COMPARATIVE EVALUATION OF STEEL MESH, STEEL FIBRE AND HIGH PERFORMANCE POLYPROPYLENE FIBRE – REINFORCED SHOTCRETE/CONCRETE IN PANEL TEST

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ABSTRACT

COMPARATIVE EVALUATION OF STEEL MESH, STEEL FIBRE AND HIGH PERFORMANCE POLYPROPYLENE FIBRE – REINFORCED SHOTCRETE/CONCRETE IN PANEL TEST

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Steel fibre–reinforced shotcrete/concrete (SFRS/C) which can be defined as mortar or concrete, containing discontinues discrete steel fibres as a reinforcement has been used extensively in most of the world for a wide variety of applications such as in slope stabilisation, as retaining walls for large excavations, at tunnel faces, rehabilitation of deteriorated marine structures etc. Especially in underground constructions, it has become more common to replace steel mesh with SFRS/C because of the difficulties in steel mesh applications. Therefore, it is important to compare the behaviour of SFRS/C with steel mesh reinforced shotcrete/concrete (SMRS/C). On the other hand, nowadays, new materials have been also investigated to replace or to use together with steel fibre in shotcrete/concete and polypropylene fibres could be one of these types of materials.

In this study, panel tests in accordance with EFNARC (European Federation of Producers and Applications of Specialist Products for Structures, European specification for sprayed concrete) were performed on steel mesh, steel fibre and high performance polypropylene

fibre–reinforced shotcrete/concrete panels having different mix designs and cured for 28 days to compare the performance characteristics, such as toughness, flexural ductility, energy absorption and load–carrying capacities etc. Also, compressive strengths of FRS/C mixes at the age of 3,7,28 days and rebound characteristics of the shotcrete mixes were determined to compare the compressive behaviour and fibre amounts after shooting of the mixes relatively.

For these purposes, seventeen different shotcrete/concrete mixes having different reinforcements in different amounts were produced to be used in the tests. Steel fibres (SF) in different geometries, high performance polypropylene fibre (HPPF) and steel mesh (SM) were reinforcements used in the tests. Steel–polypropylene and steel–steel hybrid fibre reinforced mixes were also tested in this research to investigate the effect of using hybrid fibres in shotcrete/concrete on performance of it.

Test results showed that all reinforcements, including HPPFs that are low–modulus fibres greatly imparted the flexural ductility, toughness, and load carrying capacity of the brittle matrix. It was seen that there was positive synergy effect between different type, kind and geometry of steel–steel fibres and between steel–polypropylene fibres in hybrid fibre usage from performance point of view. According to results, it can be concluded that hybrid polypropylene–steel fibre particularly hooked end can be used alternatively instead of steel mesh and mono steel fibre as reinforcement in shotcrete/concrete applications to get better efficiency.

Keywords: Shotcrete; steel fibre; steel mesh; high performance polypropylene fibre; hybrid fibre system; toughness; plate test.

ÖZ

ÇELİK HASIR, ÇELİK FİBER VE YÜKSEK PERFORMANSLI POLİPROPİLEN FİBER DONATILI (PÜSKÜRTME) BETONLARIN PANEL TEST METODU İLE KARŞILAŞTIRMALI OLARAK DEĞERLENDİRİLMESİ

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Süreksiz ve ayrık çelik fiberlerle donatılandırılmış beton ya da harç olarak tanımlanabilen çelik fiber donatılı (püskürtme) betonlar (SFRS/C) dünyanın büyük bir bölümünde; örneğin, şev stabilizesinin sağlanmasında, büyük kazılarda dayanma yapısı görevinde, tünel yüzeylerinde kaplama betonu olarak, zarar görmüş denizaltı yapılarının rehabilitasyonunda vb. çok geniş bir uygulama alanı bulmuştur. Özellikle, yeraltı yapılarında püskürtme beton uygulamalarında, çelik hasır yerine çelik fiber kullanımı gittikçe yaygınlaşmaktadır. Bunun başlıca sebebi, çelik hasır uygulamalarında karşılaşılan güçlüklerdir. Bu nedenle, çelik hasır ve çelik fiber donatılı betonların davranış özelliklerinin karşılaştırılması büyük önem taşımaktadır. Öte yandan, günümüzde çelik fiber yerine ya da çelik fiberle beraber kullanılmak üzere yeni malzeme tipleri geliştirilmektedir ve polipropilen fiberler bunlardan biridir.

Bu çalışmada, EFNARC (Yapılar için Özel Ürünler Üretici ve Uygulayıcıları Avrupa Federasyonu, püskürtme beton için Avrupa

spesifikasyonu) spesifikasyonuyla uyumlu plaka deneyleri değişik karışım dizaynlarına sahip 28 gün boyunca kür edilmiş çelik hasır, çelik fiber ve polipropilen fiber donatılı (püskürtme) beton plakalar üzerinde tokluk, süneklik, enerji emme ve yük taşıma kapasitesi gibi performans özelliklerinin belirlenmesi amacıyla uygulanmıştır. Ayrıca, fiber donatılı (püskürtme) beton karışımların 3, 7 ve 28 günlük basınç dayanımları ve püskürtme sonrası fiber miktarları da belirlenmiştir.

