated Blast Furnace Slag (GGBS) cement, class of 42.5, was used for casting all the specimens. Chemical compositions and physical properties of the cement are shown in tables 3.1 and 3.2.

Table 3.1: Chemical compositions of GGBS cement

Chemical compositions (%)									Loss on ignition	Insoluble material
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Cl^-		
39.18	10.18	2.02	32.82	8.52	–	1.14	0.3	–	1	0.88

Table 3.2: Physical properties of GGBS cement

Physical properties of GGBS cement	Specific gravity (g/cm^3)	Fineness: specific surface (cm^2/g)	Fineness (retained on 90 µm sieve)	Fineness (retained on 45 µm sieve)
	2.87	4250	0	0.8

3.2.2 Aggregates

In this investigation, crushed limestone used as both coarse (two different sizes, 10 and 14 millimeters) and fine aggregates. Before casting and mixing, sieve analysis was done and also moisture conditions for all aggregates were determined as presented in Table 3.3 through 3.7.(and Figure 3.1)

Table 3.3: Sieve analysis- coarse aggregate (D14: 14 mm maximum size)

Sieve (mm)	Weight (kg)	% Retained	Cumulative % retained	Cumulative % Passing
28	0.00	0.00	0.00	100.00
20	0.05	1.26	1.26	98.74
14	0.30	7.57	8.83	91.17
10	2.39	60.15	68.98	31.02
6.3	1.17	29.51	98.49	1.51
5	0.04	0.88	99.37	0.63
3.35	0.03	0.63	100.00	0.00
pan	0.00	0.00	100.00	0.00
	3.97			

Table 3.4: Sieve analysis- coarse aggregate (D10: 10 mm maximum size)

Sieve (mm)	Weight (kg)	% Retained	Cumulative % retained	Cumulative % Passing
28	0.00	0.00	0.00	100.00
20	0.00	0.00	0.00	100.00
14	0.00	0.00	0.00	100.00
10	0.05	2.01	2.01	97.99
6.3	1.17	47.08	49.09	50.91
5	0.54	21.53	70.62	29.38
3.35	0.49	19.72	90.34	9.66
pan	0.24	9.66	100.00	0.00
	2.49			

Table 3.5: Sieve analysis- fine aggregates

Sieve (mm)	Weight (g)	% Retained	Cumulative % retained	Cumulative % Passing
4.75	0.00	0.00	0.00	100.00
2.36	140	14.00	14.00	86.00
1.19	310	30.50	44.50	55.50
0.59	220	21.50	66.00	34.00
0.297	130	12.50	78.50	21.50
0.149	90	8.50	87.00	13.00
pan	130	13.00	100.00	0.00
	1000			

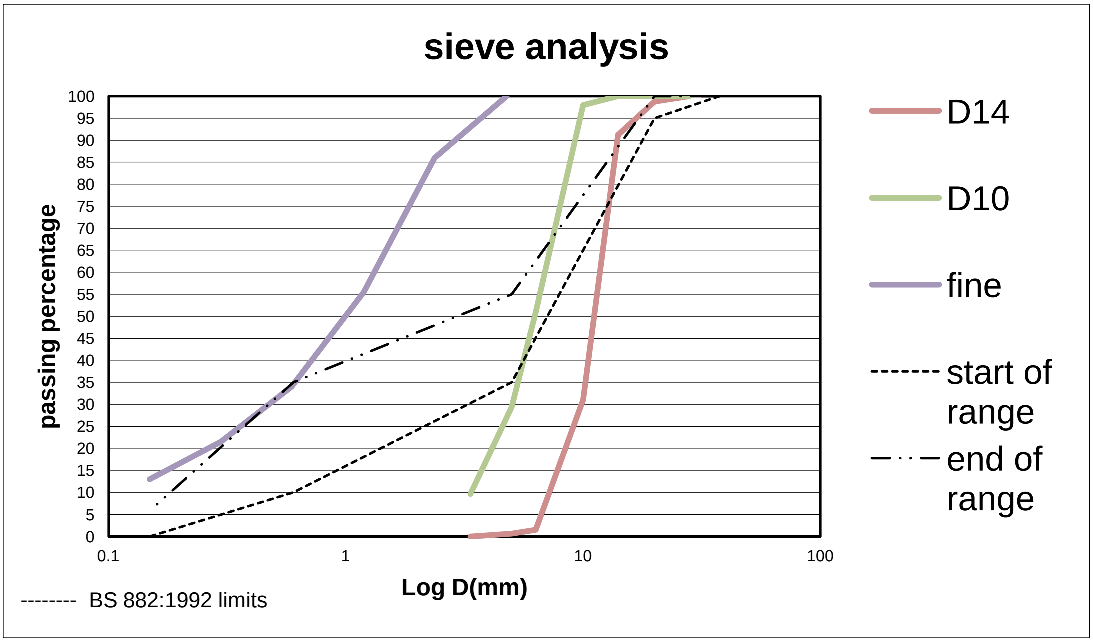

Figure 3.1: Grading curves of aggregates

Table 3.6: Water absorption of aggregates (SSD based)

Aggregates	Water absorption %
Fine	1.00
D10	1.60
D14	0.94

Table 3.7: Specific gravities of aggregates

aggregates	Bulk specific gravity		Apparent specific gravity
	Dry	SSD	
Fine	2.60	2.66	2.78
D10	2.51	2.54	2.60
D14	2.66	2.68	2.71

3.2.3 Water

Tap water was used as mixing water for casting all specimens (BS5328: Part 1, 2000).

3.2.4 Superplasticizer

Glenium 27, manufactured by BASF, as the superplasticizing admixture was used for all concrete specimens by 1.8% of cement weight. Glenium helps in producing concrete mixes with higher strength and more durability (GLENIUM).

3.2.5 Steel Fiber

In this study one type of hooked-end steel fiber with aspect ratio (l/d=length over diameter) 80 with different percentages (0, 0.5, 1, 1.5) was used in concrete. The length and diameter of fiber were 60 and 0.75 mm, respectively. Also the tensile strength of fibers was 1000 MPa (Dramix , 2011) (see Figure 3.2). (Dramix , 2011)

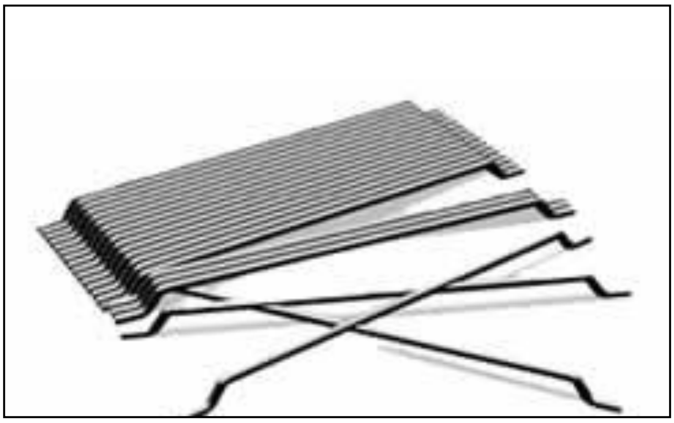

Figure 3.2: Hooked-end steel fiber(Dramix , 2011).

3.3 Methodology

Three different concrete mixes were designed according to BRE with different water cement ratios (Teychenné, 1997). Concrete samples were designed and casted based on the method of weight batching and after some trials, one of them was chosen because of satisfying compressive strength and workability. The proportions and details of concrete mixes are displayed in Table 3.8. It should be noted that four different concrete mixes were casted with four different volume fraction of steel fiber of 0%, 0.5%, 1% and 1.5% respectively.

Table 3.8: Mix design with w/c=0.35

Cement (kg/m^3)	Water (kg/m^3)	Fine aggregates (kg/m^3)	D10 (kg/m^3)	D14 (kg/m^3)	Glenium
485.7	170	628	530	636	1.8% by weight of cement
Steel fiber by percentage of concrete volume with 0, 0.5, 1, 1.5 % were added to A, B, C and D mixes, respectively.					

Test of workability was done for each concrete mix on fresh state.

Water curing condition at two testing ages (7 and 28 days) was considered for the test specimens.

3.3.1 Casting concrete

The casting process includes batching, weighing and mixing of materials, were done according to BS 1881: Part 125: 1986. For mixing process two type of mixers namely, pan and drum mixers were used. Pan mixer was used for concretes containing fibers. Impossibility for mixing and reaching a hemogenous matrix for concrete containing 1.5% steel fiber result in the usage of drum mixer.

Firstly, aggregates and cement were mixed for 30 seconds, then mixed water and Glenium was added to the blended materials and were mixed for approximately 3 minutes. In order to do Vebe test, sample was taken from fresh concrete, test was performed and then, the used concrete was poured back to the mixer for remixing and then concrete was poured into the moulds (BS 1881 : Part 125: 1986, 2009).

3.3.2 Compacting and curing

Vibration tables were used to compact the fresh concrete filled in the moulds (See Figure 3.2 and Figure 3.3).

In this study the filled concrete moulds were vibrated at four different vibration times (1, 1.5, 2 and 2.5 minutes) to investigate effect of vibration time on mechanical properties of HSSFRC.

Having casted and compacted concrete specimens, the samples were carried to curing room with a humidity over 90% and the temperature of 21°C. After 24 hours, the specimens were demoulded and put into the water tank until both of the two testing ages, 7 and 28 days.

Figure 3.3: Vibrating table I

Figure 3.4: Vibrating table Π

3.4 Tests on fresh concrete

3.4.1 Workability test

For evaluating workability of concrete, according to BS EN 12350-3:2009, Vebe test was accomplished on fresh concrete. Figure 3.4 displays the Vebe test apparatus.

Figure 3.5: VeBe test apparatus

3.5 Tests on hardened concrete

Four tests were performed on hardened concrete specimens, namely compressive strength, flexural strength, splitting tensile strength and density.

3.5.1 Compressive strength

Based on BS EN 12390-3:2009, the cubic samples of 150 mm were used for test of compressive strength at two ages namely 7 and 28 days with four different vibration times and four different amount of steel fiber.

Loading speed was adjusted to be 0.6 ± 0.2 MPa/s (BS EN 12390-3:2009, 2009). In this investigation, the loading speed was 0.4 MPa/s or sometimes 0.5 MPa/s, for all specimens during compressive strength test. The load was applied perpendicularly to the direction of casting (See Figures 3.5 and 3.6).

Figure 3.6: Compression test machine

Figure 3.7: Cubic sample under compression in the machine

3.5.2 Flexural strength

Determination of the flexural strength was done on beam specimens 150*150*550 mm according to BS EN 12390-5:2009. Prismatic specimens were subject to a bending moment by the application of load through upper rollers and the maximum load that specimens withstand was used to calculate flexural strength (See Figures 3.8 and 3.9).

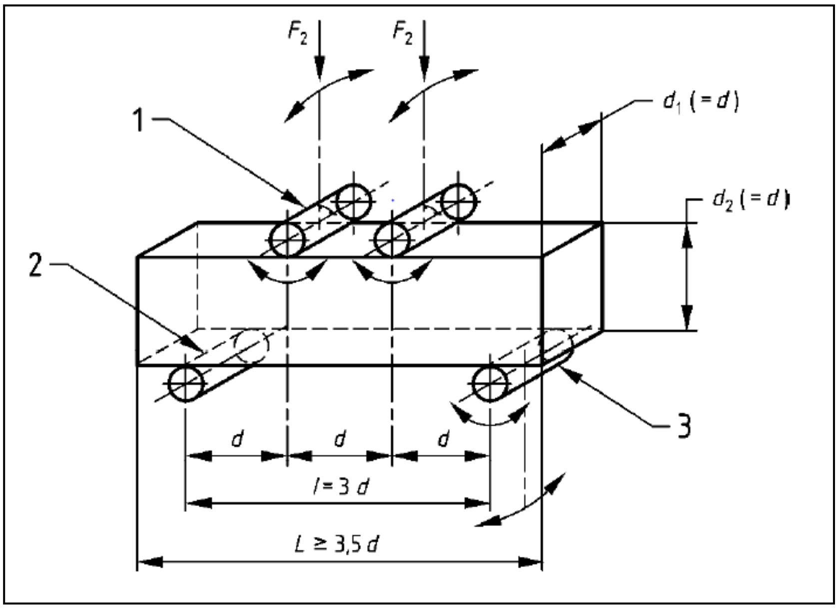

Figure 3.8: Arrangement of loading of test specimen (third-point loading) (BS EN 12390-5:2009)

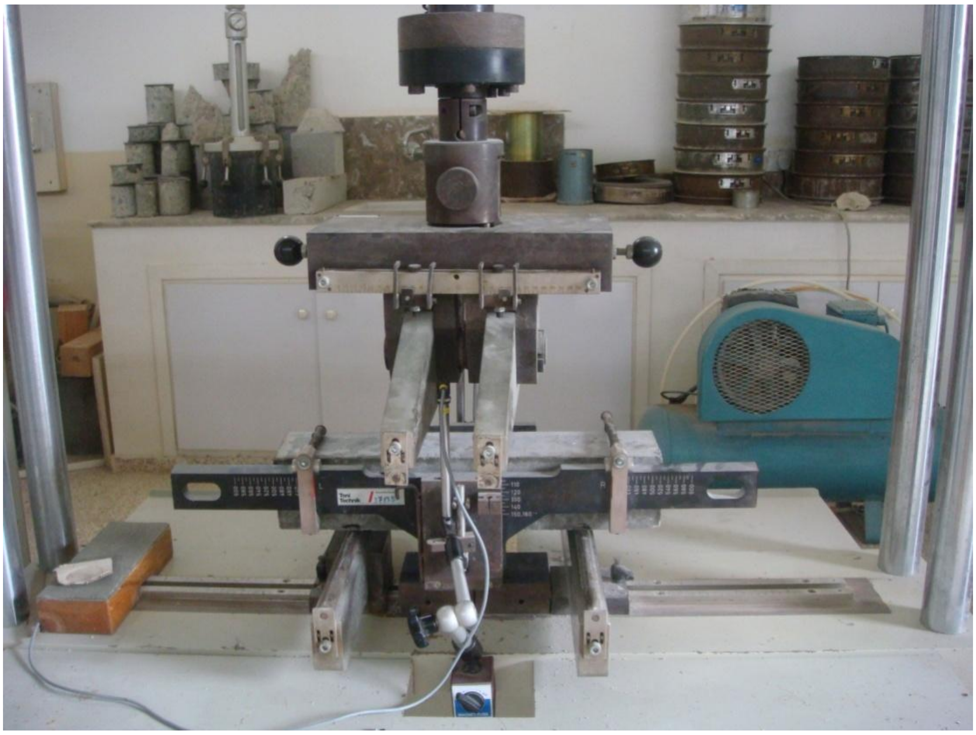
Figure 3.9: Beam specimen under flexural strength

The rate of loading should be between the ranges 0.04 MPa/s ($N/mm^2.s$) to 0.06 MPa/s ($N/mm^2.s$). In this study, for beam specimens, the speed of loading was fixed to be 0.05 MPa/s.

At the first stage, approximately 20% of the failure load was applied and then the load was applied without shock and increased constantly, at the selected speed of ± 10 %, until no superior load can be continued.

The flexural strength was calculated by equation (1):

$$f_{cf} = \frac{F \times I}{d_1 \times d_2^2} \tag{1}$$

Where,

f_{cf} is the flexural strength, in MPa (N/mm^2);

F is the maximum load, in N;

I is the distance between the supporting rollers, in mm;

d_1 and d_2 are the lateral dimensions of the specimen, in mm.

3.5.3 Splitting tensile strength test

Splitting test was performed according to BS EN 12390-6:2000, 2009**,** on cylinder specimens of 150*300 mm at the age of 28 days at four different vibration times and four various steel fiber percentages.

A compressive force applied to a narrow region along the cylindrical specimens' length. The resulting orthogonal tensile force makes the specimen to fail in tension (See figure 3.10).

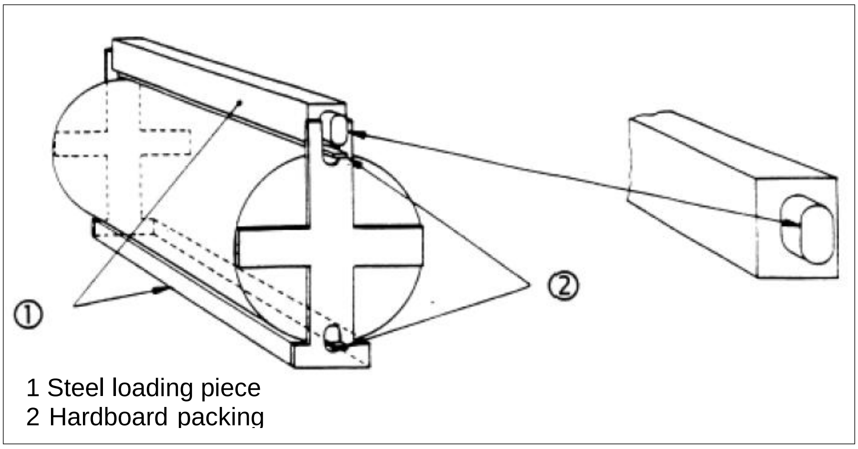

Figure 3.10: Testing cylindrical specimens under splitting tension (BS EN 12390-6:2000)

After removing specimens form water tank they were placed into the machine to be tested (See Figure 3.11)

Figure 3.11: Cylinder specimen under splitting tension

3.5.4 Determination of concrete density

For determination of concrete density according to BS EN 12390-7, 2009, the cubic specimens of size 150 mm were weighted to calculate density.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The results of all the experiments will be shown in this chapter as figures and tables. Discussions will be done for each experimental result as well.

Results derived from experiments including the VeBe test on fresh concrete, and hardened density, compressive strength, flexural strength and splitting tensile strength on hardened concrete were displayed.

4.2 Tests on fresh concrete

4.2.1 VeBe test

For each type of concrete with four different percentage of steel fiber, Vebe test was done and results are displayed in table 4.1.

Table 4.1: VeBe test results

Mix	VeBe (s)
Control mix	0
SFRC0.5%	8
SFRC1%	12
SFRC1.5%	14

Regarding the results, it was observed, in spite of low water to cement ratio (w/c=0.35) the control mix acts as a kind of self compacting concrete with VeBe time of zero due to usage of Glenium (1.8% of cement weight). Furthermore, with increasing the amount of steel fiber from 0.5% to 1.5%, the VeBe time is increasing from 8 seconds to 14 seconds. From the results it can be said that workability reduces by increasing amount of steel fibers. However the same amount of superplastisizer was utilized in SFRC with 1.5% fiber, the workability decreased considerably because of increases fiber volume fraction and thereby increases the interfacial surface between the particles which causes more friction to result in less workability.

4.3 Tests on hardened concrete

4.3.1 Hardened density

Hardened concrete density test was performed according to BS EN 12390-7, 2009 for all concrete mixes on cubic samples (150 mm) and the results are illustrated in tables 4.2, 4.3, 4.4..

Table 4.2: Hardened density test results at 7 days

Age (days)	Mix Design	Vibration Time (min)	Average Density (kg/m³)	Change based on control mix (%)	Change between vibration times (%)
7	Control mix	1.00	2472	—	—
		1.50	2424	-1.94	-1.94
		2.00	2468	-0.16	1.81
		2.50	2445	-1.10	-0.94
	SFRC0.5%	1.00	2513	1.64	2.77
		1.50	2471	-0.06	-1.67
		2.00	2442	-1.20	-1.14
		2.50	2453	-0.76	0.45
	SFRC1%	1.00	2545	2.96	3.74
		1.50	2550	3.14	0.17
		2.00	2550	3.16	0.02
		2.50	2525	2.14	-0.99
	SFRC1.5%	1.00	2532	2.44	0.29
		1.50	2514	1.68	-0.74
		2.00	2511	1.56	-0.12
		2.50	2521	1.98	0.41

Table 4.3: Hardened density test results at 28 days

Age (days)	Mix Design	Vibration Time (min)	Average Density (kg/m³)	Change based on control mix (%)	Change between vibration times (%)
28	Control mix	1.00	2366	—	—
		1.50	2413	1.96	1.96
		2.00	2436	2.96	0.98
		2.50	2440	3.11	0.15
	SFRC0.5%	1.00	2512	6.16	2.95
		1.50	2501	5.68	-0.45
		2.00	2507	5.93	0.24
		2.50	2490	5.22	-0.67
	SFRC1%	1.00	2518	6.41	1.13
		1.50	2475	4.59	-1.71
		2.00	2497	5.53	0.90
		2.50	2471	4.40	-1.07
	SFRC1.5%	1.00	2545	7.55	3.02
		1.50	2556	8.01	0.43
		2.00	2482	4.88	-2.90
		2.50	2553	7.87	2.85

Table 4.4: The average of hardened density

Mix	Average density (kg/m³)	Change (%)
control mix	2433	—
SFRC0.5%	2486	2.17
SFRC1%	2516	1.22
SFRC01.5%	2527	0.41

The changing that was observed in hardened density of same mix at different vibration times are not significant and the amount of changes are less than 2%. However fluctuations observed in change trend can be related to pouring concrete out of moulds. Furthermore, hardened density from one mix to another mix (with increasing the amount of steel fiber) increased up to 8%. The higher density of steel compared to concrete could be a significant factor in increasing hardened density of SFRC by increasing volume fraction of steel fiber.

4.3.2 Compressive strength

Compressive strength test was performed on cubic samples for all of the four concrete mixes at the ages of 7 and 28 days. The results for control mix at both ages are presented in Table 4.5.

Table 4.5: Compressive strength results of control mix with varying vibration times and ages

Age (days) \ Vibration Time (min)	1.00	1.50	2.00	2.50
7	73.80	72.70	78.40	72.20
	74.20	70.10	80.50	75.60
	78.10	75.20	73.60	82.70
28	73.30	84.30	82.50	97.10
	86.20	88.00	85.20	99.90
	85.60	88.60	78.00	87.40

The curves presented in Figure 4.1 and Figure 4.2 illustrate the behavior of control mix at 7 and 28 days. As it is observed in both figures, compressive strength increases by 2% by increasing vibration time at the age of 7days, and by 16% at the age of 28 days. The big difference between ages can be attributed to concrete bond strength at the age of 7 days. The cement mortar is the controlling factor of compressive strength, at earlier age which decreases the deviation in results of specimens. On the other hand, at the age of 28 days, stronger concrete bond due to completed hydration reactions which makes the results be more deviated.

However control mix is a kind of self compacting concrete and there is no need to vibrate, the compressive strength of samples increases with increases in vibration time and the reason could be due to higher amount of removed air bubbles from matrix leading to a better bond between mortar and aggregate.

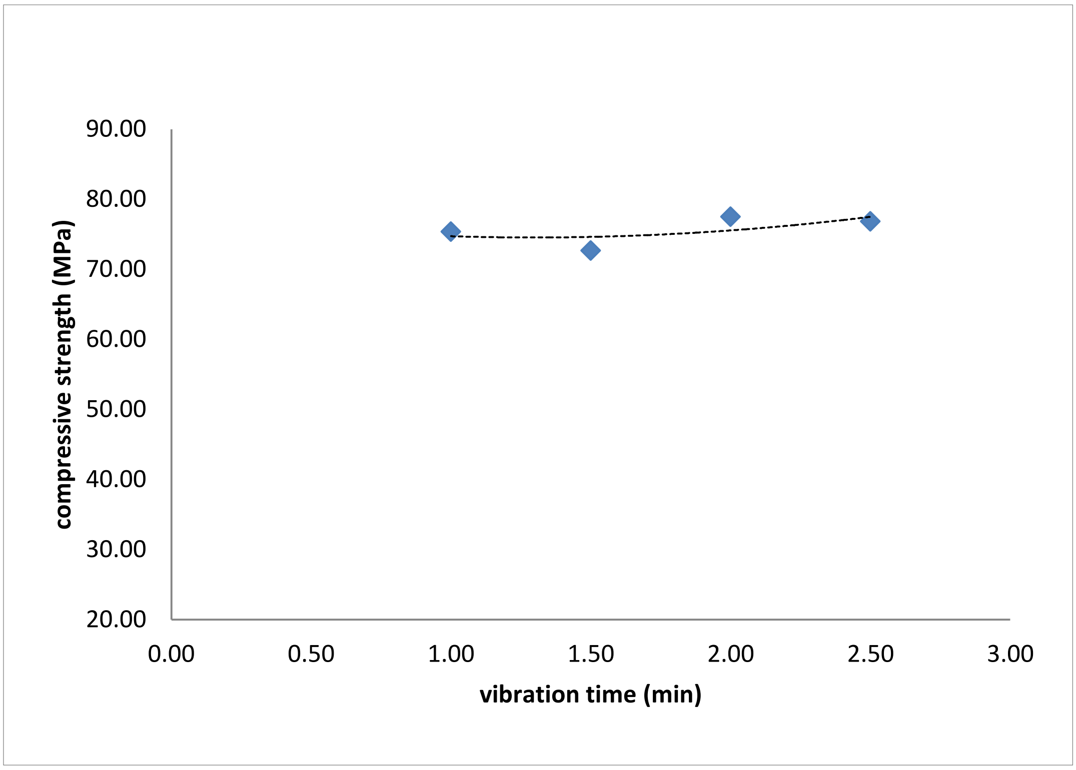

Figure 4.1: Compressive strength of control mix at four different vibration times at the age of 7days

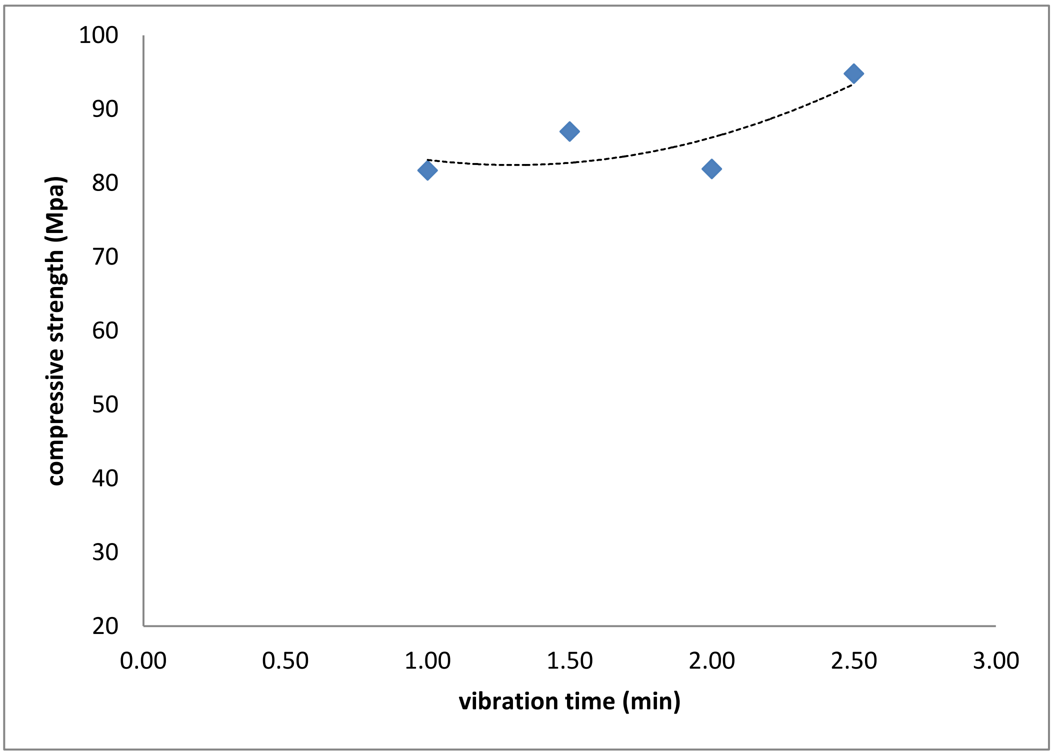

Figure 4.2: Compressive strength of control mix at four different vibration times at the age of 28days

It should be noted that the low water to cement ratio and also high amount of Glenium in the matrix (1.8% by weight of cement) have not permitted segregation to occur at high level of vibration even until 2.5 minutes. So, the compressive strength is increasing with higher vibration time due to stronger bond between mortar and aggregates.

For concrete incorporating 0.5% steel fiber, outcomes of test are shown in Table 4.6.

Table 4.6: Compressive strength of SFRC0.5%

Age (days) \ Vibration time (min)	1.00	1.50	2.00	2.50
7	84.60	75.30	76.00	83.60
	81.50	85.00	81.00	83.00
	78.50	84.30	77.90	83.60
28	101.30	96.50	97.50	96.30
	88.70	100.50	95.30	93.90
	102.70	100.60	99.00	99.70

Moreover, Figure 4.3 and Figure 4.4 display behavior of SFRC0.5% at age 7 and 28 days for different vibration times. The trend of curves is different in a way that at the age of 7 days there is an improvement in compressive strength (by 2%) by increasing vibration time although there is a low compressive strength at 2 minutes vibration time. In contrast, a very slightly inclining is observed in compressive strength (less than 1%) with increasing vibration time at the age of 28 days. The reason for increasing compressive strength by increasing vibration time is due to more removal of entrapped air bubbles form concrete samples which gives out stronger bond in matrix between aggregate, mortar and steel fibers. The reason for decreasing compressive strength at 28 days might be related to fully hydrated reaction in long term ages. In other words, at the age of 28 days concrete is strong enough to carry loads and the effect of steel fiber is insignificant compared to strength at the age of 7 days because of incomplete hydration. Due to incomplete hydration reactions, steel fibers carry the applied load.

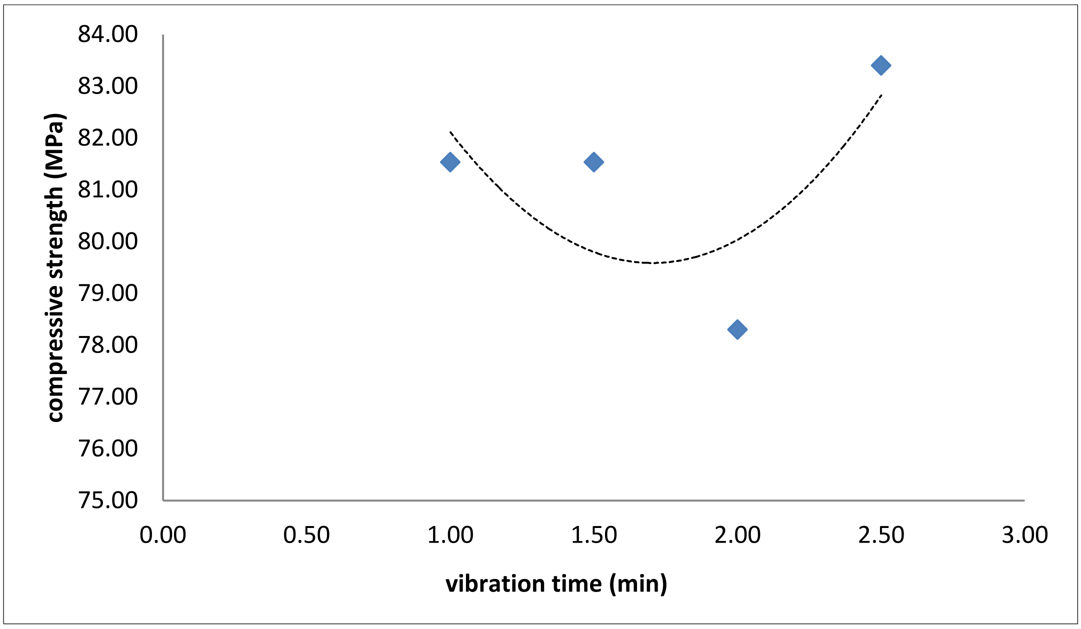

Figure 4.3: Compressive strength of SFRC0.5% at four different vibration times at the age of 7days

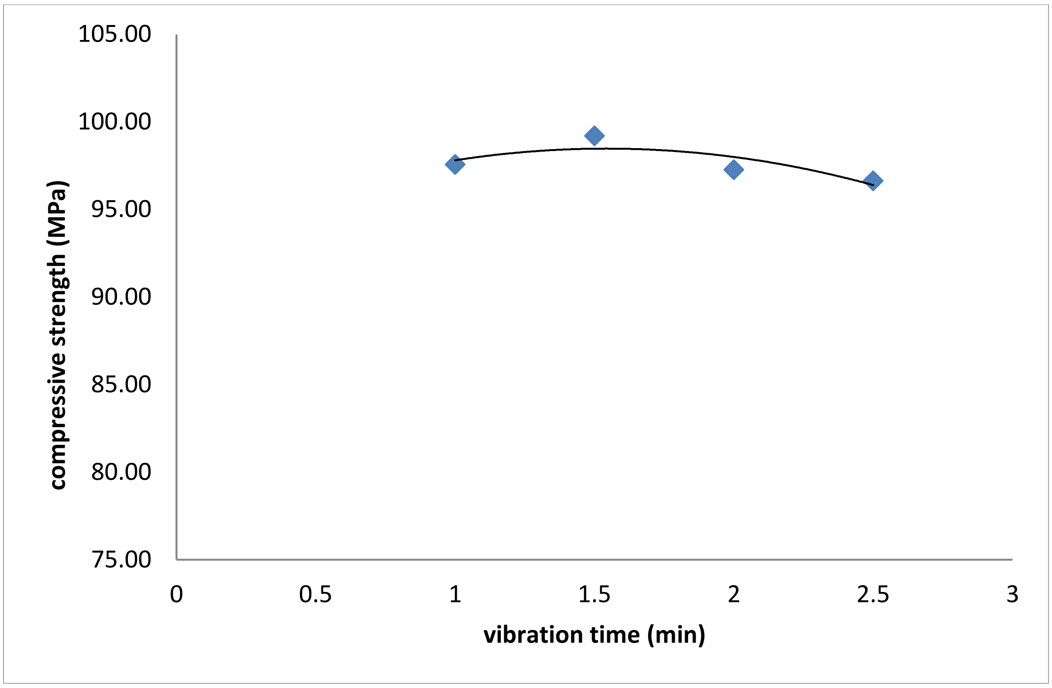

Figure 4.4: Compressive strength of SFRC0.5% at four different vibration times at the age of 28 days

Table 4.7: Compressive strength of SFRC1%

Age (days) \ Vibration time (min)	1.00	1.50	2.00	2.50
7	85.40	85.90	88.60	86.20
	86.70	87.50	84.30	90.80
	82.50	84.40	85.80	89.00
28	92.90	94.40	91.50	89.00
	95.50	95.60	101.50	89.80
	98.90	92.90	88.10	84.10

Based on results shown in Table 4.7, Figure 4.5 and Figure 4.6, it could be concluded that the compressive strength of SFRC1% is improved (by 4%) with increasing vibration time at the age of 7days while the same mix at 28 days acts inversely and the trend is downward (decrease by 8%). This can be also attributed to the mentioned reason for SFRC0.5%.

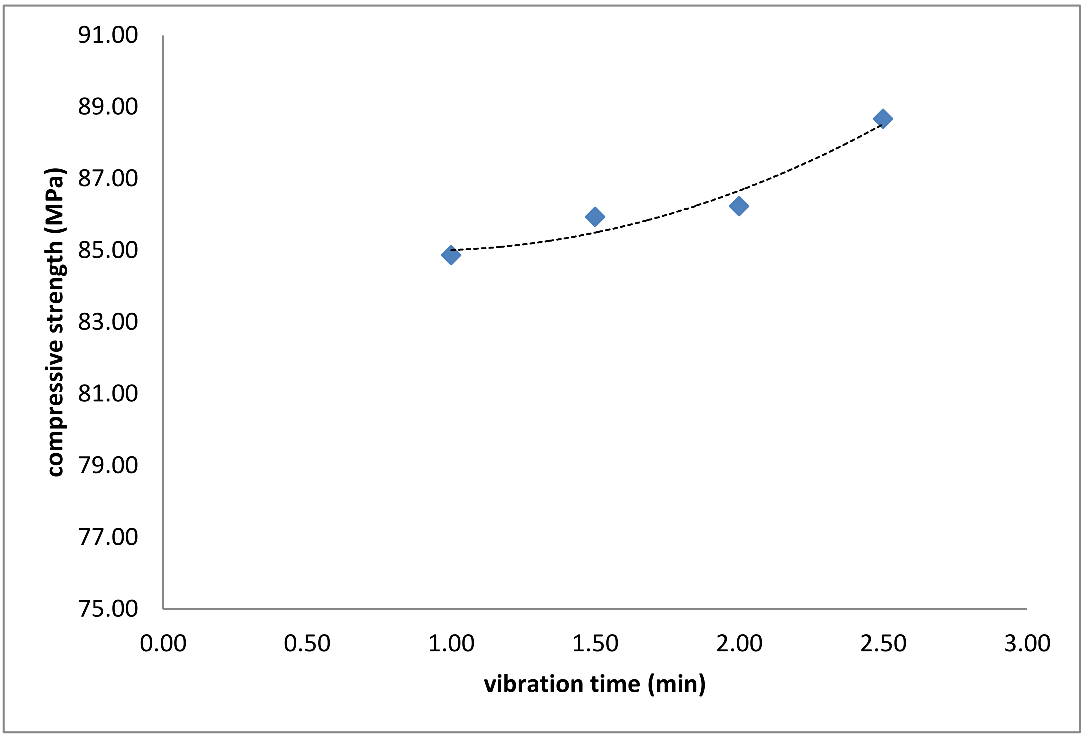

Figure 4.5: Compressive strength of SFRC1% at four different vibration times at the age of 7 days

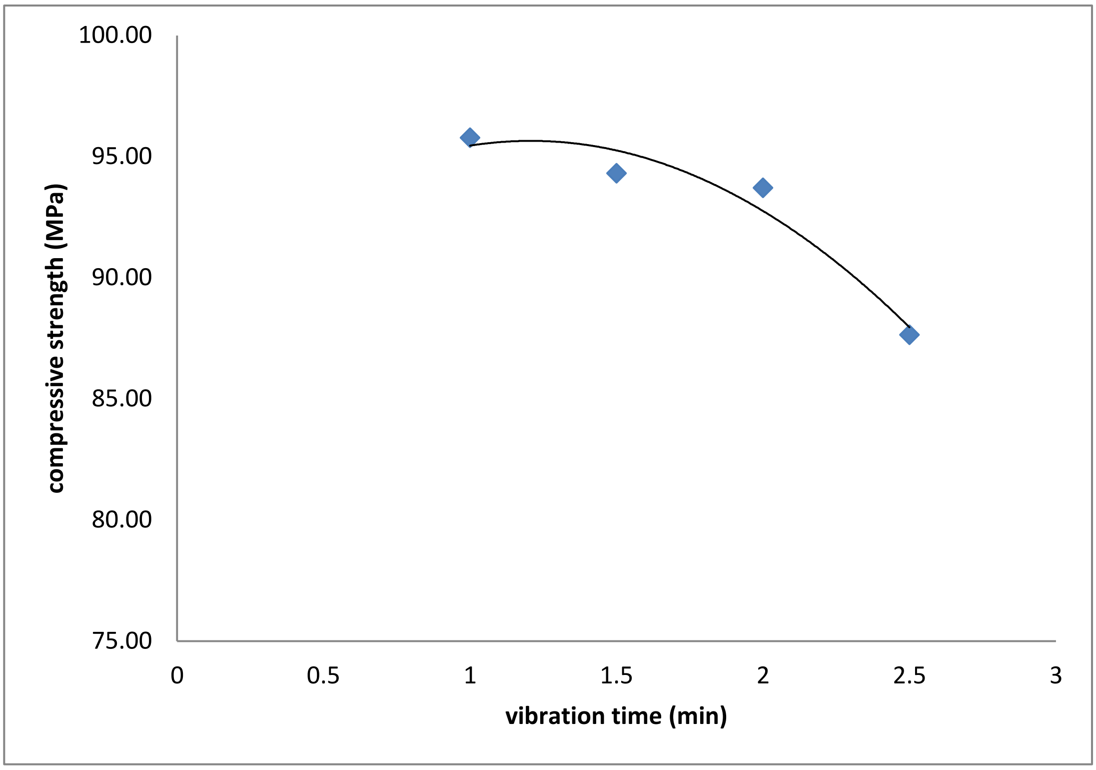

Figure 4.6: Compressive strength of SFRC1% at four different vibration times at the age of 28 days

The compression test was performed on concrete mix with 1.5% steel fiber and the results are shown in Table 4.8.

Table 4.8: Compressive strength results of SFRC1.5%

Vibration time (min) / Age (days)	1.00	1.50	2.00	2.50
7	61.30	68.60	60.40	64.80
	45.60	71.20	62.30	66.60
	63.00	72.90	68.30	64.70
28	96.60	71.80	94.60	89.40
	89.00	95.00	85.40	69.20
	90.90	83.40	108.00	108.00

The graphs of compressive strength versus vibration time of SFRC1.5%, for both 7 and 28 days, are presented in Figure 4.7 and Figure 4.8. As it is obvious form the curves, the compressive strength is increasing by 15% at 7 days age and decreasing very slightly by 3% at 28 days age with increasing vibration time from 1 minute to 2.5 minutes. This behavior is due to removal of entrapped air bubbles from matrix and also completion of hydration reaction in the long term ages (28 days).

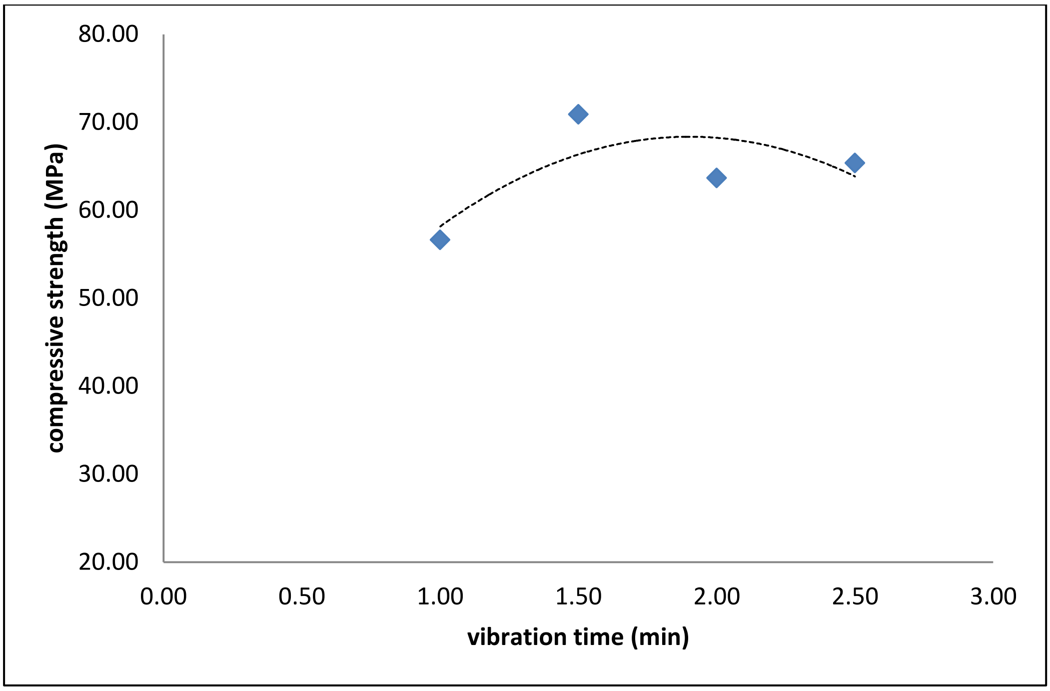

Figure 4.7: Compressive strength of SFRC1.5% at four different vibration times at the age of 7 days

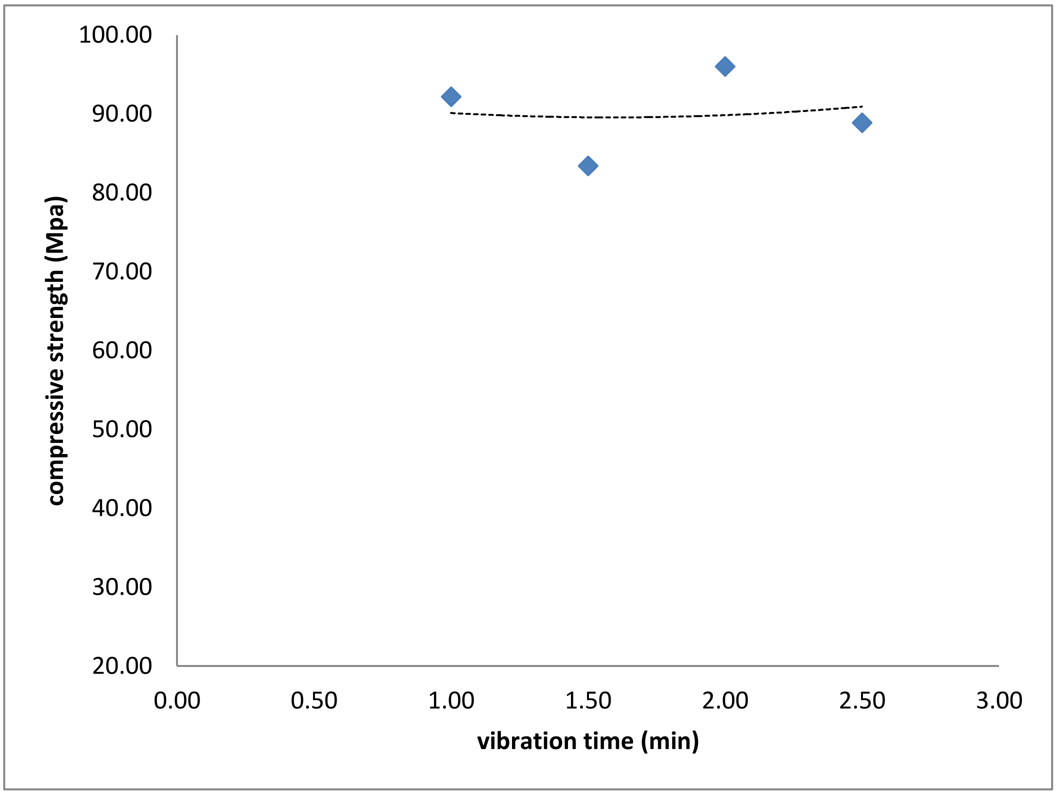

Figure 4.8: Compressive strength of SFRC1.5% at four differenet vibration times at the age of 28 days

Compressive strength behavior of all mixes is shown together in same graph for two different ages (7 and 28 days) in Figures 4.9 and 4.10.