Bu amaçlarla, miktar veya çeşit açısından farklı donatılara sahip on yedi (püskürtme) beton karışımı hazırlanmıştır. Bu karışımlarda donatı olarak, değişik geometrilerdeki çelik fiberler (SF), yüksek performanslı polipropilen fiberler (HPPF) ve çelik hasır (SM) kullanılmıştır. Karışık fiber kullanımının betonun mekanik özelliklerini nasıl etkilediğinin belirlenebilmesi için çelik-polipropilen ve çelik-çelik hibrid fiber karışımları da test edilmiştir.

Yapılan çalışmalar sonucunda; tüm donatıların, düşük elastik modüllü HPP fiberler de dahil olmak üzere, gevrek beton matrisinin tokluk, süneklik ve yük taşıma kapasitesi gibi mekanik özelliklerini büyük miktarda geliştirdiği gözlenmiştir. Ayrıca, değişik tip ve geometrideki hibrid çelik-çelik ve çelik-propilen fiberler arasında performans açısından pozitif sinerjik bir etkileşme olduğu belirlenmiştir. Sonuç olarak, (püskürtme) betondan daha yüksek bir verim elde etmek amacıyla, çelik hasır ve çelik fiber yerine polipropilen fiberlerin, özellikle kanca uçlu çelik fiberlerle birlikte hibrid olarak kullanılmasının daha avantajlı olabileceği saptanmıştır.

Anahtar Kelimeler: Püskürtme beton (Shotcrete); çelik fiber; çelik hasır; yüksek performanslı polipropilen fiber; hibrid fiber sistemi; tokluk; plaka deneyi.

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INTRODUCTION

1.1 General

A composite is a material having two or more distinct constituents that are called matrix which is continuous and is often present in the greater quantity in the composite and reinforcement that enhances or reinforces the mechanical properties of the matrix in most cases which is harder, stronger and stiffer.

Thus we can classify bricks made from mud reinforced with straw, which were used in ancient civilisations, as a composite. A versatile and familiar building material that is also a composite is concrete; concrete is a mixture of stones, known as aggregate, held together by cement [1].

Fibre reinforced concrete/shotcrete FRC/S can be also classified as a composite which consists of a matrix i.e. concrete/shotcrete and reinforcement named discontinuous, randomly distributed fibres. It's bearing strength is determined by the combination of its two constituents: the concrete/shotcrete and the fibres [2].

One of the fibre – reinforced composites is steel fibre – reinforced concrete/shotcrete (SFRC/S). It can be defined as mortar or concrete, containing discontinues discrete steel fibres, which are pneumatically projected at high velocity on to a surface." [3]. Steel fibres are added into shotcrete to improve its crack resistance, ductility, energy absorption and impact resistance characteristics.

Nowadays, it has become more common to use SFRS/C instead of steel mesh reinforced shotcrete/concrete (SMRS/C) especially for underground constructions. Because in steel mesh–shotcrete/concrete applications; installation of steel mesh is difficult, time consuming, hazardous under loose rocks and expensive; in addition, lining quality can be poor, that is, not a uniform bond between shotcrete and rock, forming low quality shadow areas behind the wire and bad reinforcement due to irregular mesh positions etc. On the other hand, steel fibre–reinforced shotcrete having high ductility provide immediate reinforced support, homogeneous fibre reinforcement and strong bond to the surface which is required to make the underground self–supporting by filling up voids [4].

1.2 Object and Scope

In general, steel fibres are incorporated in the shotcrete to enhance its crack resistance, ductility, energy absorption, and impact resistance characteristics. Properly designed, SFRS/C, can reduce, or even eliminate cracking, a common cause for concern in plain shotcrete.

Since the early 70's when the first experimental work was undertaken with (SFRS/C), it has been the subject of many field and laboratory studies in the past [5,6] and is the focus of many current investigations [4,7,8]. Also, it has been used extensively in most of the world for a wide variety of applications, in new constructions, in the repair and rehabilitation of older and deteriorated structures such as in slope stabilization, as retaining walls for large excavations, at the tunnel faces, rehabilitation of deteriorated marine structures etc. [4,7,9,10,11].

On the other hand, nowadays, new materials have been also investigated to replace or to use together with steel fibre in shotcrete/concrete. Polypropylene fibres could be one of this type of materials. It has been shown earlier [12-14] that cracking resulting from shrinkage and differential settlements during the fresh state of the concrete can be effectively inhibited by them (PP) [15] In addition, they can be used to improve hardened concrete properties.

This study showed that the use of high performance polypropylene fibre having low fibre content with or without steel fibre reinforcement in shotcrete can greatly impart the flexural ductility, toughness, and load – carrying capacity and therefore possibly can be used with steel – fibre reinforcement especially in tunnel applications to improve the shotcrete/concrete performances.