At the age of 7 days, based on presented curves, it could be demonstrated that mix with 1% steel fiber has highest compressive strength (88MPa). SFRC0.5%, control mix and SFRC1.5% have less strength such as 83MPa, 76MPa and 70MPa, respectively.

There is also same trend of improvement in compressive strength by increasing vibration time except for SFRC1.5% at 2 minutes vibration time.

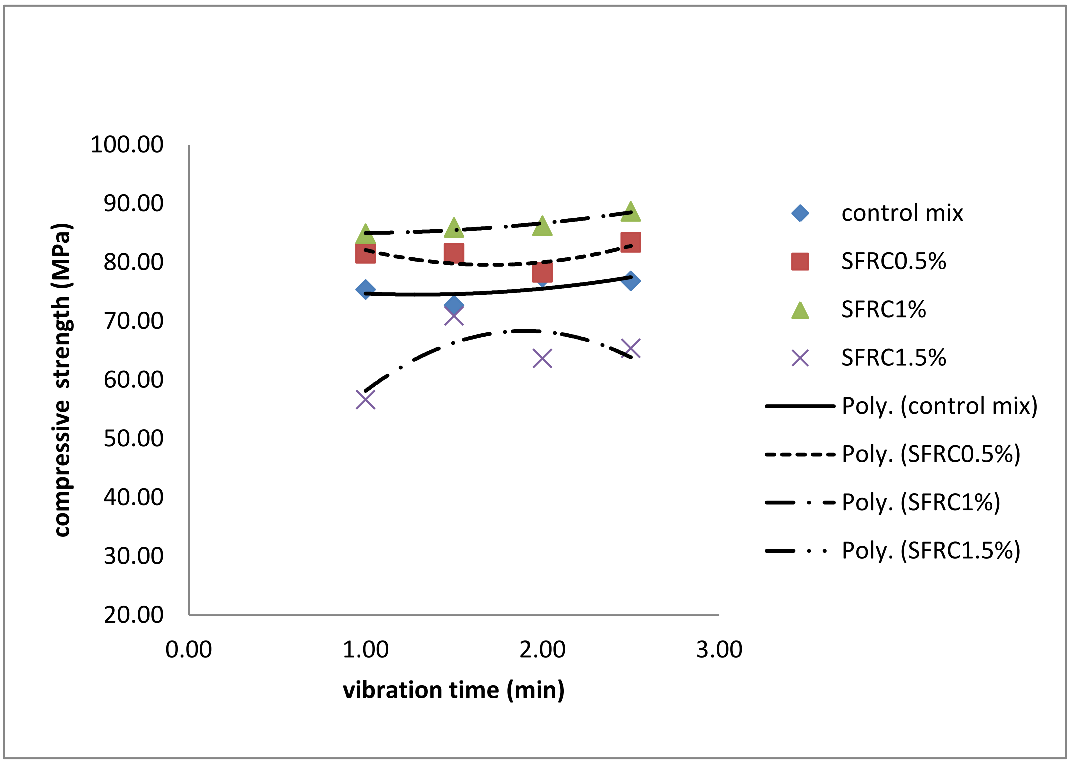

Figure 4.9: Compressive strength of four mixes at four different vibration times at the age of 7 days

Figure 4.10 shows decreases in compressive strength by increasing vibration time for all mixes including steel fibers due to over vibration leading to the loss of uniformity of matrix which the steel fibers tend to go to bottom on samples. Furthermore, highest compressive strength was obtained for SFRC0.5% at 28 days (99MPa).

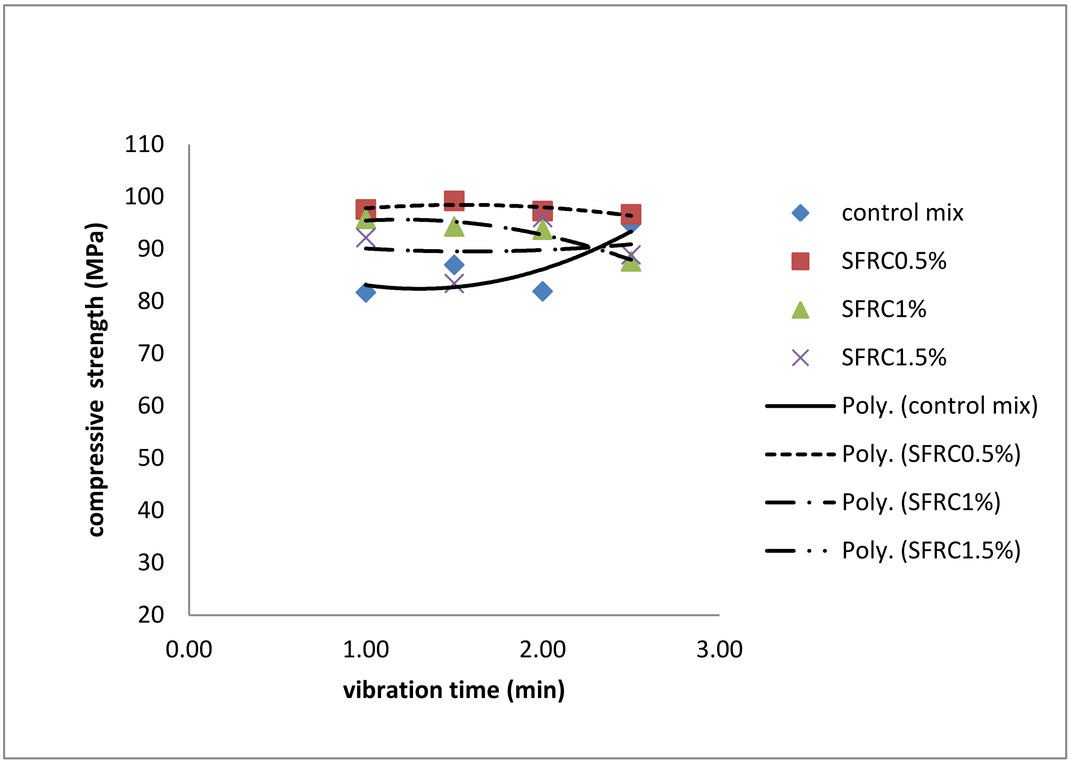

Figure 4.10: Compressive strength of four mixes at four different vibration times at the age of 28 days

4.3.3 Flexural strength

According to BS EN 12390-5:2009, the flexural strength test was done for all beam samples and the flexural strength was calculated by using equation (1) given below:

(1)

Where,

f_{cf} is the flexural strength, in MPa (N/mm²);

F is the maximum load, in N derived from test;

l is the distance between the supporting rollers, in mm (300)

d_1 and d_2 are the lateral dimensions of the specimen in mm, $(d_1 = d_2 = 100)$

The calculated flexural strengths of specimens at the age of 28 days at four different vibration times are presented in Table 4.9.

Table 4.9: Flexural strength results of mixes

Mix \ Vibration time (min)	1.00	1.50	2.00	2.50
Control mix	7.27	7.67	7.73	8.43
SFRC0.5%	8.18	8.91	8.24	8.72
SFRC1%	9.35	10.07	8.06	9.74
SFRC1.5%	8.18	8.84	8.59	7.95

Changes of flexural behavior by vibration time at 28 days are shown in Figure 4.11 to Figure 4.14. There is an improvement (by 16%) in flexural strength by increasing vibration time (See Figure 4.11) for control mix. The same trend is observed for SFRC0.5% by 6.5%, SFRC1% by 4% increase, while flexural strength of SFRC1.5% decreases by 2.8%. The reason could be related to removal of entrapped air bubbles form matrix by increasing the vibration time. Nevertheless, flexural strength of SFRC1.5% is reduced due to damaged uniformity due to high vibration time.

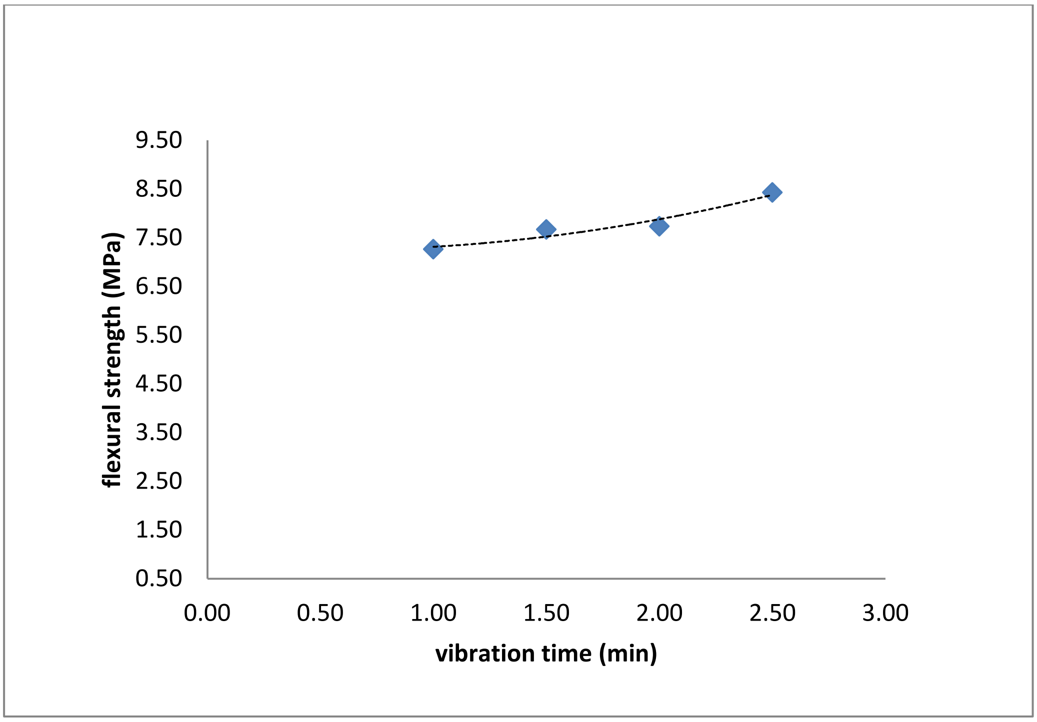

Figure 4.11: Flexural strength of control mix at four different vibration times at the age of 28 days

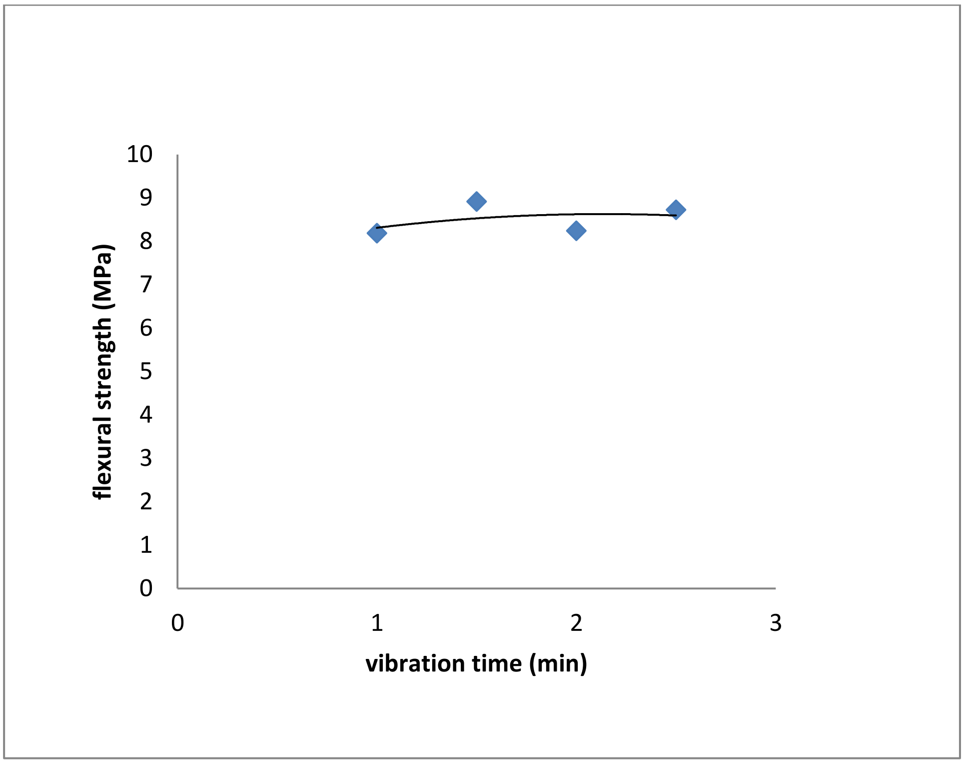

Figure 4.12: Flexural strength of SFRC0.5% at four different vibration times at the age of 28 days

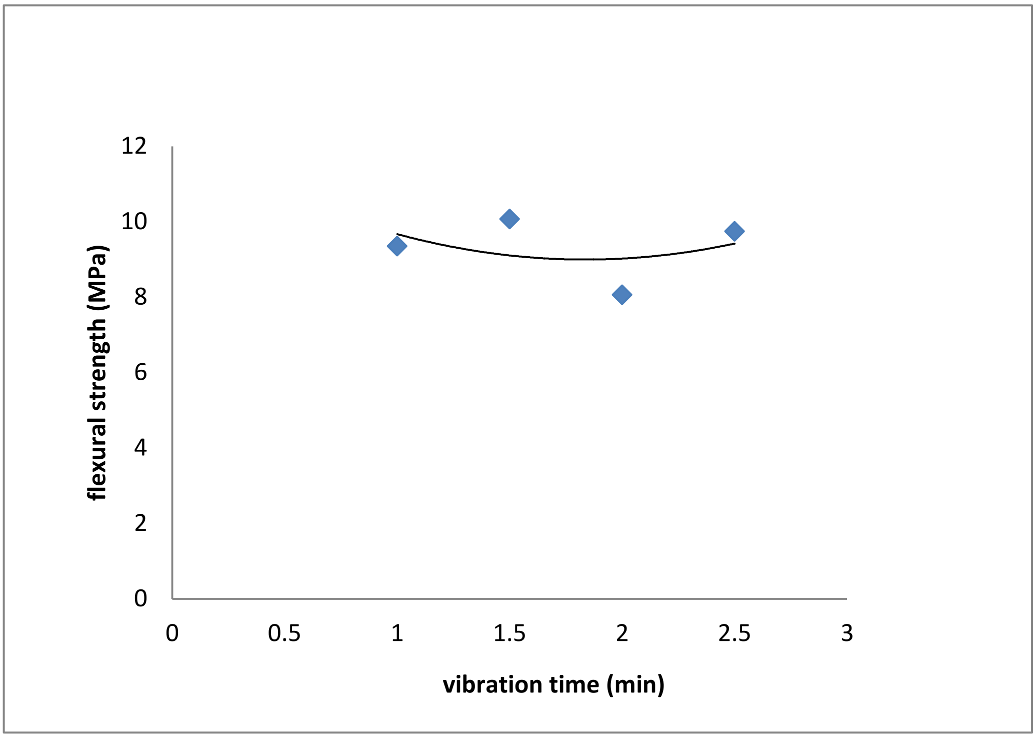

Figure 4.13: Flexural strength of SFRC1% at four different vibration times at the age of 28 days

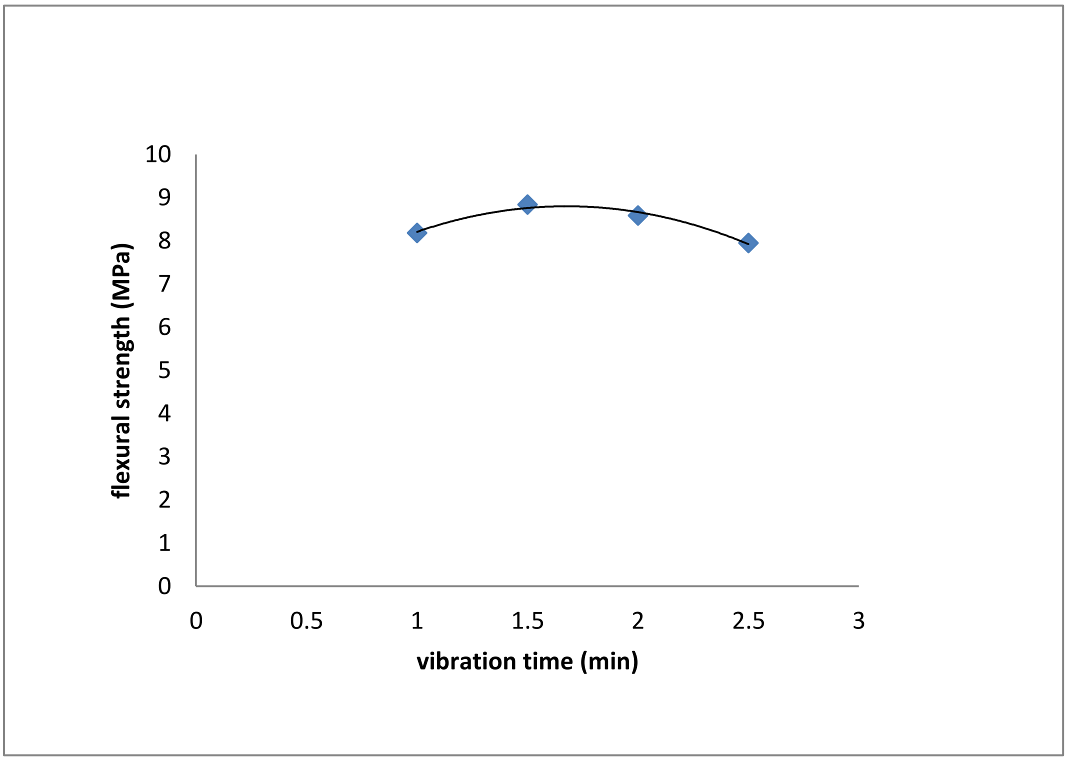

Figure 4.14: Flexural strength of SFRC1.5% at four different vibration times at the age of 28 days

All the flexural strength results at 28 days are put together in a graph to be compared with each other (See Figure 4.15).

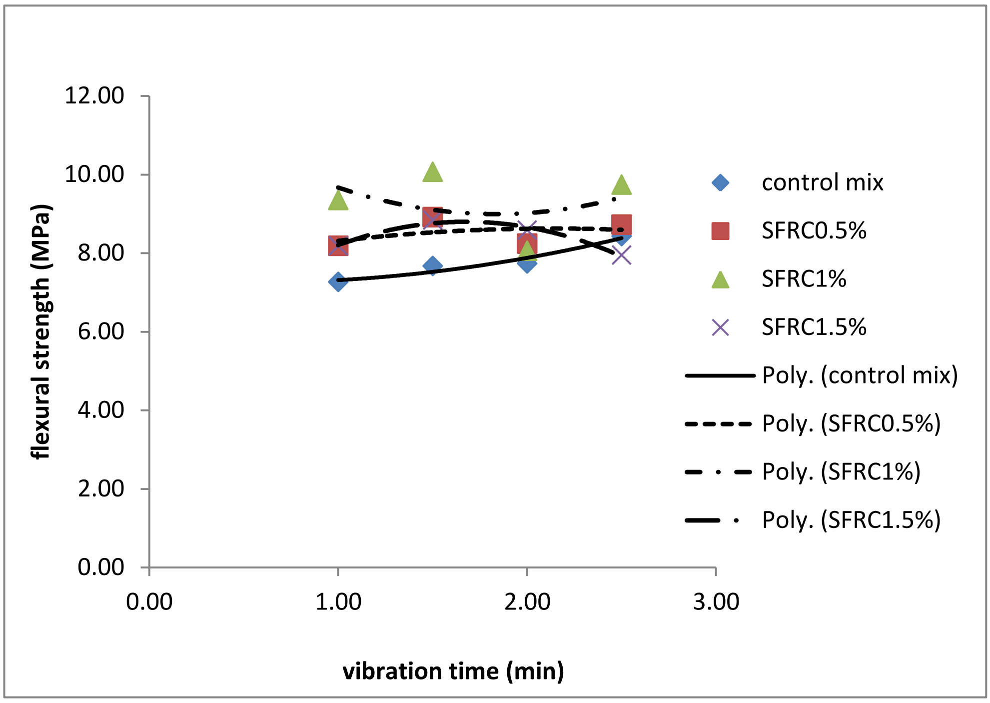

Figure 4.15: Flexural strength of four mixes at four differenet vibration times at the age of 28 days

It is observed that the highest flexural strength was obtained for concrete incorporating 1% steel fibers. Considering the trend of increasing flexural strength for control mix, SFRC0.5% and SFRC1% and the different trend for SFRC1.5 %(reduction in flexural strength), it should be mentioned that the reason for the attitude could be related to usage of different mixer (drum mixer) for SFRC1.5 % which results in less uniformity in mix with 1.5% steel fiber. This is due to difficulties faced with the usage of pan mixer for high amount of fibers.