Accordingly, the main object of this investigation is to evaluate the mechanical behaviours of steel mesh, steel fibre and high performance polypropylene fibre–reinforced hardened shotcrete/concrete mixes according to toughness, flexural ductility, energy absorption and load–carrying capacity characteristics. Not only the mix of PP fibres with steel fibres but also the mix of different type of steel fibres in different ratios were used as mixes to get the best efficiency from fibre–reinforced concrete matrix. Effect of fibre addition on compressive behaviour of hardened shotcrete/concrete matrix and rebound characteristics of the shotcrete mixes were also investigated in this study.

For these purposes, seventeen different shotcrete/concrete mixes having different reinforcements in different amounts were produced. The shotcrete and concrete mixes had different mix designs and they were all cured for 28 days for panel tests to evaluate the performance characteristics, such as toughness, flexural ductility, energy absorption, and load – carrying capacities etc.

Also, compressive strength tests were performed on these FRS/C mixes at the age of 3, 7, 28 days to determine the compressive load – carrying capacities of them.

CHAPTER 2

THEORETICAL CONSIDERATIONS

2.1 Definition of Composites

In the continuing request for improved performance, which may be specified by various criteria including less weight, more strength and lower cost, currently–used materials frequently reach the limit of their usefulness. Thus materials scientists, engineers and scientists are always striving to produce either improved traditional materials or completely new materials. Composites are an example of the latter category.

A *composite* is a material having two or more distinct constituents or phases and thus we can classify bricks made from mud reinforced with straw, which were used in ancient civilisations, as a composite. A versatile and familiar building material that is also a composite is concrete; concrete is a mixture of stones, known as aggregate, held together by cement. [1]

2.2 Main Constituents of Composites

It is known that composites have two (or more) chemically distinct phases on a microscopic scale, separated by a distinct interface, it is important to be able to specify these constituents. The constituent that is continuous and is often present in the greater quantity in the composite is termed the *matrix.*

The second constituent is referred to as the reinforcing phase, or *reinforcement,* as it enhances or reinforces the mechanical properties of the matrix. In most cases the reinforcement is harder, stronger and stiffer than the matrix.

2.2.1 Types of Reinforcements

The reinforcement is described as being either fibrous i.e. *fibre* reinforced or *particulate*. Particulate reinforcements having various shapes have dimensions that are approximately equal in all directions and the orientation of the particles is considered, for practical purposes, to be random (Figure 2.1.a). On the other hand, a fibrous reinforcement is characterised by its length being much greater than it's cross – sectional dimension. In addition, the ratio of length to the cross – sectional dimension, known as the aspect ratio, can vary considerably. In single – layer composites long fibres with high aspect ratios give what are called continuos fibre reinforced composites, where as discontinuous fibre composites are fabricated using *short* fibres of low aspect ratio relatively. The orientation of the discontinues fibre may be random or preferred (Figure 2.1.b and c) and the frequently encountered preferred orientation in the case of a continuous fibre composites termed unidirectional reinforcement (Figure 2.1.d).

Multi – layered composites are another category of fibre reinforced composites. These are classified as either *laminates* or *hybrids.* Laminates are sheet constructions that are made by stacking layers in a specified sequence. On the other hand, hybrids are usually multi – layered composites with mixed fibres and are becoming commonplace. The fibres may be mixed in a ply or layer by layer and these composites are designed to benefit from the different properties of the fibres employed [1].

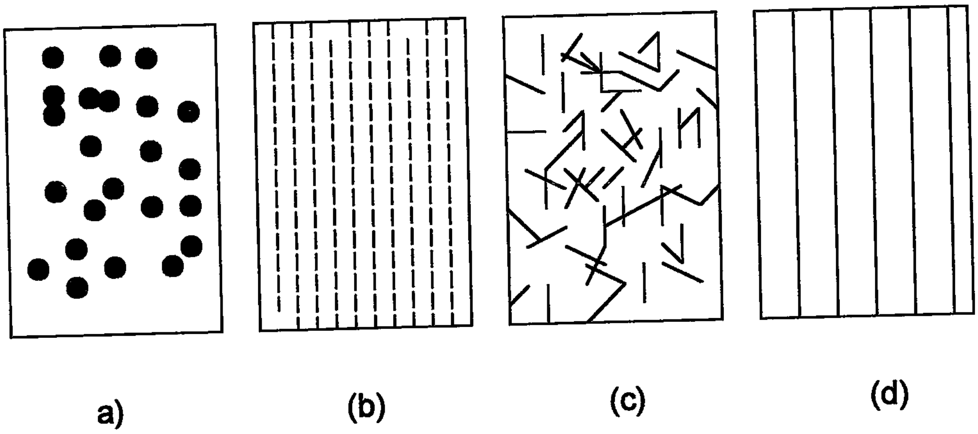


Figure 2.1 Examples of Composites: (a) particulate, random; (b) discontinuous fibres, unidirectional; (c) discontinuous fibres, random; (d) continuous fibres, unidirectional.