Load-deformation behaviors of concretes containing steel fibers are also presented in figures 4.16 to 4.20.

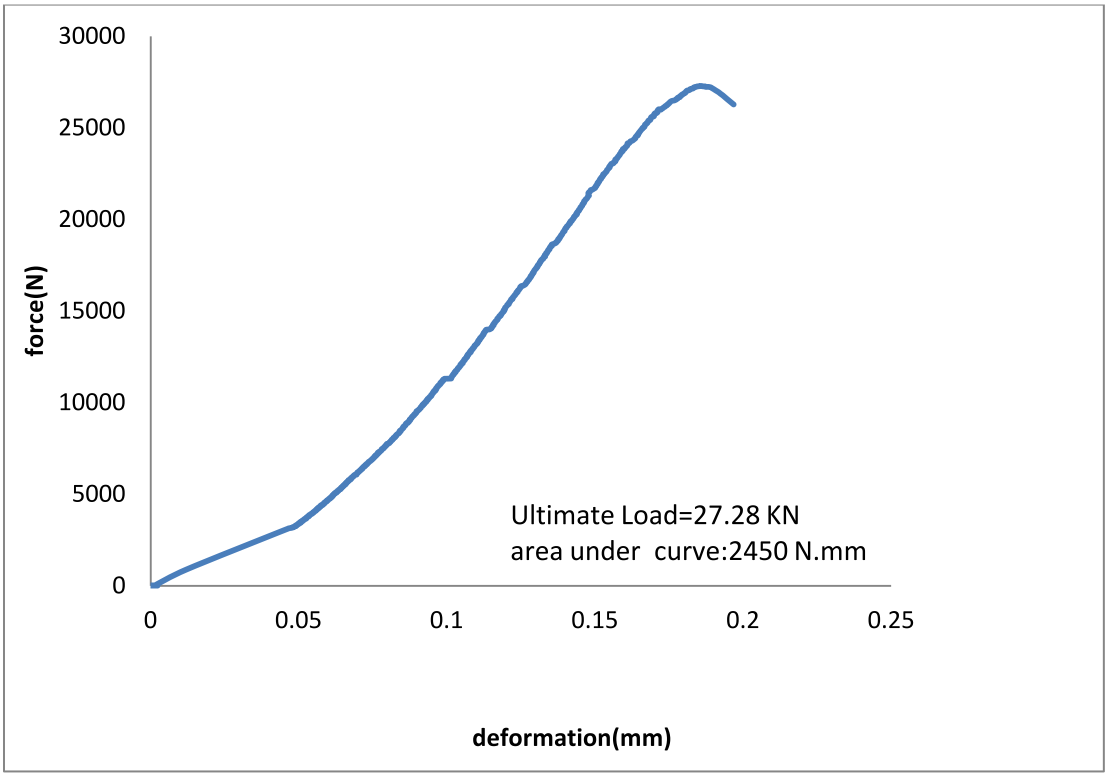

Figure 4.16: Load-deformation behavior for SFRC0.5%, 1 minute vibration time, at the age of 28 days

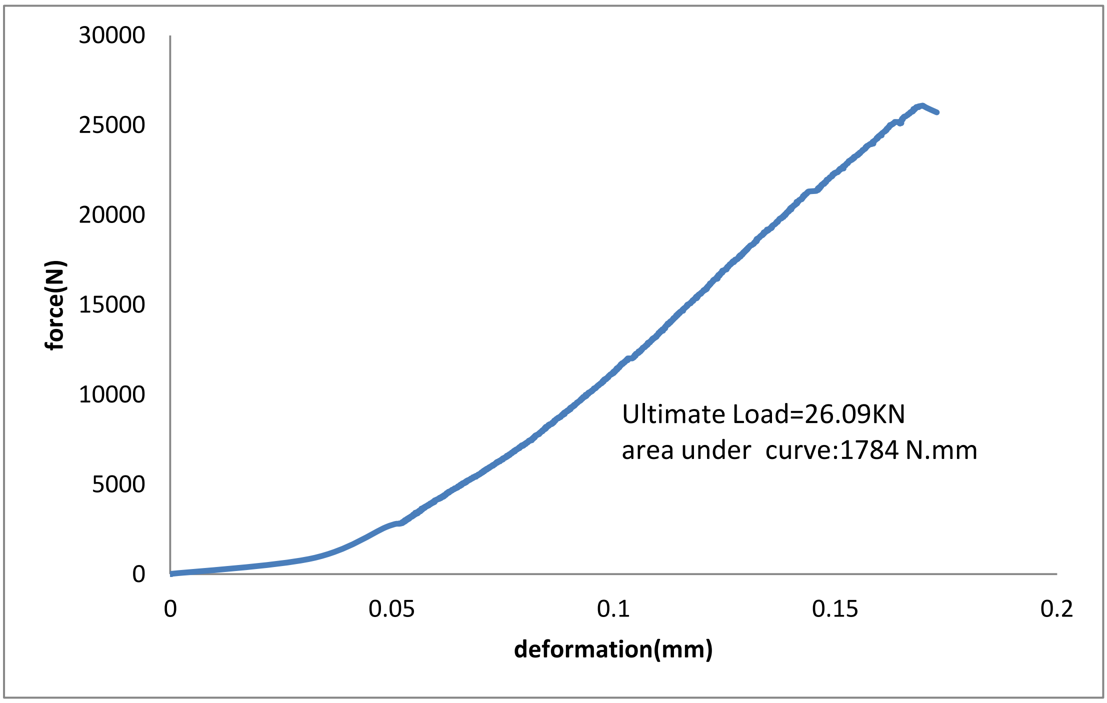

Figure 4.17: Load-deformation behavior for SFRC0.5%, 1.5 minutes vibration time, at the age of 28 days

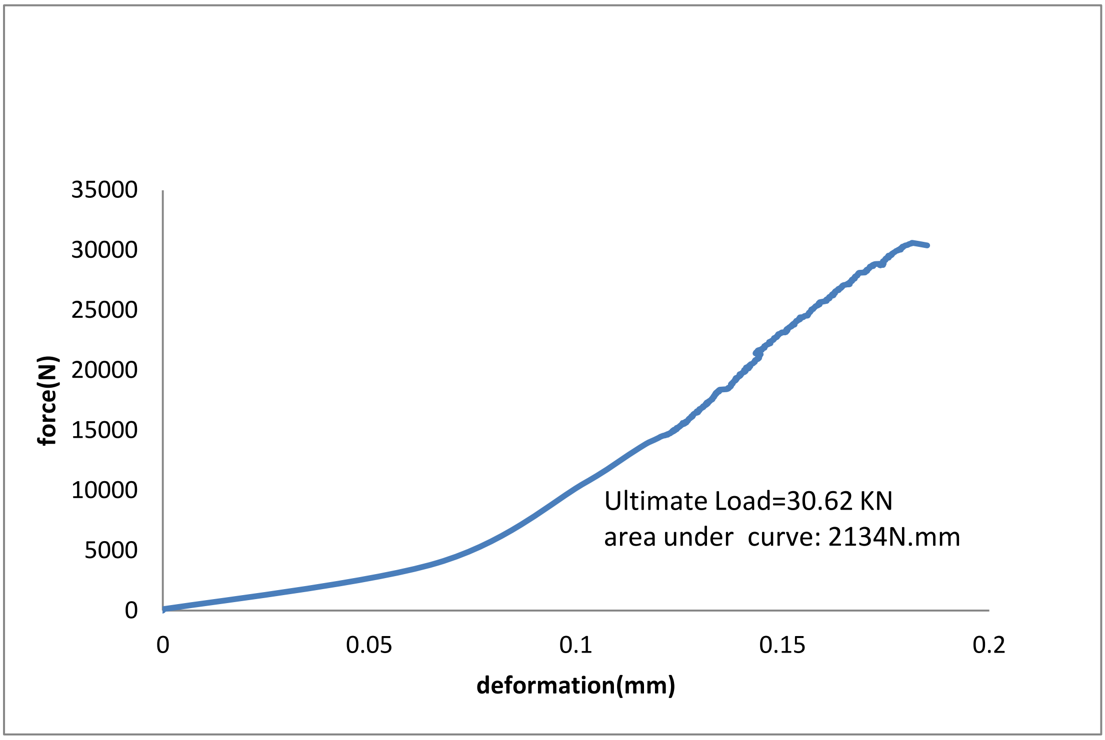

Figure 4.18: Load-deformation behavior for SFRC0.5%, 2 minute vibration time, at the age of 28 days

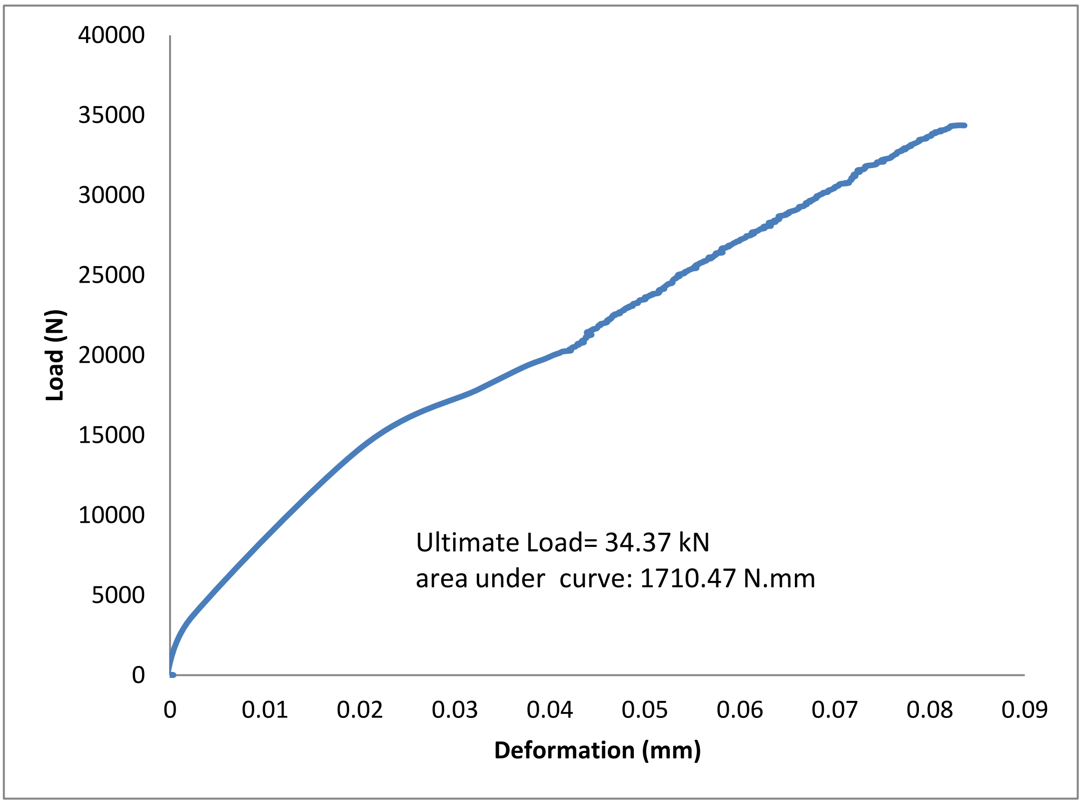

Figure 4.19: Load-deformation behavior for SFRC0.5%, 2.5 minute vibration time, at the age of 28 days

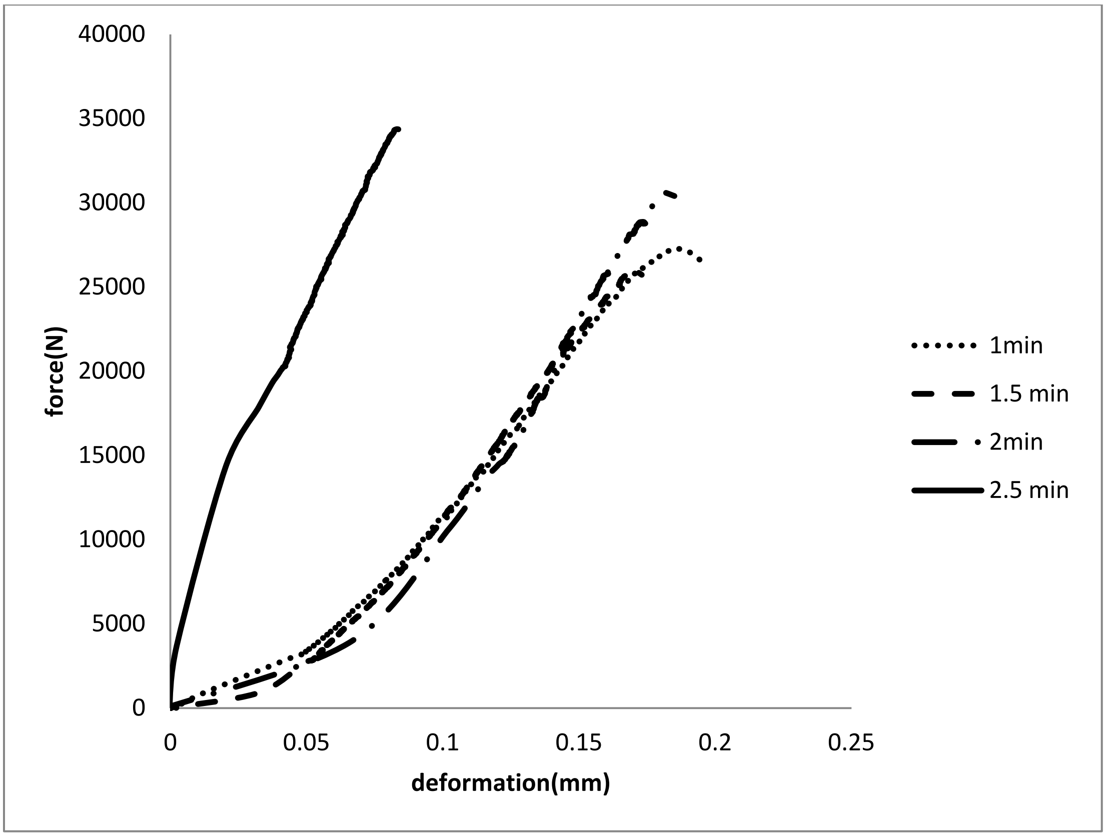

Figure 4.20: Load-deformation behavior for SFRC0.5%, in four vibration times, at the age of 28 days

According to Figure 4.20 it can be observed that SFRC0.5% is brittle due to failure at low strain values. Moreover, by increasing the vibration time, the ultimate load is increasing slightly, although deformation at the peak point is declining. It can be concluded that with increasing vibration time concrete becomes more brittle and the effect of steel fiber would be lower. This is most probably due to low fiber content that is not very effective on the development of flexural strength hence ductility improvement. It also can be mentioned that for vibration times less than 2.5 minutes the increasing trend of graphs is mild in the beginning while at vibration time of 2.5 minutes, the growing trend is sharp from the beginning. The reason of this behavior could be due to the fact that increasing vibration time results in more concentration of steel fiber in the bottom of concrete samples.

Load–deformation behaviors of SFRC 1% at four different vibration times at the age of 28 days are presented in Figure 4.21 to Figure 4.25.

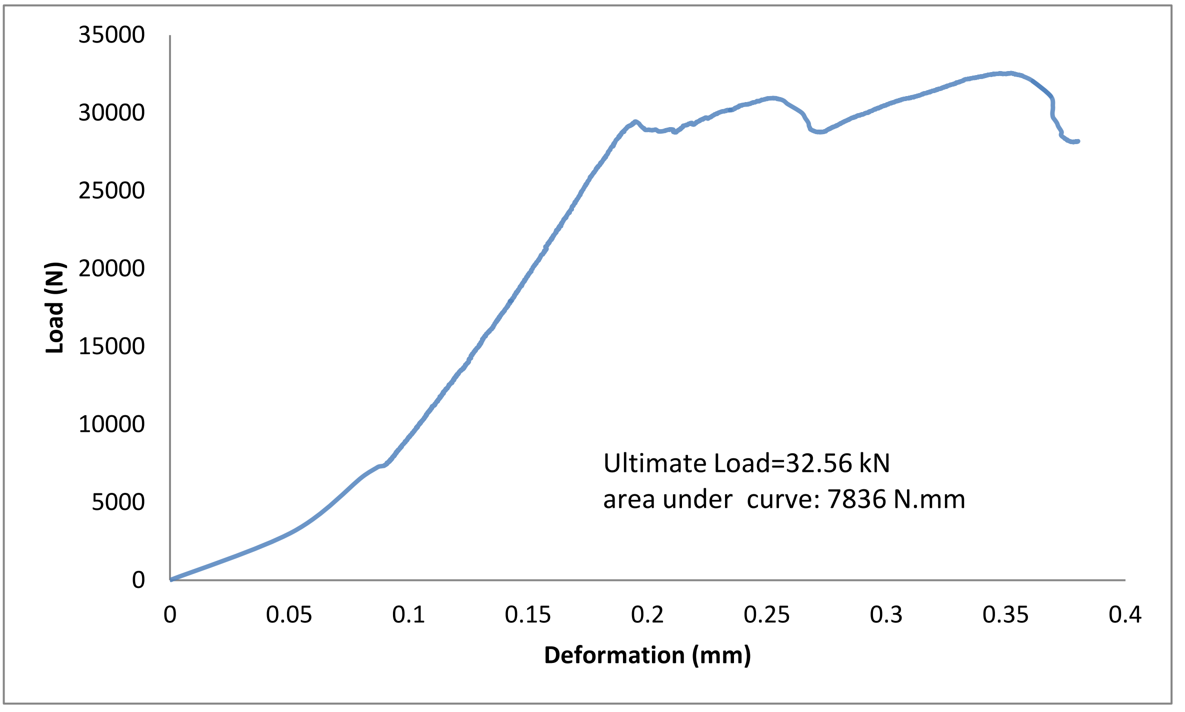

Figure 4.21: Load-deformation behavior for SFRC1%, 1 minute vibration time, at the age of 28 days

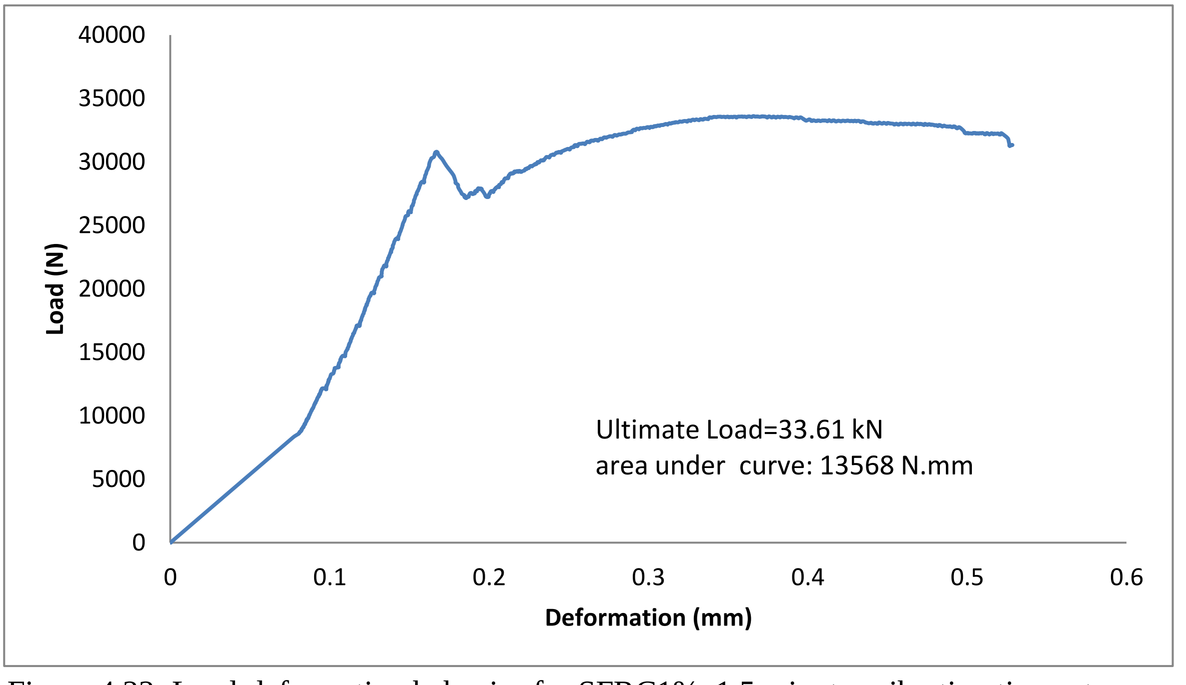

Figure 4.22: Load-deformation behavior for SFRC1%, 1.5 minutes vibration time, at the age of 28 days