2.3 Fibre Reinforced Shotcrete/Concrete (FRS/C)

FRS/C can be classified as a composite material which consists of a matrix i.e. concrete/shotcrete and reinforcement named discontinuous, randomly distributed fibres.

Its bearing strength is determined by the combination of its two constituent's parts: the concrete/shotcrete and the fibres.

$$P_c = P_m + P_f$$

where the subscript c is for composite; m is for matrix; f is for fibre.

Especially, in the post elastic phase, the tensile strength in the composite can be calculated approximately by supposing $\sigma_m = 0$;

$$\sigma_c = k \times \sigma_f \times v_f$$

σ_c =strength of fibre – reinforced concrete (composite),

σ_f =strength of fibre,

v_f =volume fraction of fibre (V_f / V_c)

k =coefficient

This means that the strength of the composite can be greatly controlled if measures are taken to position and volume fraction of the majority of the fibres in predetermined planes [2].

According to The Law of Mixtures this explanation can be generalised as follows :

$$X_c = X_m v_m + X_f v_f \quad \text{(The Law of Mixtures)}$$

where X_c represents an appropriate property of the composite, v is the volume fraction and the subscripts, m and f refer to the matrix and reinforcement, respectively [1].

This assumes, there is a close interaction between the two materials. Where a load is applied, this results in a deformation of the composite. Depending on the state of deformation of the composite, this interaction is governed by:

- The ratio between the elasticity moduli ($n = E_f / E_m$)
- The transmission of the stress from the concrete/shotcrete to the fibres.
- The uniformity of the distribution of the fibres [16].

2.4 Steel Fibre Reinforced Shotcrete/Concrete (SFRS/C)

One of the fibre – reinforced composites is steel fibre – reinforced concrete/shotcrete (SFRC/S). It can be defined as mortar or concrete, containing discontinues discrete steel fibres, which are pneumatically projected at high velocity on to a surface." [3].

Since the early 70's when the first experimental work was undertaken with the steel fibre reinforced – shotcrete/concrete (SFRS/C), it has been the subject of many field and laboratory studies in the past [5,6] and is the focus of many current investigations [4,7,8]. Also, it has been used extensively in most of the world for a wide variety of applications, in new constructions, in the repair and rehabilitation of older and deteriorated structures such as in slope stabilization, as retaining walls for large excavations, at the tunnel faces, rehabilitation of deteriorated marine structures etc. [4,7,9,10,11].

As noted by ACI committee 544, the composite has potential for many more applications, specially, in the area of structural elements. A number of researchers are evaluating the possibility of using steel-fibre reinforced concrete for structural applications. Strength and ductility are among the important factors to be considered in the design of seismic resistant reinforced concrete structures. Under seismic condition, the structure may be subjected to large deformations. The addition of steel – fibres significantly improves many of the engineering properties of mortar and concrete, notably impact strength and toughness [11,17,18,19].

2.4.1 Comparison of Steel Fibres with Steel Mesh in Shotcrete/Concrete Applications

In general terms, steel fibres are incorporated in the shotcrete to enhance its crack resistance, ductility, energy absorption and impact resistance characteristics. Properly designed, SFRS/C, can reduce, or even eliminate cracking, a common cause for concern in plain shotcrete. The integrity of the SFRS/C across the crack (i.e. the ability to continue to carry load) can be maintained provided the cracks are not so wide that the steel fibres can deteriorate from corrosion.

Therefore, especially, in underground constructions, it has become more common to use steel fibre – reinforcement instead of steel mesh reinforcement in concrete and shotcrete. Because in steel mesh – shotcrete/concrete applications; installation of steel mesh is difficult, time consuming, hazardous under loose rocks and expensive; in addition, lining quality can be poor, that is, not a uniform bond between shotcrete and rock, forming low quality shadow areas behind the wire and bad reinforcement due to irregular mesh positions etc.

On the other hand, the main reasons for using shotcrete for tunnel linings are:

- To prevent or minimize rock displacement in loosening ground by
    - a) stiffening and strengthening the rock mass by filling open joints and fractures,
    - b) transferring the rock load to adjacent stable rock through adhesion or shear,
    - c) acting as a membrane in bending or tension when shotcrete bond is low and the shotcrete layer is continuos.

- In oxidising and slaking ground to seal the rock and prevent ravelling and sloughing, which occur because of exposure of the rock to moist air and/or ground water.
- To control water and ice formation by redirecting, draining or stopping water flow [4].

For these purposes, fibre usage in shotcrete is much more suitable and fibres eliminate the need for conventional concrete reinforcing steel, welded wire mesh or the chain link mesh, and this alone results in a significant placement ease. They impart toughness or energy absorption capability to hardened shotcrete resulting in improved deformability and impact resistance [7]. Additionally, steel fibre – reinforced shotcrete having high ductility provide immediate reinforced support, homogeneous fibre reinforcement and strong bond to the surface which is required to make the underground self – supporting by filling up voids [4].

In fact, fibres added to the shotcrete/concrete have also a positive effect on crack bridging as a confinement. They strengthen the composites not only because they carry part of the applied load, but also strengthen the matrices by their crack and pore – bridging capability. The resulting mechanism of crack control leads to a delay of failure [15]. They tend to spread the cracking over the entire specimen length in the form of many small cracks [20] and Aveston [21] were first to demonstrate that cracking would take place in a wider zone when steel fibres are added to the concrete mix. Basically, the fibres can act as additional bridging mechanisms as shown in Figure 2.2.

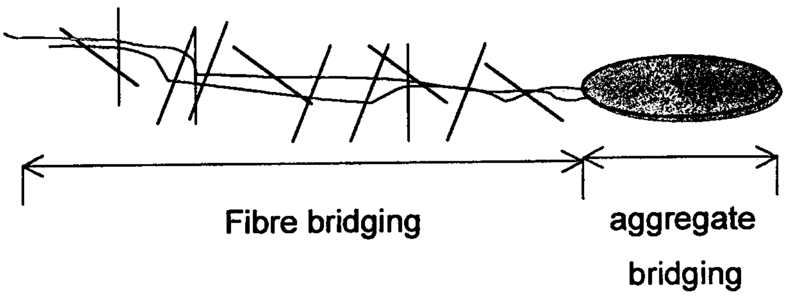


Figure 2.2 Fibre Bridging Mechanism in Cracks.

When the crack face bridging by grains has failed, stress transfer over the crack is possible through fibres intersecting with the crack. The maximum bridging stress that can be reached depends then on the elasticity of the fibres, the number of fibres, the shape and the inclination of the fibres with respect to the crack faces, and the pull-out behaviour [22].

2.5 Possible Usage of Polypropylene Fibres (PPF) in Shotcrete/Concrete

On the other hand, nowadays, new materials have been also investigated to replace or to use together with steel fibre in shotcrete/concrete. Polypropylene fibres could be one of this type of materials. It has been shown earlier [12-14] that cracking resulting from shrinkage and differential settlements during the fresh state of the concrete can be effectively inhibited by them (PP) [15]. In addition, they can be used to improve hardened concrete properties like toughness, flexural ductility, ultimate load capacity etc. This study also showed that the use of high performance polypropylene fibre having low fibre content with or without steel fibre reinforcement in shotcrete can greatly impart the flexural ductility, toughness, and ultimate load capacity and therefore possibly can be used with steel – fibre reinforcement especially in tunnel applications.

2.6 Hybrid Fibre Systems and Possible Usage of PP Fibres together with Steel Fibres (SF)

The underlying philosophy in the design of fibre composite materials is to find or to make a fibre material of high elastic modulus and strength, and preferably low density, and then to arrange the fibres in a suitable manner to give useful engineering properties to the final product [1].

PP fibres have large numbers in less amounts relative to steel fibres with low density and can be properly distributed in concrete matrix but their modulus of elasticities (E) are very low relatively. As a consequence, it can be expected that they cannot prevent the formation and propagation of cracks at high stress level. Neither can they bridge large cracks.

On the other hand, steel fibres have equal or larger length and higher Young's modulus as compared to the PP fibre. This leads to an improved potential for crack control. But volumetric density is high, and steel is conductive in electric and magnetic fields. So, steel fibre content has to be reduced to below a certain level in structures such as tunnels and continuous slabs for high – speed railway systems, where the communication system can be disturbed [15]. In addition, there are also differences in behaviours of the steel fibres; therefore, optimisation of mechanical and conductivity properties can be achieved by combining different kinds, types, and sizes of fibres.

In this study, not only the mix of PP fibres with steel fibres but also the mix of different type of steel fibres in different ratios were used in panels to get efficient results from fibre – reinforced concrete matrix. Because the different sizes of steel fibres contribute to different mechanical properties, at least to a different degree [15].

According to Bentur and Mindness [8] the advantages of hybrid fibre systems are as follows:

1- To provide a system in which one type of fibre, which is stronger and stiffer, improves the first crack stress and ultimate strength, and the second type of fibre, which is more flexible and ductile, leads to improved toughness and strain capacity in the post cracking zone.

2- To provide a hybrid reinforcement, in which one type of fibre is smaller, so that it bridges microcracks of which growth can be controlled. This leads to a higher tensile strength of the composite. The second type of fibre is larger, so that it can arrest the propagating macrocracks and can substantially improve the toughness of the composite. The basic purpose in using hybrid fibres is to control cracks at different size levels, in different zones of the concrete (cement paste or interface zone between paste and aggregate), at different curing ages and at different loading stages. The large and the strong fibres control large cracks. The small and soft fibres control crack initiation and propagation of small cracks [23].

3- To provide a hybrid reinforcement, in which the durability of fibre types is different. The presence of the durable fibre can increase the strength and / or toughness retention after age while another type is to guarantee the short-term performance during transportation and installation of the composite elements.