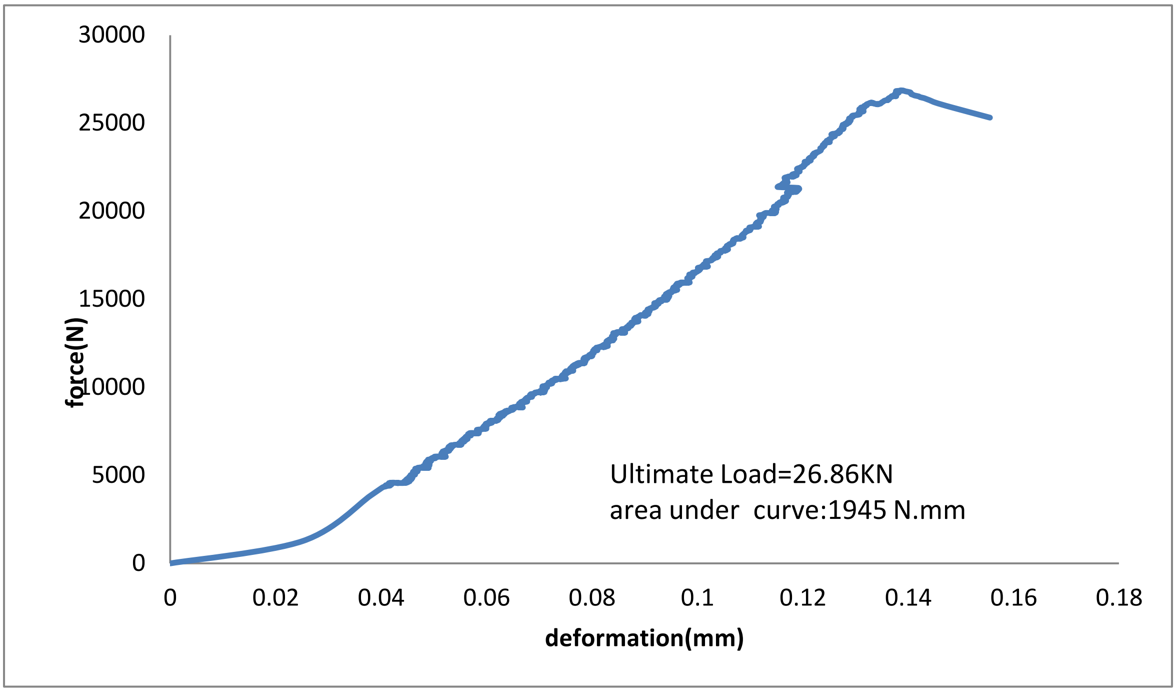

Figure 4.23: Load-deformation behavior for SFRC1%, 2 minutes vibration time, at the age of 28 days

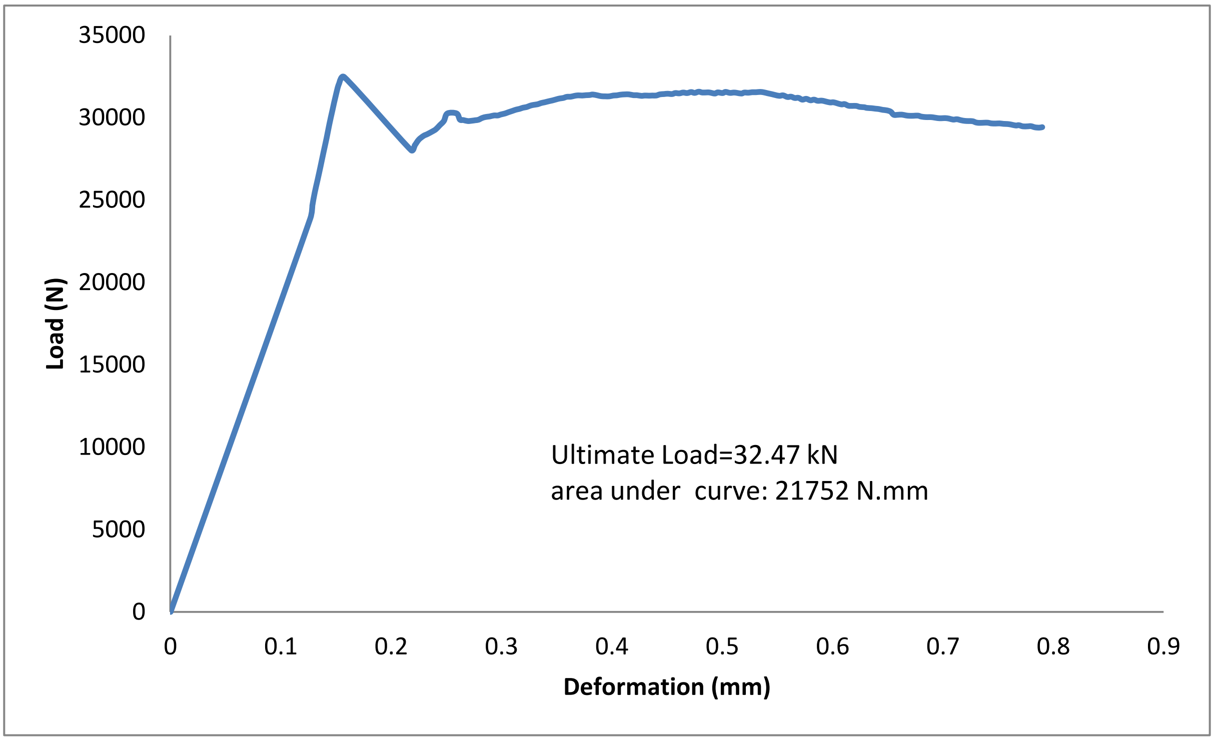

Figure 4.24: Load-deformation behavior for SFRC1%, 2.5 minutes vibration time, at the age of 28 days

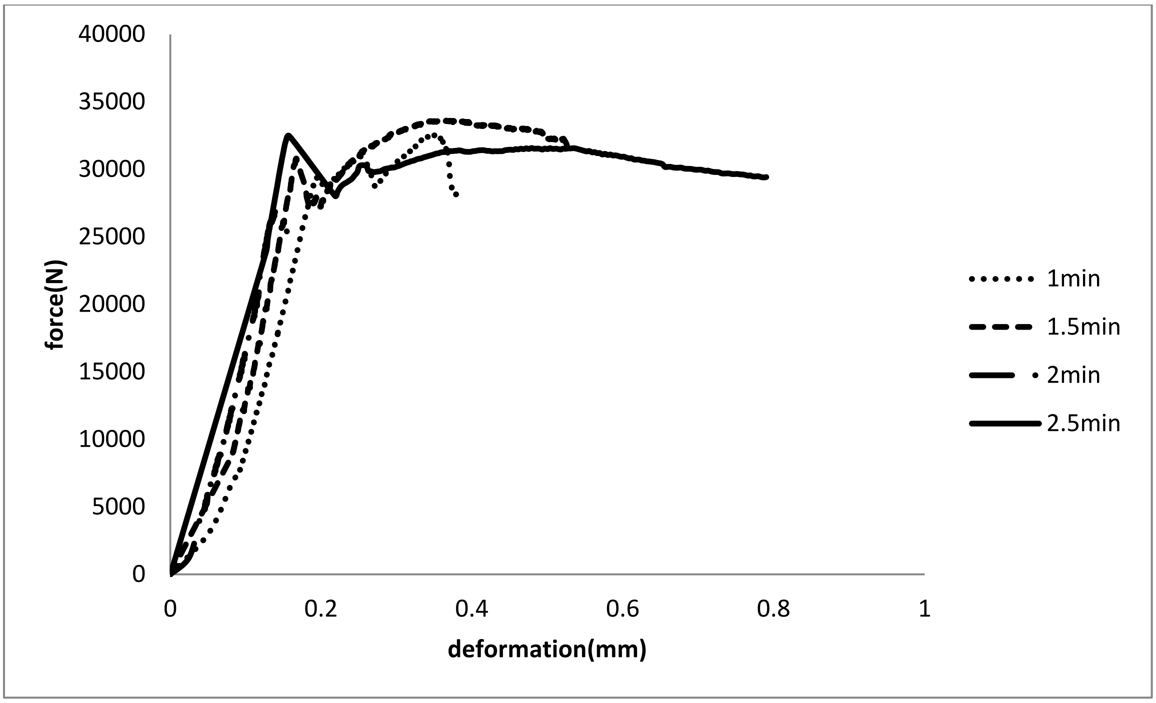

Figure 4.25: Load-deformation behavior for SFRC1%, in four vibration times, at the age of 28 days

Referring to Figure 4.25, the maximum ultimate load seems to be for concrete in 2.5 minute vibration time, 1.5 min and 1, respectively. Also with increasing vibration time, maximum deformation is decreasing, in other words it can be said that the higher the vibration time, the more brittle behavior of the concrete.

It should be noted that the result of beam with 2 minutes vibration time has been influenced by some experimental error and could be deleted among the results.

Furthermore, in SFRC1% there is post-peak performance at all graphs related to different vibration time.

Based on observation in Figure 4.25, it can be said that after the peak point with increasing vibration time, post-peak region increases for 2.5 minutes vibration time.

In the following, the curves of load-deformation for SFRC1.5% at four different vibration times are illustrated in Figures 4.26 to 4.30.

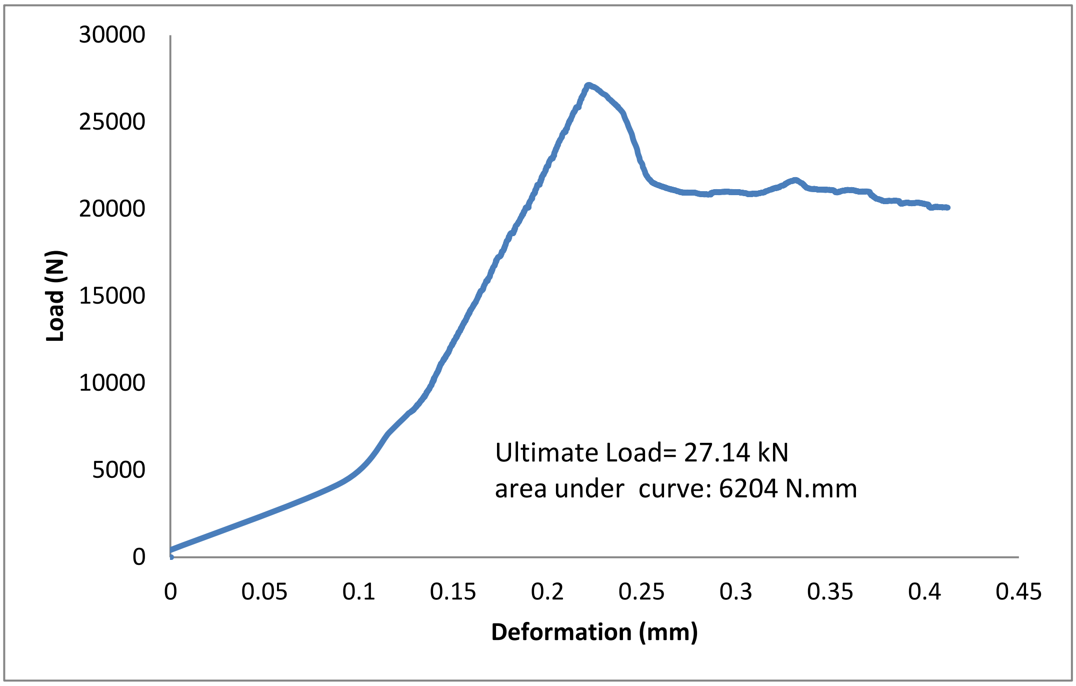

Figure 4.26: Load-deformation behavior for SFRC1.5%, 1 minute vibration time, at the age of 28 days

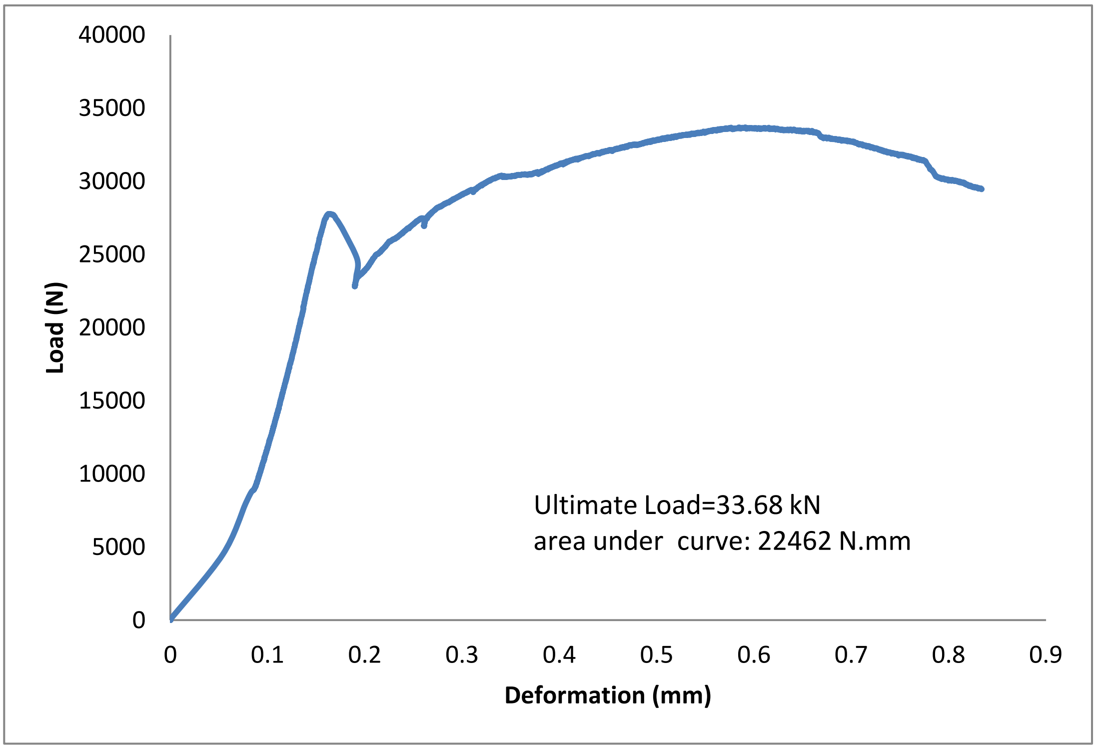

Figure 4.27: Load-deformation behavior for SFRC1.5%, 1.5 minutes vibration time, at the age of 28 days

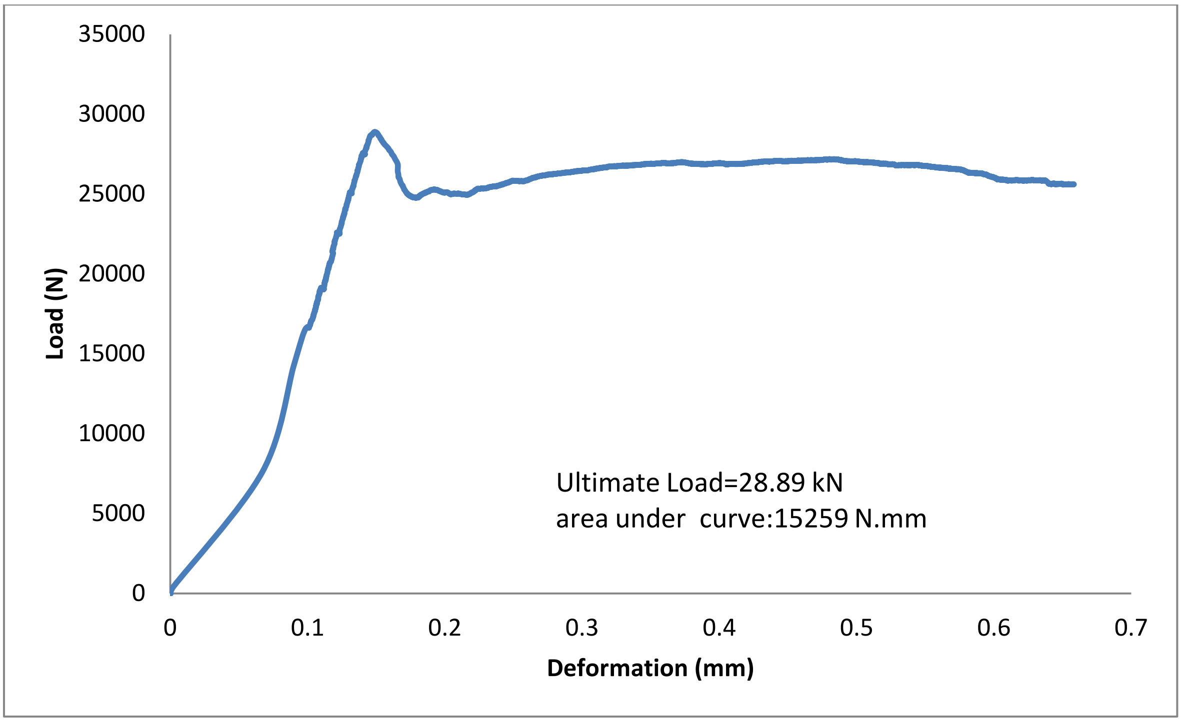

Figure 4.28: Load-deformation behavior for SFRC1.5%, 2 minutes vibration time, at the age of 28 days

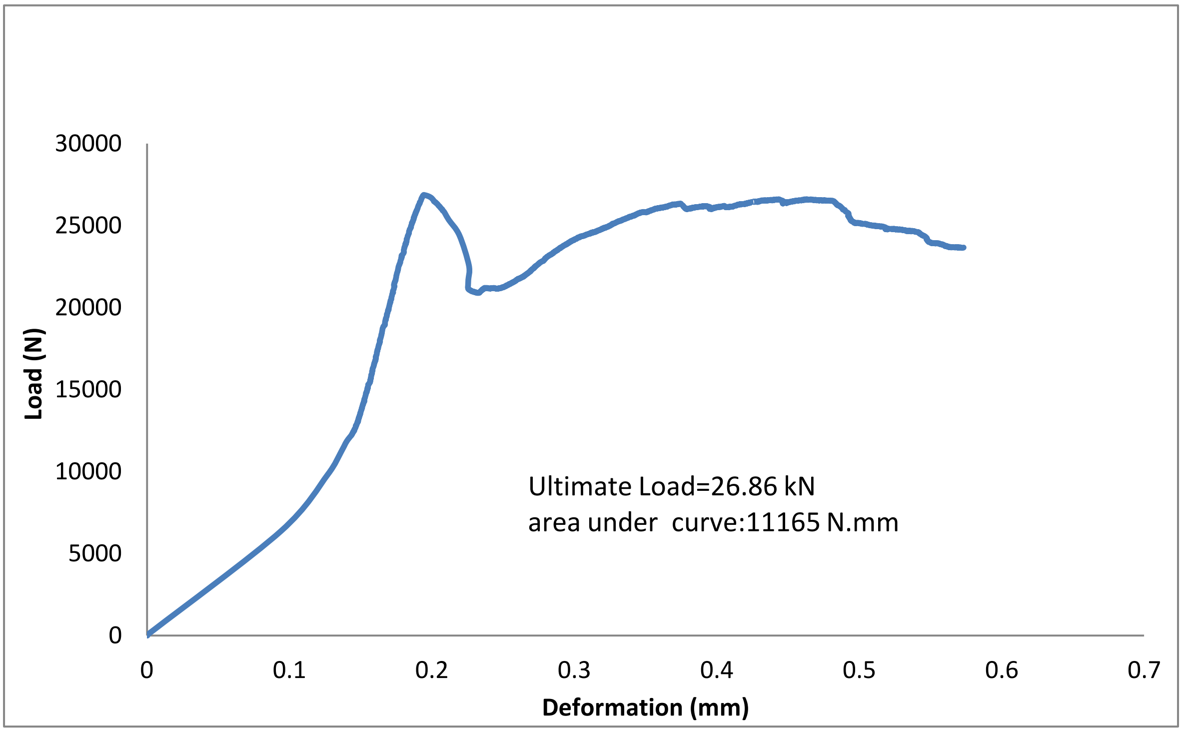

Figure 4.29: Load-deformation behavior for SFRC1.5%, 2.5 minutes vibration time, at the age of 28 days

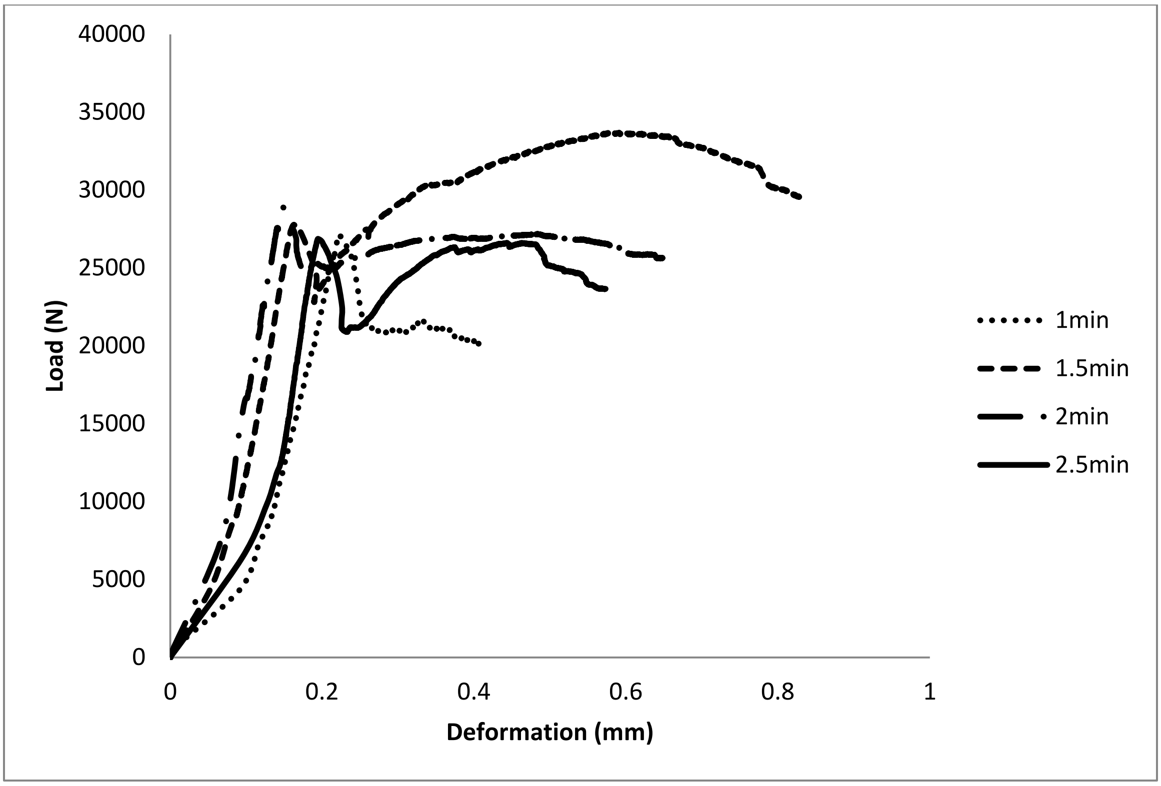

Figure 4.30: Load-deformation behavior for SFRC1.5%, in four different vibration times, at the age of 28 days

The pre-peak regions related to vibration time of 2.5 minutes and 1 minute are smaller because of less uniform concrete matrix.

The maximum load is allocated to vibration time of 2 minutes. The ultimate load at vibration time 2.5 minutes and 1 minute are close to each other. Also, the deformation relating to vibration time 1 minute is the maximum value as compared to others and deformation for 2.5 minutes, 1.5 minutes and 2 minutes vibration times are smaller. It means that at high percentage of steel fiber, the deformation of concrete beams decreases till vibration time 2 minutes and then, the deformation increases.

According to Figure 4.30, trend of all graphs of SFRC1.5% with different vibration times shows that the post-peak performance of 1.5 minutes is the best behavior maybe with increasing vibration time for high percentage of fibers considering usage of different mixer, the uniformity of concrete gets the minimum.

The area under the load-deformation curves which is known to be toughness, have been calculated and are showed in Table 4.10. The related graphs are displayed in Figure 4.31.

Table 4.10: flexural toughness of control mix

Mixes \ Vibration Time (min)	1.00	1.50	2.00	2.50
SFRC0.5%	2450	1784	2134	1710
SFRC 1%	7836	13568	1945	21752
SFRC 1.5%	6204	22462	15259	11165

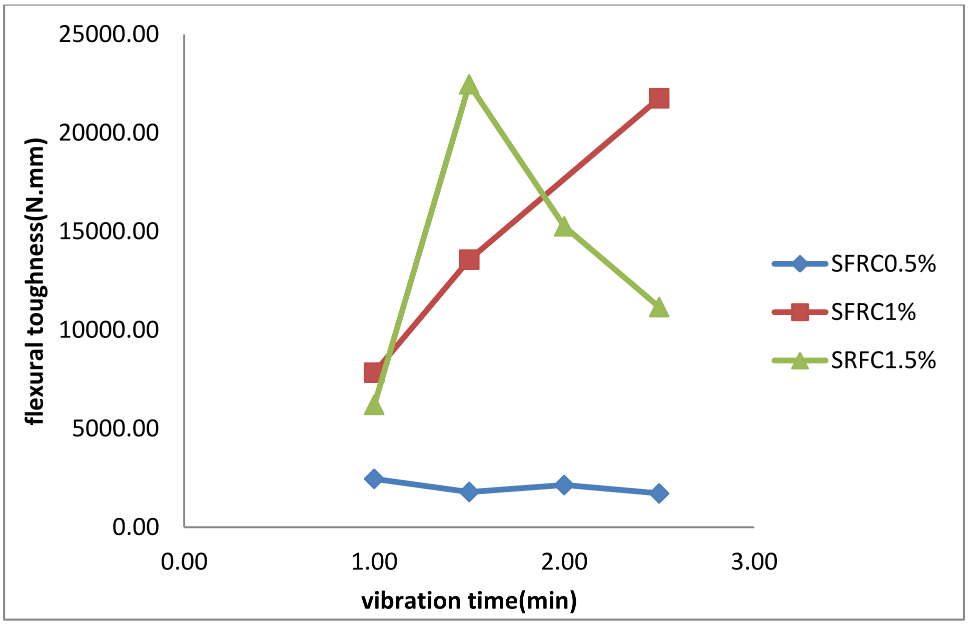

Figure 4.31: Flexural toughness behaviour of all mixes in four different vibration time, at the age of 28 days

Regarding the curves for SFRC 0.5%, it is observed that the flexural toughness is not changed significantly comparing to SFRC1% and SFRC1.5%. In the case of SFRC1.5% with different vibration times, by increasing vibration time there is a sharp jump in the beginning till 1.5 minutes and then there is a decrease in the amount of flexural toughness.

Regarding to skip the result of vibration time 2 minute for SFRC 1%, it can be claimed that the flexural toughness of high strength steel fiber reinforced concrete increases till an optimum vibration time. However the mentioned optimum vibration time is dependent on the percentage of steel fiber which influences uniformity of SFRC.

In the following section, load-deformation figures are drawn that are arranged by vibration time for SFRC0, 5%, SFRC1%, and SFRC1.5% at the age of 28 days.

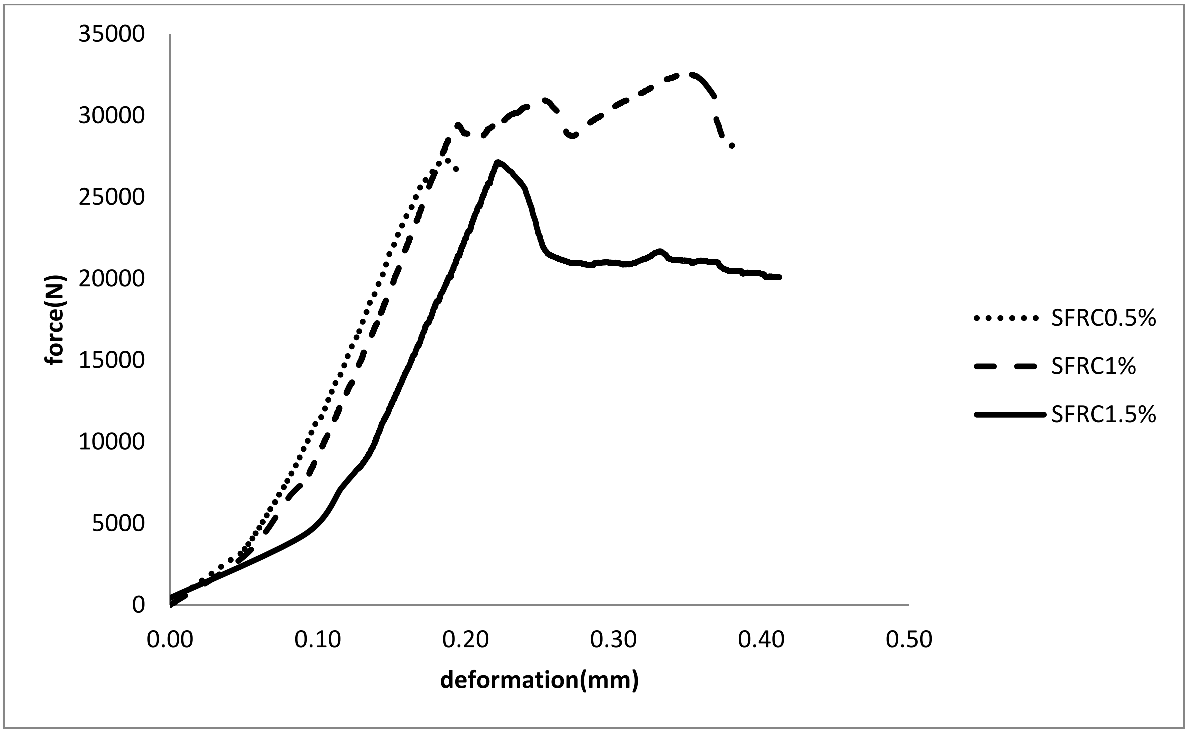

Figure 4.32: Load-deformation behavior for all mixes, 1 minute vibration time, at the age of 28 days

According to Figure 4.32, at vibration time 1 minute the maximum load is allocated to SFRC1% while the maximum deformation is related to SFRC1.5%.

In continuance Figure 4.33 indicates that SFRC1% has highest ultimate load however the highest deformation belongs to SFRC1.5%. In other words, results derived from Figure 4.33 are similar to Figure 4.32 .

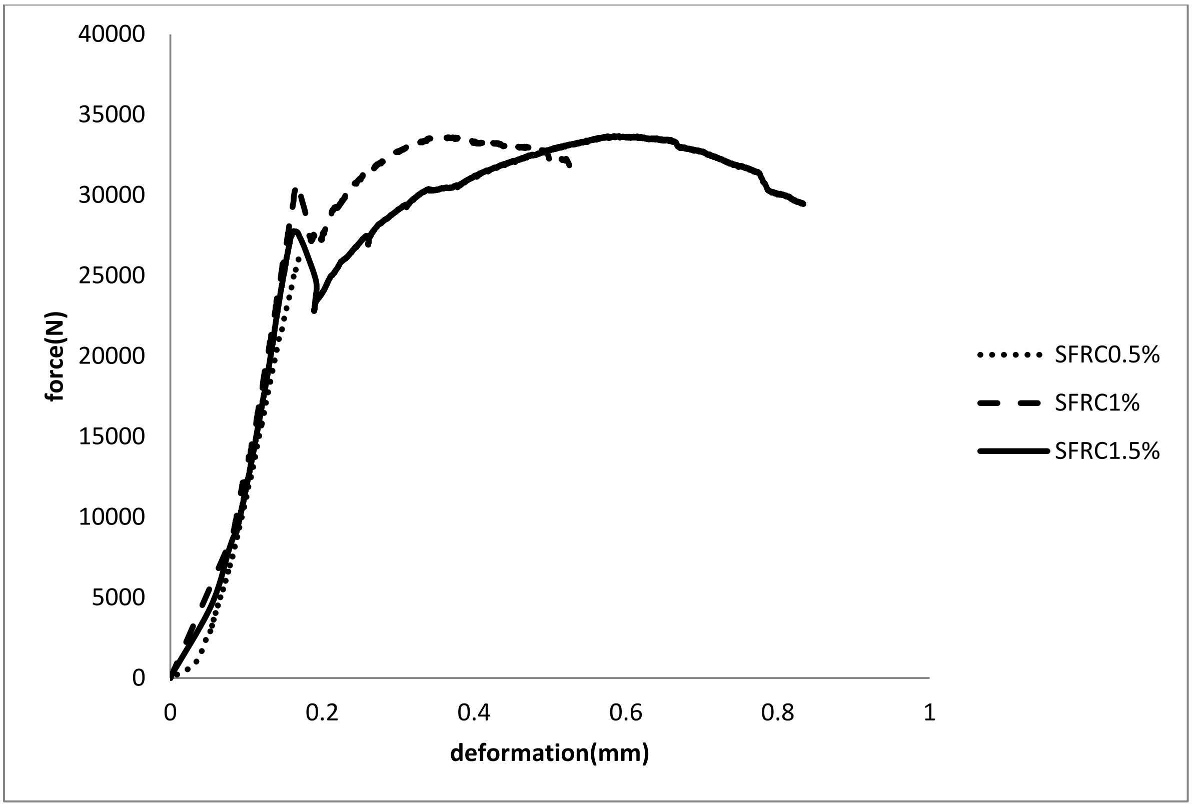

Figure 4.33: Load-deformation behavior for all mixes, 1.5 minutes vibration time, at the age of 28 days

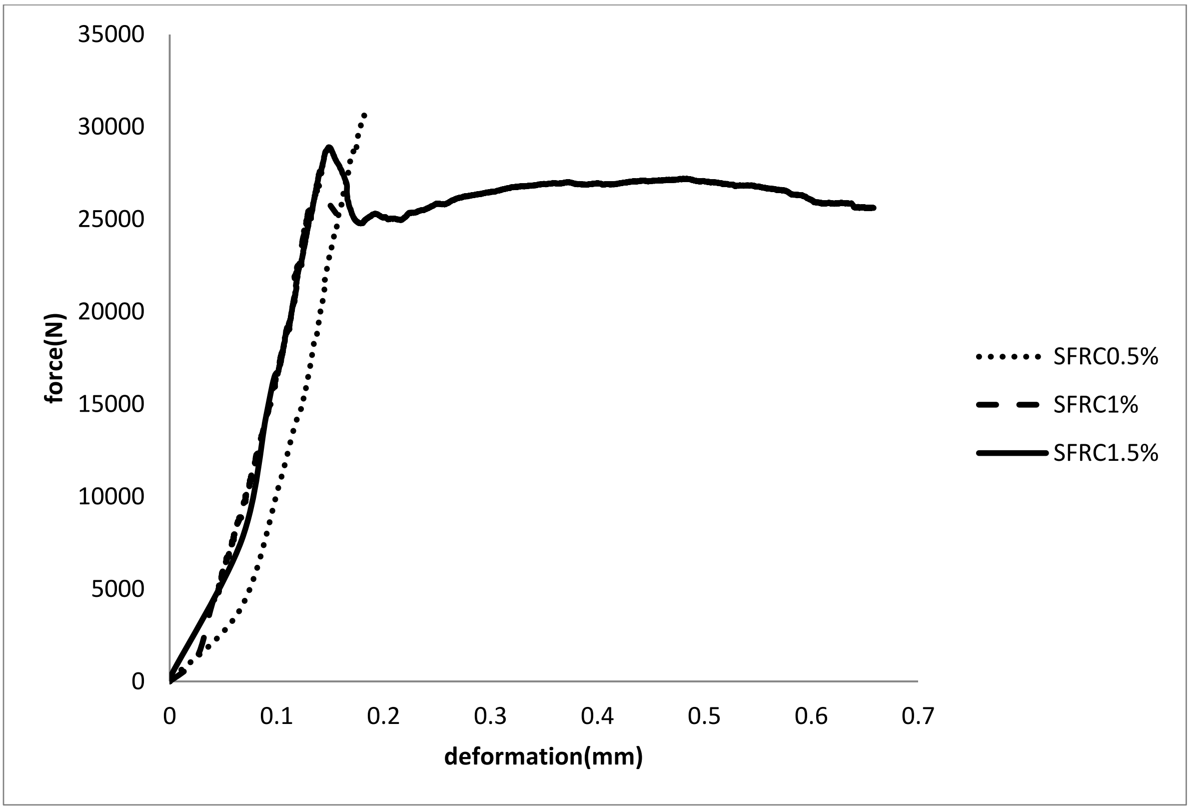

Figure 4.34: Load-deformation behavior for all mixes, 2 minutes vibration time, at the age of 28 days

Regarding Figure 4.34, the maximum deformation is allocted to SFRC1.5% and maximum load is related to SFRC 0.5% at vibration time of 2 minutes.

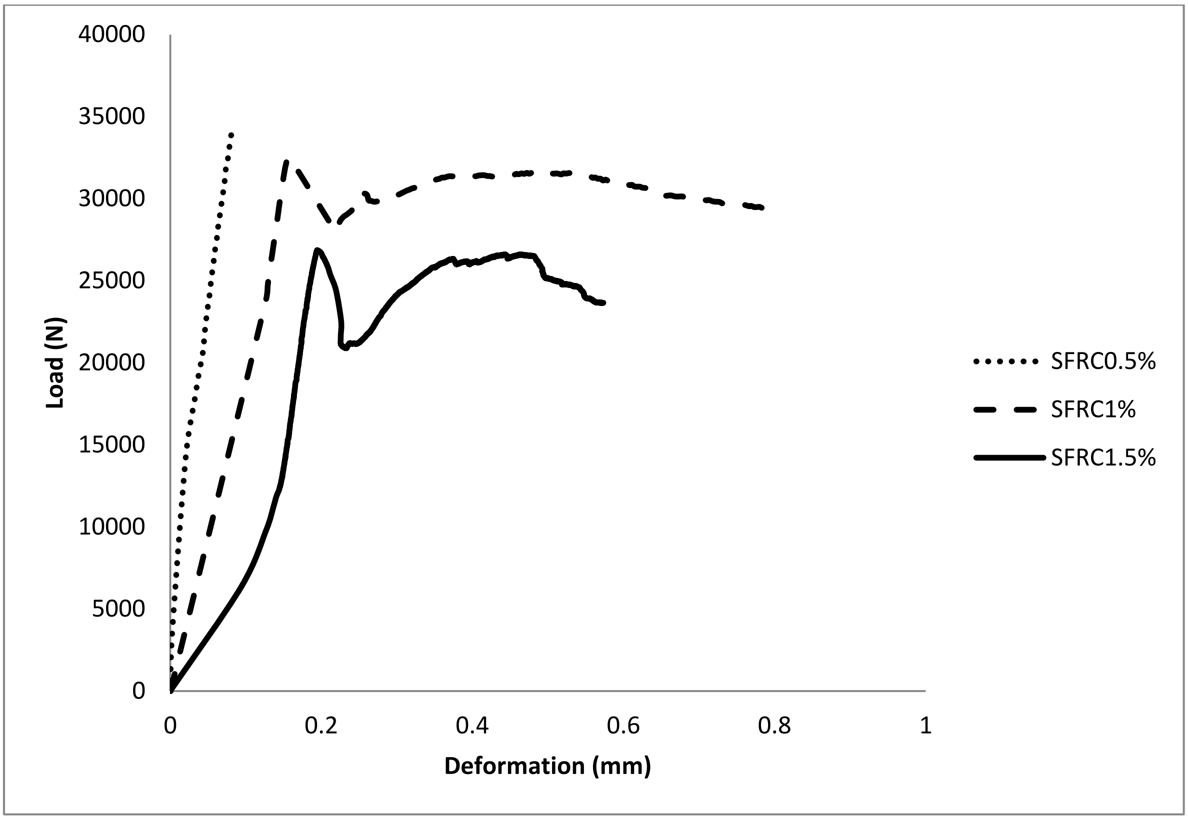

Figure 4.35: Load-deformation behavior for all mixes, 2.5 minutes vibration time, at the age of 28 days

Considering Figure 4.35 it can be seen that the ultimate load belongs to SFRC0.5% and maximum deformation belongs to SFRC1%.

Therefore, regarding to withdrawal of graph SFRC1% at vibration time of 2 minutes, it can be concluded that with increasing vibration time the ultimate load and also maximum pre-peak deformation have not changed siginificantly. It seems that the behavior of graphs after peak point, post-peak performance, improves by increasing vibration time . This observation is more pronounced for concretes having high percentage of steel fibers (1% and 1.5%).

Consiering the results, it can be concluded that the effect of vibration time is pronounced significantly on felxural toughness and post-peak behavior as compared to the amount of maximum or minimum strength.

Due to better placement in terms of placement and bonding between fibers and matrix, it can be claimed that the post-peak performance of the concrete improves, without any threat of segregation.

Improvement of post-peak performance and thereby flexural toughness means that a large amount of energy is dissipated during the fracture process which can be a possitive feature in the case of resistance against cyclic loads and impacts.

4.3.4 Splitting Tensile Strength

In this experimental part, splitting tensile strength test was done on cylindrical specimens at the age of 28 days and the results are presented in Table 4.9 and Figures 4.36 to 4.39.

Table 4.11: spliting tensile strength results

Vibration Time (minutes)	1	1.5	2	2.5
control mix	6.12	5.66	5.29	7.33
SFRC0.5%	9.28	7.49	7.89	10.10
SFRC1%	10.69	12.3	10.38	9.21
SFRC1.5%	6.72	9.62	10.84	6.98

The behaviors of splitting tensile strength by vibration time are shown in Figures 4.36 to 4.39. All graphs related to splitting tensile test are collected in Figure 4.40.