2.7 Toughness, Ductility and Brittleness

It must be stated that *toughness* which can be defined as the measure of the ability of the material to absorb energy during deformation estimated using the area under the stress-strain curves [17] or load-deformation curves and *ductility,* high fracture strains, are the most important characteristics which must be improved in the properties of concrete/shotcrete composites and the main reason for incorporating fibres in concrete and shotcrete is to impart ductility and toughness to an otherwise brittle material.

The effectiveness of the toughening mechanisms of composites depends to varying degrees on :

- size, morphology and volume fraction of the reinforcement (fibre);
- interfacial bond
- properties (e.g., mechanical, thermal expansion) of the matrix (concrete) and the reinforcement (fibre); and
- phase transformations. [1].

On the other hand, brittleness (as opposed to toughness) can be conveniently expressed by the quotient of stored elastic energy and fracture energy following:

$$\frac{elastic\ \ energy}{fracture\ energy} = \frac{L^3 f_t^2 / E}{L^2 G_f} = \frac{L f_t^2}{E G_f}$$

where L is a characteristic size of the structure, f_t is the tensile strength of the material, E is the Young's modulus and G_f is the fracture energy of the material in [J/m^2] or [N/m]. A structure behaves as brittle if the stored elastic energy is much larger than the energy needed to fracture the structure. On the other hand, ductility or toughness of the structure is improved when the fracture energy is larger than the stored elastic energy [22].

Fibre reinforcement improves the energy absorption and crack resistance of matrix, in this way enables concrete/shotcrete to continue to carry load after cracking, the so – called post – crack behaviour [4] which helps maintain structural integrity and cohesiveness in the material. Further, if properly designed, fibres undergo a pullout process, and the frictional work needed for pullout leads to a significantly improved energy absorption capability. This energy absorption attribute of SFRC/S is often termed toughness [24].

CHAPTER 3

REVIEW OF PREVIOUS RESEARCH ON STEEL FIBRE REINFORCED SHOTCRETE/CONCRETE (SFRS/C)

3.1 Flexural Behaviour of Steel Fibre – Reinforced Shotcrete/Concrete (SFRS/C)

The enhanced performance of fibre-reinforced concrete compared to its unreinforced counterpart comes from its improved capacity to absorb energy during fracture. While a plain matrix fails in a brittle manner at the occurrence of cracking stresses, the ductile fibres in fibre reinforced concrete to carry stresses well beyond matrix cracking, which helps maintain structural integrity and cohesiveness in the material [24].

The addition of steel fibre significantly improves many of the engineering properties of mortar and concrete, especially impact strength, flexural toughness and ductility [11,17].

Steel fibre reinforced concrete (SFRC) is superior to plain concrete in toughness, that is the energy absorption at fracture [25]. If properly designed, fibres undergo a pullout process, and then frictional work needed for pullout leads to a significantly improved energy absorption capability. This energy absorption attribute of SFRC is often termed toughness [24].

3.1.1 Effects of Properties of Matrix and Fibres on the Flexural Behaviour of SFRS/C

The performance of SFRC is influenced by the properties (geometry and strength) of fibre, the fibre contents, the fibre distribution, and the performance of the matrix concrete and so on [25].

The fibre geometry and matrix strength is very effective on the characteristics of SFRC, especially on toughness and ductility. However, as pointed out by Balaguru [26], a great deal of earlier research was conducted with straight, undeformed fibres, which are now rarely used in field applications. In addition, most investigators have used unrealistically high fibre volume fractions with little relevance to the quantities used in the field [24].

According to the study of Nataraja and Dhang [24] which is based on JSCE (Japan Society of Civil Engineers) approach; two aspect ratios of fibre and two different concrete strengths were considered. The toughness factor as measured by the JSCE approach was reported. It was observed that there exists a good correlation between flexural toughness with the fibre-reinforcing index and it can be seen that the flexural toughness and flexural toughness index increase as the fibre volume fraction is increased for a given aspect ratio. It also increases as the aspect ratio is increased for a given volume fraction. In addition, flexural toughness increases as the strength of the matrix is increased.

In the research of Norihiko, Minoru and Toshiro [25]; the properties of various kinds of steel fibre reinforced concrete were evaluated by means of the tension softening diagrams which can describe the post – cracking behaviour of concrete in tension. At first, the applicability of the tension softening diagram to SFRC was investigated.

Then, the fracture mechanics parameters were adopted as indices for the evaluation of properties of various kinds of SFRC. The influence of the tensile strength of the steel fibre on the failure behaviour of SFRC was examined. The efficiency of the fracture mechanics parameters was examined through comparison with conventional indices.

In this study, three kinds of steel fibres in contents of 1%, 2%, 4% and 6% by volume were used. Third-point loading tests were carried out. The loads and loading point displacements were recorded. The tensile strength tests of the steel fibres were also carried out and tension softening diagrams were determined. The flexural toughness was calculated through " The test method for flexural toughness of SFRC" proposed by JCI [27].