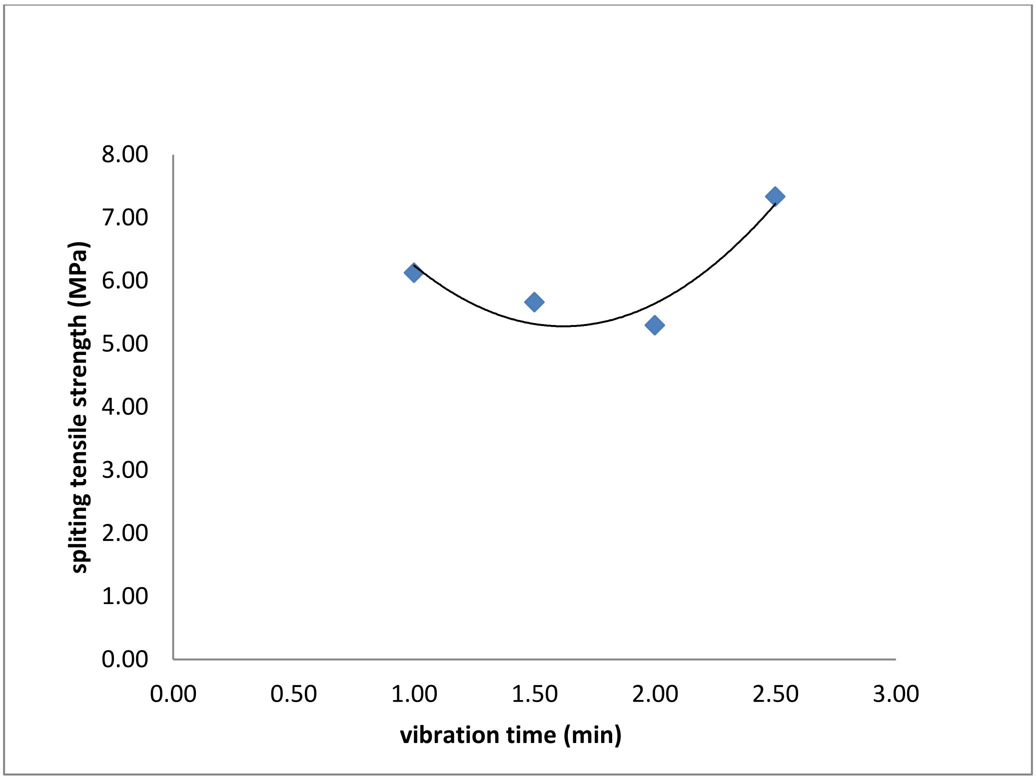

Figure 4.36: Spliting tensile strength behavior of control mix at four different vibration times, at the age of 28 days

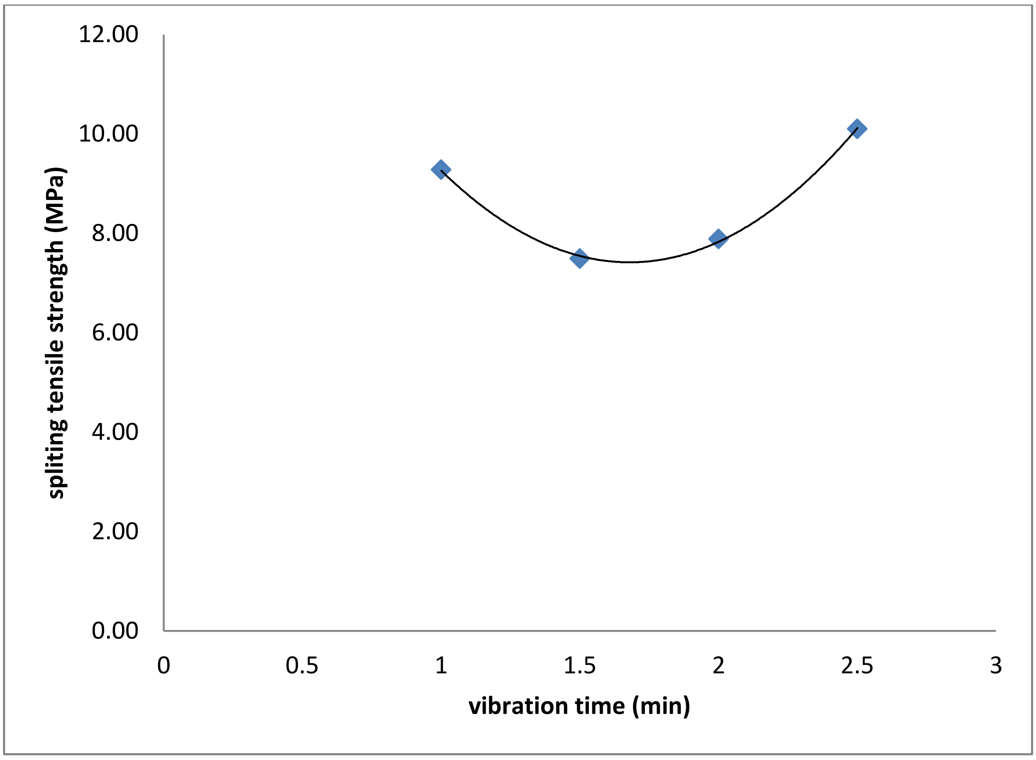

Figure 4.37: Spliting tensile strength behavior of SFRC0.5% at four different vibration times, at the age of 28 days

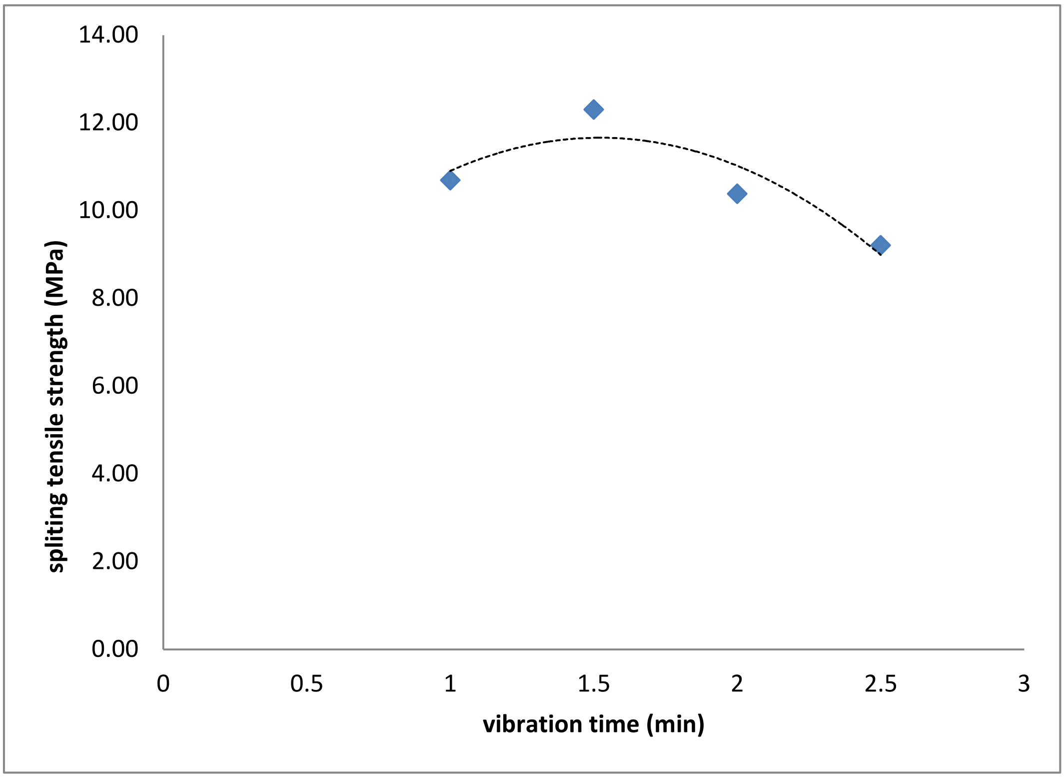

Figure 4.38: Spliting tensile strength behavior of SFRC1% at four different vibration times, at the age of 28 days

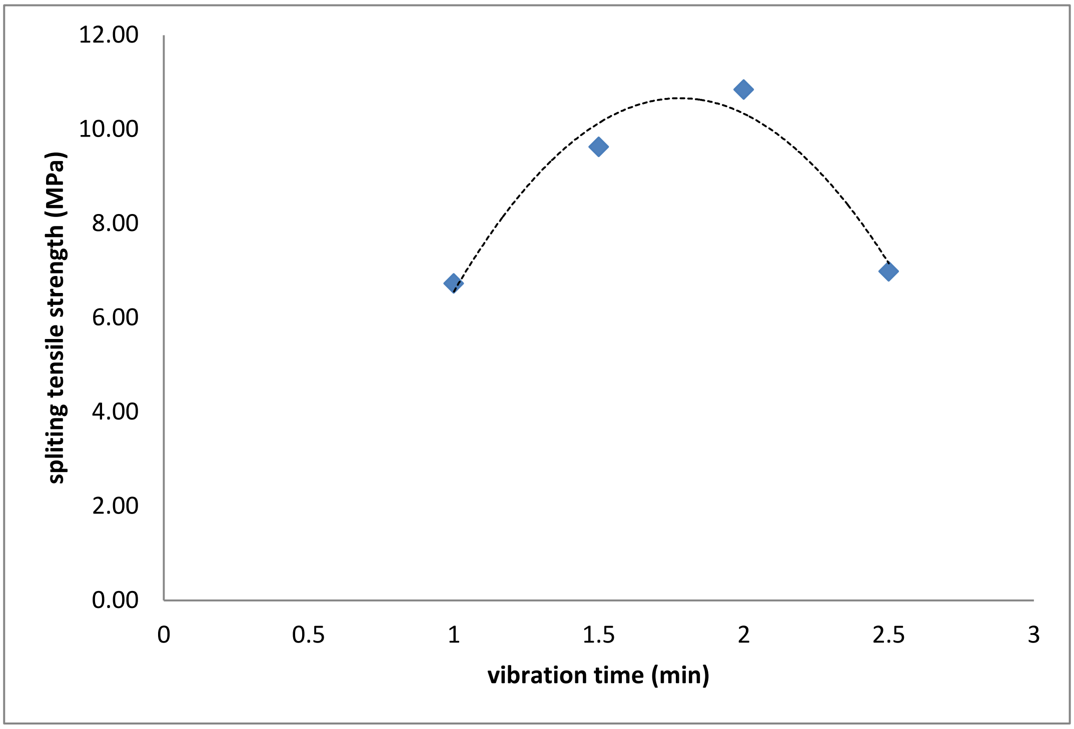

Figure 4.39: Spliting tensile strength behavior of SFRC1.5% at four different vibration times, at the age of 28 days

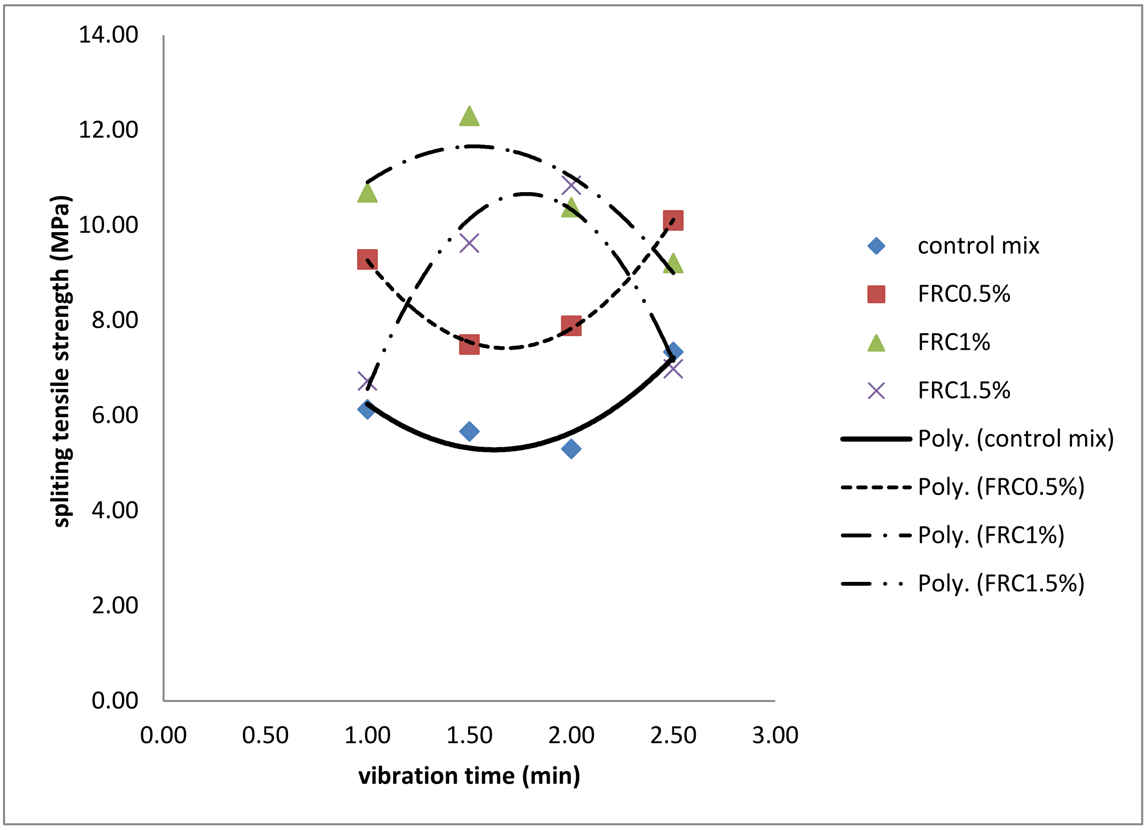

Figure 4.40: Spliting tensile strength behavior of all mixes at four different vibration times, at the age of 28 days

According to Figure 4.40, for control mix, splitting tensile strength reduces by 13.5% by increasing vibration time from 1 minute to 1.50 minutes. For SFRC0.5%, when vibration time increases from 1.5 minutes to 2 minutes splitting tensile increases by 15%. However after the minimum splitting tensile strength, an increase can be observed to be 38% and 28% for control mix and SFRC0.5% mix, respectively.

In the case of SFRC1% and 1.5%, the behavior is different in a way that there is an improvement in splitting tensile strength by increasing vibration time up to maximum point which are 1.5 minute for SFRC1% and 2 minutes for SFRC1.5%. The splitting tensile strength is enhanced by 15% for SFRC 1% and 43% for SFRC 1.5% up to mentioned optimum vibration time and after these points the trends start to decline and the amount of reductions obtained are by 25% for SFRC 1% and by 27% for SFRC 1.5%.

Based on Figure 4.36, it can be said that the maximum values of splitting tensile strength are obtained to be for SFRC1% and SFRC1.5% at vibration times of 1.5 minutes and 2 minutes, respectively. The optimum vibration time can change with the amount of steel fibers in matrix. Over-vibration causes accumulation of steel fiber at the bottom of samples decreasing the uniformity of concrete.

It can be said that the behavior of concrete matrix containing no steel fiber or low fiber volume fraction is more similar to each other in comparison to concrete with higher amount of steel fibers (1 and 1.5%).

Chapter 5

CONCLUSIONS

The aim of this study was to investigate the effect of different vibration times on mechanical properties of high strength steel fiber reinforced concrete. Four different mixes with water to cement ratio of 0.35 and 1.8% superplastisizer, including three different percentages of steel fiber including 0.5%, 1%, 1.5% and control mix with no steel fiber compacted at four different vibration times of 1, 1.5, 2, 2.5 minutes were studied. The tests including hardened density and compressive strength were performed on cubic samples. Also, beams for flexural strength and cylindrical samples for splitting tensile strength were used. Through the analyses of test results, effect of vibration time on each property was compared to others to find out how the vibration time can be effective on high strength steel fiber reinforced concrete.

Based on analyses of results the following conclusions were achieved:

1. Vibration time is not very effective on hardened density of high strength steel fiber reinforced concrete.

2. Compressive strength increases at both 7 days and 28 days with increasing vibration time for control mix.

3. Furthermore, for all percentages 0.5%, 1% and 1.5% steel fibers, the compressive strength increases at 7days but decreased at 28 days.

4. Comparing all mixes together, it can be said that mix with 1% steel fiber has highest compressive strength compared to SFRC 1.5%. Also, there is a reduction in compressive strength by increasing vibration time for all mixes including steel fibers.

5. In terms of flexural strength there is an improvement by increasing vibration time however this change is reduced with increasing the amount of steel fibers in concrete.

6. However for SFRC1.5%, because of high amount of fiber the uniformity of concrete is reduced so that at 2.5 minutes vibration time the flexural strength is decreased.

7. Concerning comparison among all concrete mixes, it can be said that the highest flexural strength was allocated to concrete containing 1% steel fibers. The increasing trend of flexural strength for control mix, SFRC0.5% and SFRC1% is observed while the decreasing trend observed for SFRC1.5%.

8. Regarding analyses of result of load-deformation curves for the beams, it can be claimed that SFRC0.5% is brittle and there is not any significant improvement in post-peak performance. Moreover, the ultimate load is increasing slightly by the increasing vibration time although deformation at the peak point is declining. It can be stated that with increasing vibration time the effect of steel fiber would be lower.

9. For SFRC1%, the maximum ultimate load was obtained from concrete vibrated for 2.5 minutes. Also with increasing vibration time the maximum deformation is decreased slightly. In other words it can be claimed the more vibration time, the more brittle behavior. Moreover, after the peak point with increasing vibration time, post-peak region improves for 2.5 minutes vibration time.

10. In the case of SFRC1.5%, the maximum load belongs to vibration time of 2 minutes and the ultimate load at 2.5 minutes is minimum.

11. In the case of flexural toughness, it can be said that flexural toughness increases till an optimum vibration time. This optimum time is reliant on the amount of steel fiber which influences on uniformity of SFRC.

12. Vibration time is not an effective factor on ultimate load and maximum pre-peak deformation. In fact, the most significant effect of vibration time it can be related to post-peak performance which is improved by increasing vibration time . It should be added that this behavior is more prominent at high volume fraction of steel fiber (1% and 1.5%).

13. Splitting tensile strength increases by increasing vibration time especially for control mix.

14. Splitting tensile strength of SFRC0.5% reduces at to a minimum value at 1.5 minutes and 2 minutes vibration time.

15. For SFRC1% and SFRC1.5%, by increasing vibration time there is an enhancement in splitting tensile strength up to a maximum point at 1.5 minutes and 2 minutes. At 2.5 minutes vibration time, splitting tensile strength reduces. The maximum values of splitting tensile strength are allocated to SFRC1% and1.5% for 1.5 minutes and 2 minutes vibration times, correspondingly.

16. The effect of vibration time on flexural toughness and post-peak performance is very significant compared to other mechanical properties.

Recommendation :

There could be an equation between optimum vibration time and the percentages of steel fiber in matrix. For future study to achieve the equation, more experimental trials is recommended.

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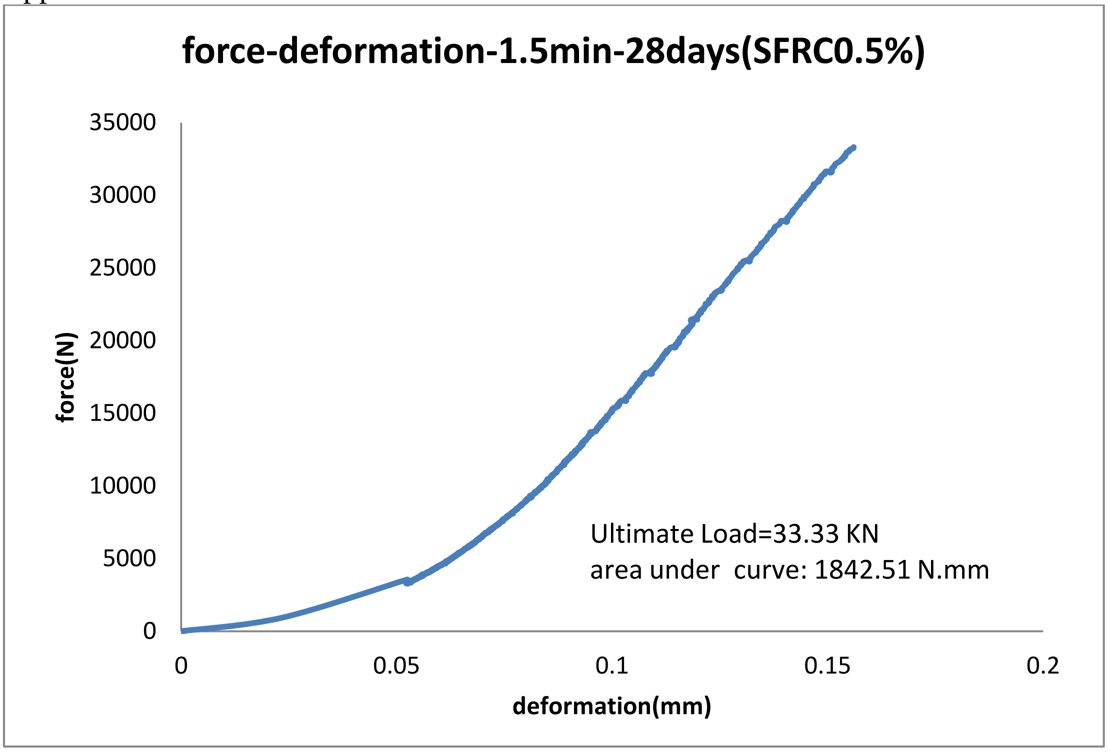
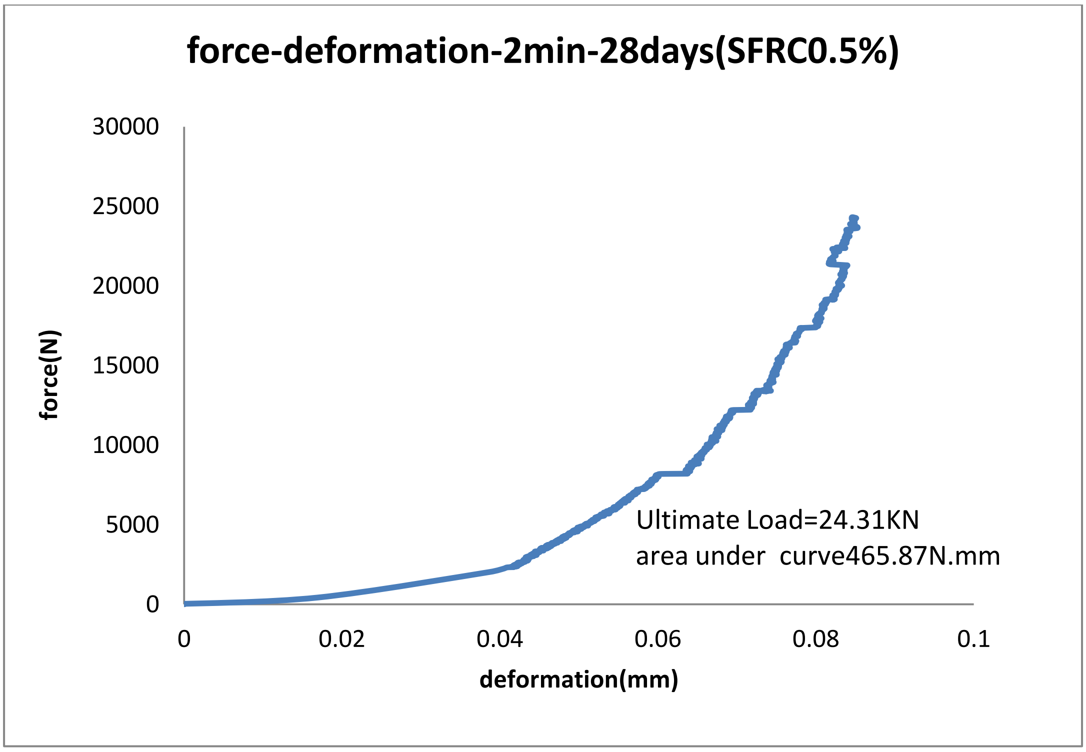
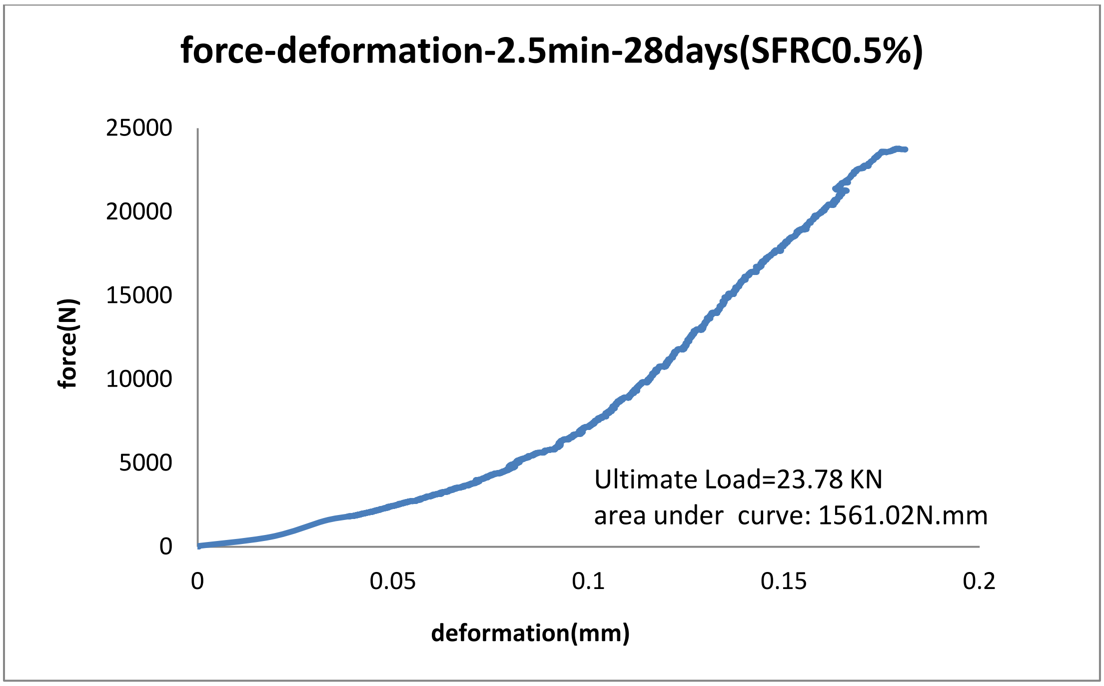
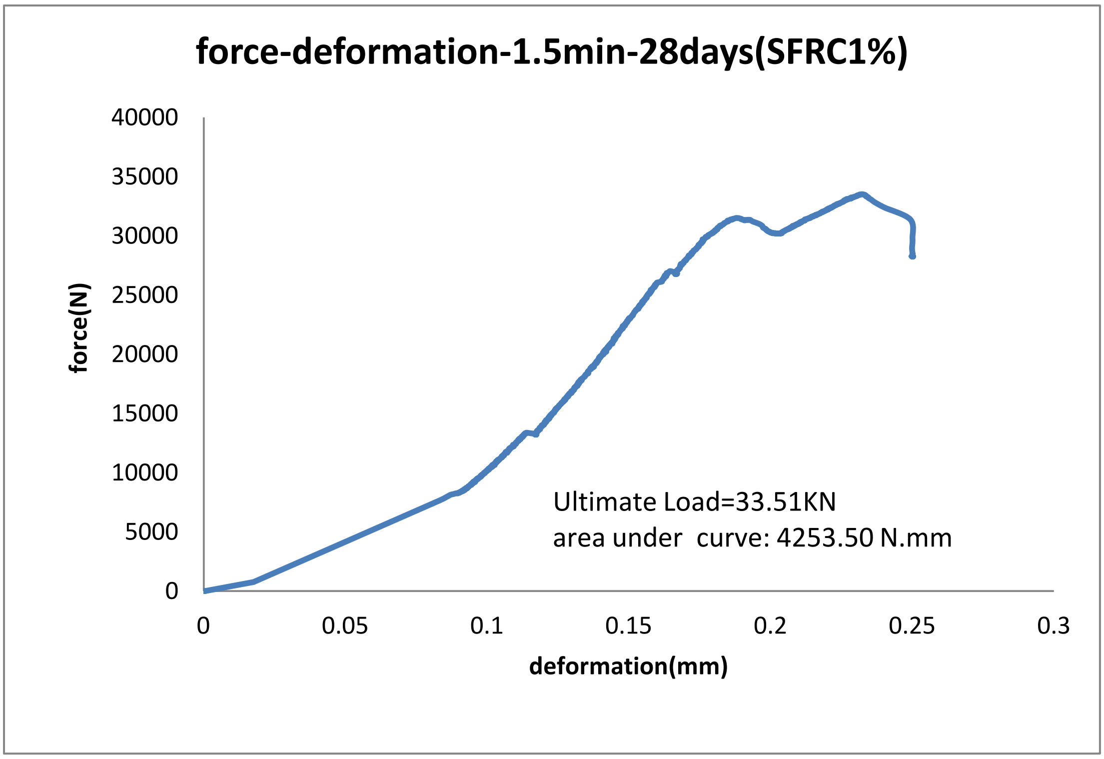
APPENDIX