The properties of SFRC were evaluated by the fracture energy, the flexural toughness and the equivalent flexural strength. It was concluded that the influence of the properties of added fibres on the performance of SFRC was great when the matrix strength was high. For the evaluation of the properties of SFRC with different matrix strength, the shape of the tension softening diagram and the fracture energy the area under the tension softening diagram were superior to the flexural strength. Also, in the case of SFRC with high strength matrix, the toughness improved by adding steel fibres was dependent on the properties of the fibres. Finally, the flexural toughness directly depended on the specimen size and the equivalent flexural strength tended to depend on the size. Therefore, the fracture energy was a more suitable index than the flexural toughness and the equivalent flexural strength for the evaluation of the properties of SFRC [25].

Balaguru, Narahari and Patel [26] evaluated three fibre types, three fibre lengths, four fibre volume fractions and four matrix compositions. The results indicate that fibre content in the range of 50 to 100lb/yd^3 (30 to 60kg/m^3) provide excellent ductility for normal strength concrete. The fibre content has to be increased to about 90kg/m^3 for high strength concrete. Hooked-end fibre geometry provides better results than corrugated and deformed end geometry. Fibre length in the range of 30 to 60 mm does not have a significant effect on toughness for hooked-end fibres. Ductile behaviour can be obtained using 120kg/m^3 of fibres even for concrete containing %20 silica fume by weight of cement.

Apart from these, it is well known that steel fibres reduce the deflection of reinforced normal strength concrete beams as documented by other researchers [28,29]. As shown references [30,31], the addition of steel fibres can also reduce the deflection of reinforced high strength concrete beams and improve post-cracking behaviour significantly.

Quian and Indubhushan [32] studied the properties of high strength steel fibre reinforced concrete beams in bending. The investigations were made on ten high strength reinforced concrete beams and steel fibre reinforced high strength concrete beams, with steel fibre content of 1% by volume. The enlarged ends of mild carbon steel fibres with three different dimensions were selected. This research shows that the flexural rigidity before yield stage and the displacement at 80% ultimate load in the descending curve improved and crack number and length at comparable loads is reduced after the addition of steel fibres. The descending part of the load displacement curve of the concrete beams without steel fibres is much steeper than that with steel fibres, which shows that the addition of steel fibres makes the high strength concrete beams more ductile.

For steel fibre-reinforced concrete with practical fibre volume fractions, the major post-peak energy dissipation mechanism is the pullout of fibres across a crack. With undeformed, smooth fibres, post-peak energy dissipation or `toughness' is mainly a function of fibre-matrix adhesional bond, whereas for the highly stressed deformed fibres, properties of the bulk matrix also become important. High-performance matrices tend to be brittle, and addition of pozzolanic admixtures, particularly silica fume, further increases the brittleness. An increased matrix brittleness can cause crushing and splitting of the matrix and in turn, curtail the ability of fibres to transfer stresses during pullout, thus reducing the overall toughness.

In the research of Dubay, Ashis and Banthia [33], it was studied the influence of high-reactivity metakaolin and silica fume on the flexural toughness of high-performance steel fiber-reinforced concrete. They examined the influence of two pozzolanic materials-high-reactivity metakaolin (HRM) and silica fume-on the toughness characteristics of high-performance fibre-reinforced concrete. It was concluded that HRM was particularly effective in improving the post-peak energy absorption capacity of concrete with fibres, and unlike silica fume, no particular post-peak brittleness was seen to occur.

Eren and Çelik [34] also investigated the effect of silica fume and steel fibers on some properties of high-strength concrete (HSC). The influence of silica fume on the properties of HSFRC were studied by using silica fume of two different percentages and three different hooked-end fibres namely, 30/0.50, 60/0.80 and 50/0.60 length/diameter (mm/mm). Fibres were added to concrete in three different volume percentages of 0.5, 1.0 and 2.0 by volume of concrete.

The results indicated that there is a linear function between splitting tensile strength (F_{splt}) and volume percentage of fibres (V_f) [i.e. $F_{splt} = A(V_f) + B$, where A and B are correlation coefficients] as well as between splitting tensile strength (F_{split}) and compressive strength (F_c) of plain series A concrete [i.e. $F_{split} = C(\sqrt{F_c}) + D$, where C and D are correlation coefficients]. These relations can describe the development of splitting tensile strength of HSFRC containing no silica fume, 5% silica fume and 10% silica fume by weight of cement. On the other hand, although silica fume has an effect on compressive strength, volume percentage and aspect ratio of steel fibers has little effect.

3.1.2 Effects of Manufacturing Techniques and Environmental Conditions on the Flexural Behaviour of SFRS/C

Prevention of moisture loss and immediate water curing are directly related to the mechanical properties and durability of concrete. Research shows air curing is not reliable curing procedure because it greatly influences the durability and strength [35,36]. Steam curing is recommended in concrete that contains mineral additives, such as silica fume and slag, to improve strength and durability [37].

Fly ash can be an important ingredient to be added to the fibrous concrete mixtures. The addition of fly ash to the fibre concrete mixture increases the volume of paste content and thus facilitates the accommodation of the fibres, minimising the fibre settlement. Furthermore, fly ash improves workability and pumpability of fibre reinforced concrete. Results show that a number of mechanical properties of fibre-reinforced concrete are positively affected by the curing procedure, matrix composition and fibre size, fibre content, fibre spacing and arrangement, fibre direction vs. testing direction, and addition of fly ash [37].