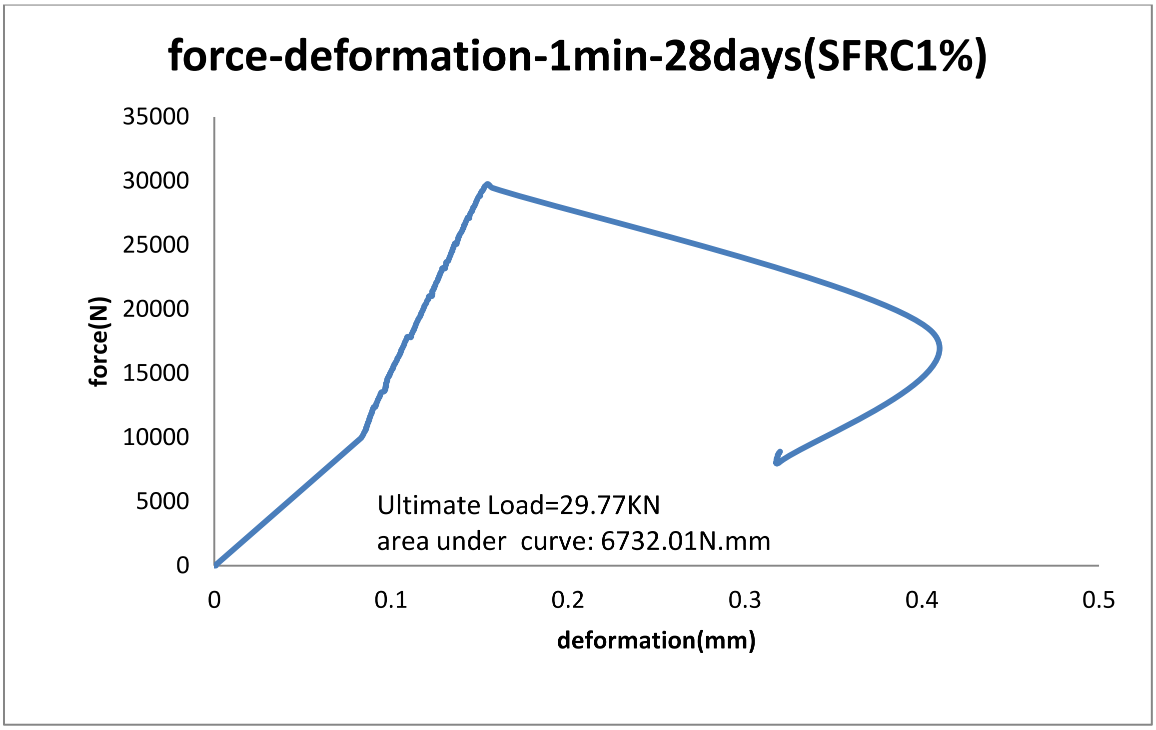
Appendix I: Load-deformation behavior of SFRC in different vibration times

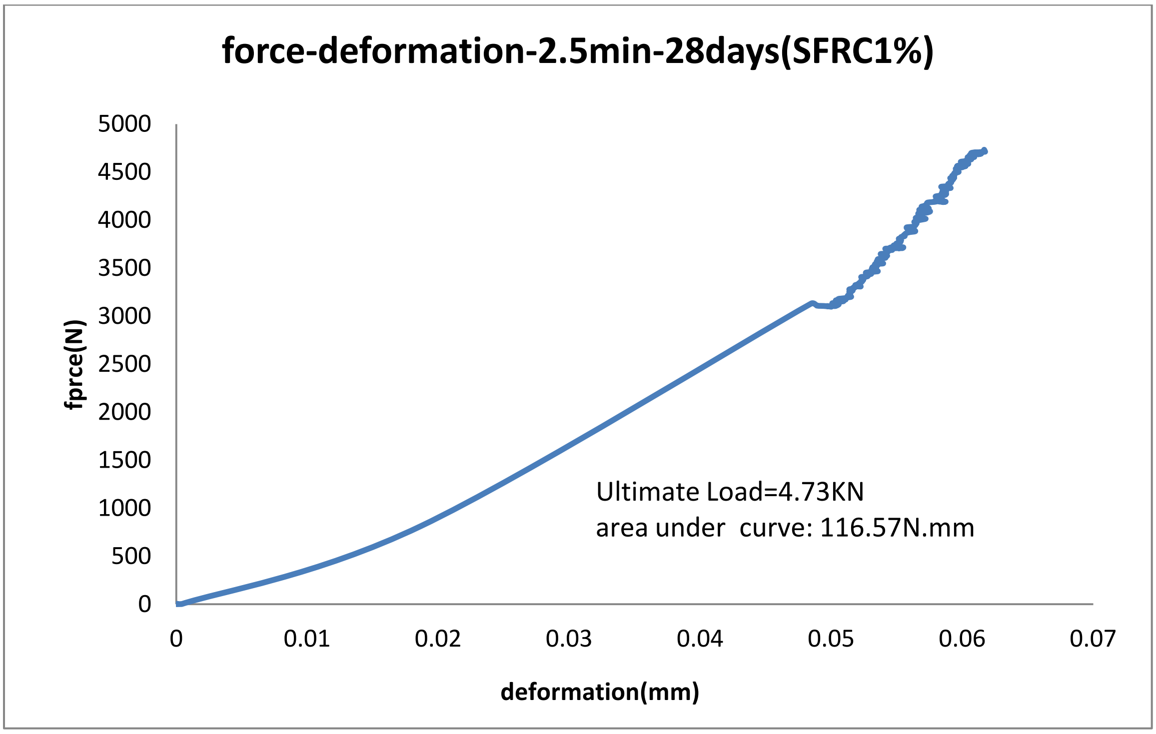


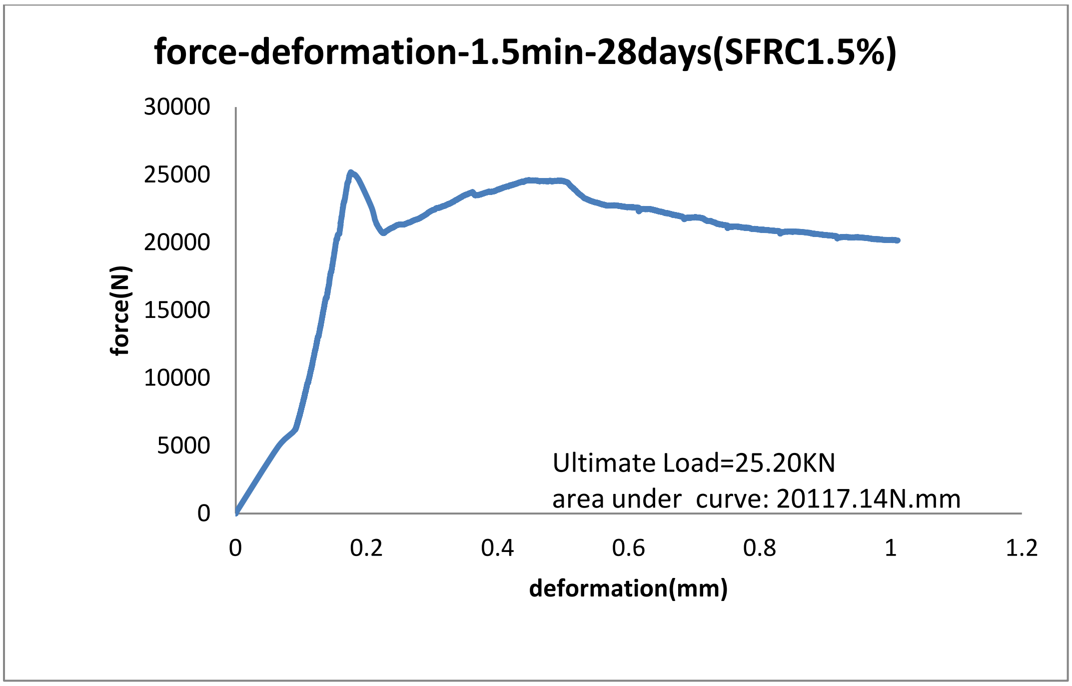


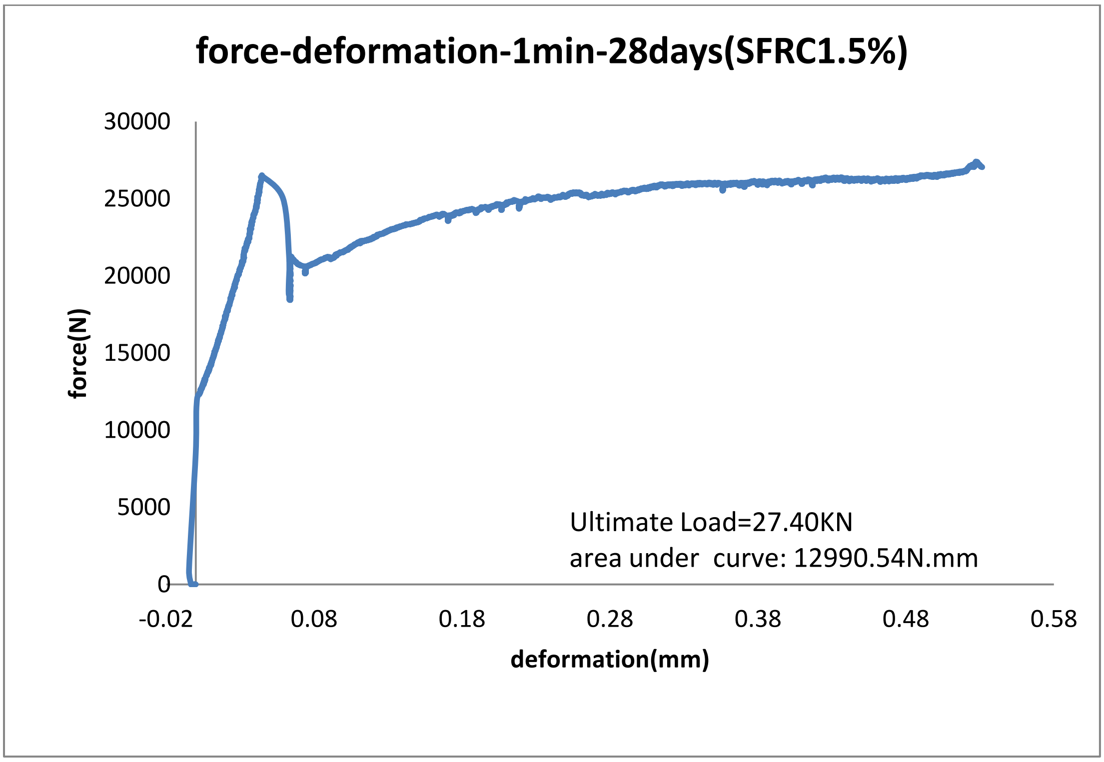

force-deformation-2.5min-28days(SFRC0.5%)
25000
20000
15000
10000
5000
0
force(N)
0
0.05
0.1
0.15
0.2
deformation(mm)
Ultimate Load=23.78 KN
area under curve: 1561.02N.mm

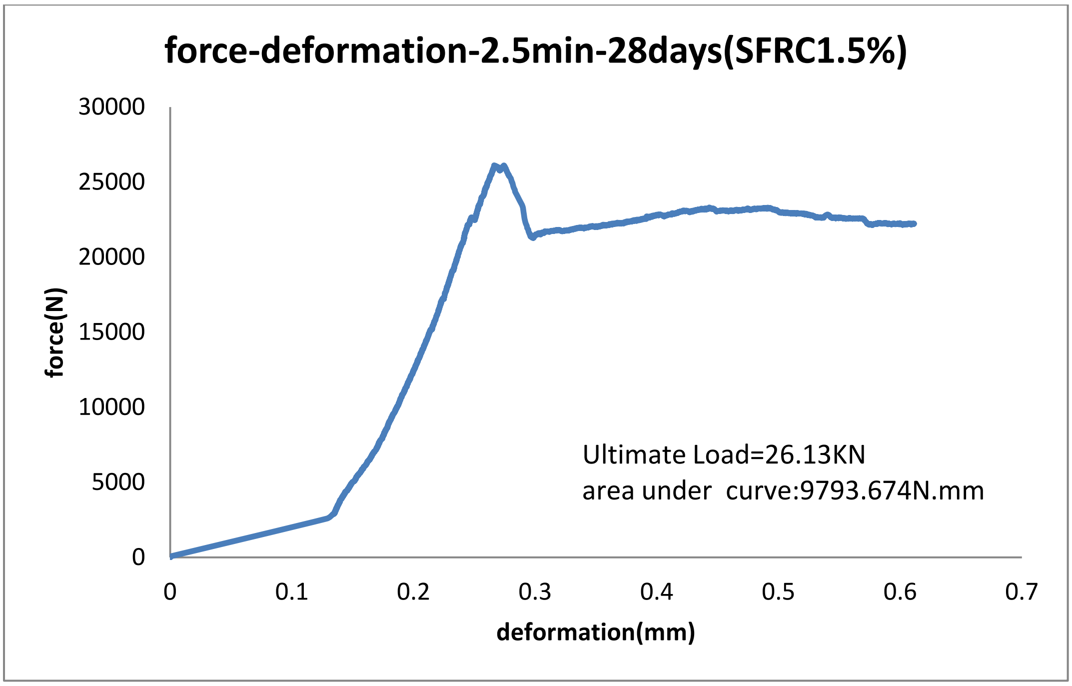

force-deformation-1.5min-28days(SFRC1%)
40000
35000
30000
25000
20000
15000
10000
5000
0
force(N)
0
0.05
0.1
0.15
0.2
0.25
0.3
deformation(mm)
Ultimate Load=33.51KN
area under curve: 4253.50 N.mm

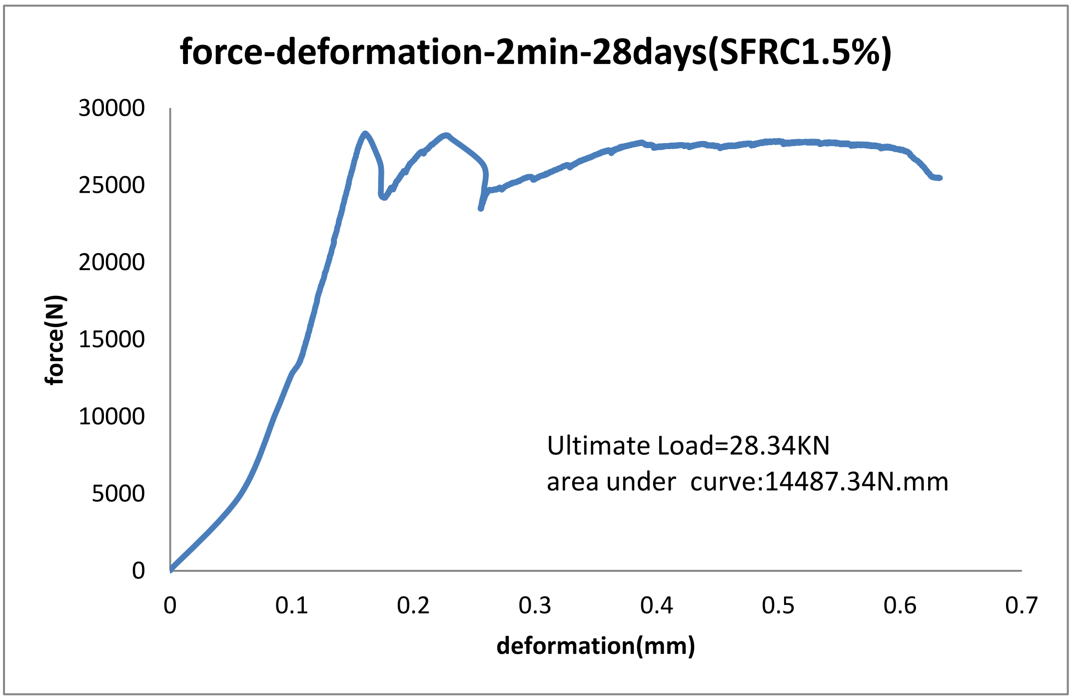

force-deformation-1min-28days(SFRC1%)
force(N)
35000
30000
25000
20000
15000
10000
5000
0
0
0.1
0.2
0.3
0.4
0.5
deformation(mm)
Ultimate Load=29.77KN
area under curve: 6732.01N.mm


force-deformation-2.5min-28days(SFRC1%)
fprce(N)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
deformation(mm)
Ultimate Load=4.73KN
area under curve: 116.57N.mm


force-deformation-1.5min-28days(SFRC1.5%)
30000
25000
20000
15000
10000
5000
0
force(N)
0
0.2
0.4
0.6
0.8
1
1.2
deformation(mm)
Ultimate Load=25.20KN
area under curve: 20117.14N.mm


force-deformation-1min-28days(SFRC1.5%)
30000
25000
20000
15000
10000
5000
0
force(N)
-0.02
0.08
0.18
0.28
0.38
0.48
0.58
deformation(mm)
Ultimate Load=27.40KN
area under curve: 12990.54N.mm


force-deformation-2.5min-28days(SFRC1.5%)
force(N)
30000
25000
20000
15000
10000
5000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
deformation(mm)
Ultimate Load=26.13KN
area under curve:9793.674N.mm


force-deformation-2min-28days(SFRC1.5%)
force(N)
30000
25000
20000
15000
10000
5000
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
deformation(mm)
Ultimate Load=28.34KN
area under curve:14487.34N.mm