Upon placement and compaction of steel fibrous concrete, the fibres tend to settle towards the bottom part of the beam. During flexural testing, depending on the relative location of testing direction compared to the casting (placement) direction, fibre settlement may affect test results. Depending on the flowability of fibrous mixture, fibre settlement may be extensive, moderate or mild, and test results are affected accordingly. ASTM C 1018, which describes flexural test methods utilised on fibre reinforced concrete (using beam with third point loading) [38], specifies that testing direction be perpendicular to casting direction for thick specimens. This eliminates the effect fibre settlement; which may lead to non-uniform fibre dispersion (more fibres in the lower half of the beam). This fibre settlement effect can be utilized to enhance the flexural behaviour of steel fibre concrete in application fields such as slabs, floor systems etc

Toutanji and Bayasi [37] investigated the effects of curing environments and that of testing direction relative to casting direction on the mechanical properties of fibre reinforced concrete. In this study, specimens were cured in three different environmental conditions: steam, moisture, and air. Results showed that steam curing, as compared to moisture curing, did not enhance the flexural strength of steel fibrous concrete but reduced the flexural toughness. As expected, air curing showed detrimental effects on all aspects of the test results, as compared to steam and moisture curing.

They also reported that the flexural behaviour of steel fibre reinforced concrete was strongly affected by testing direction. When testing direction was perpendicular to casting direction, specimens exhibited reductions in both flexural strength and toughness compared to the case when testing and casting directions were parallel. The effect of testing direction relative to casting direction on flexural strength and toughness increased with increasing the workability of the fibrous mixture, which encouraged fibre settlement during placement.

Chen and Mindess [39] had determined the first – cracking strength and flexural toughness of steel-fibre-reinforced concrete specimens with different dimensions using the procedures outlined in ASTM C 1018 and JSCE-SF4 and they calculated the ASTM toughness indices and JSCE toughness parameters. It was found that variation in specimen size influenced not only the stress and deflection at first crack, and the ultimate strength, but also all the toughness parameters. Toughness parameters decreased in an increase in the span-to-depth ratio of the specimens. All toughness parameters were significantly affected by the width of the specimen, even when both depth and span were unchanged; the toughness increased with an increase in width.

In the research of Pigeon and Cantin [40] the mechanical properties of steel fibre-reinforced concrete at low temperatures were determined using the standard ASTM C 1018 flexure test. The tests were performed at normal room temperature (20 ^{0}C) at -10 ^{0}C, and at -30 ^{0}C. In addition to the temperature, the variables investigated were the type of cement (Both normal Portland cement and silica fume cement were used.), the water binder ratio (0.45, 0.35 and 0.30), the type of fibre (two very different geometries were chosen), the fibre dosage (40kg/m^3 and 60 kg/ m^3). The results show that the toughness of SFRC under flexural loading increases with a decrease in temperature. This increase appear to be related to the increase in the strength of the matrix at low temperatures (because of the freezing of water in the capillary pores.), which increases the energy required for fibre pull-out. The toughness increase was observed both for normal and high performance concrete, and for both types of fibres at both dosages. In these tests, the influence of the fibre geometry was found to be relatively small.

3.1.3 Comparison of the Test Methods to Investigate the Flexural Toughness of SFRS/C

Several methods have been proposed to evaluate the fracture toughness of cement –based materials [41-46,27]; for example, ASTM C1018 (four-point bending), RILEM 50-FMC Draft Recommendation (three – point bending with notched beam), Japan Institution of Standard (four – point bending), Canadian post-crack strengths etc. The most widely used standard test methods are the ASTM C 1018 standard test method and the Japan Society of Civil Engineers (JSCE) standard SF-4 method.

The ASTM 1018 [38] standard method is based on determining the amount of energy required first to deflect and crack a fibre – reinforced concrete beam loaded at its third points, and then to further deflect the beam out to selected multiples of the first – crack deflection (Figure 3.1).

Toughness indices I_5 , I_{10} , I_{20} , I_{30} etc.. are then calculated by taking the ratios of the energy absorbed to a certain multiple of first – crack deflection and the energy consumed up to the occurrence of first crack. For example, standard toughness indices I_5 , I_{10} , I_{30} are defined for a deflection up to 3δ, 5.5δ and 15.5δ, where δ is the deflection at the first crack.

Expressed in general terms.

I_N = Energy absorbed up to a certain multiple of first-crack deflection/ Energy absorbed up to the first crack.

The subscript N in these indexes are based on the elasto – plastic analogy such that, for a perfectly elasto – plastic material, the index I_N would have a value equal to N. Here, the given FRC is compared with a conceptual material that behaves in an ideally elasto –plastic manner. Implicitly, the scheme also assumes that plain concrete is ideally brittle and; hence, the various toughness indexes in its case assume a constant value of 1.

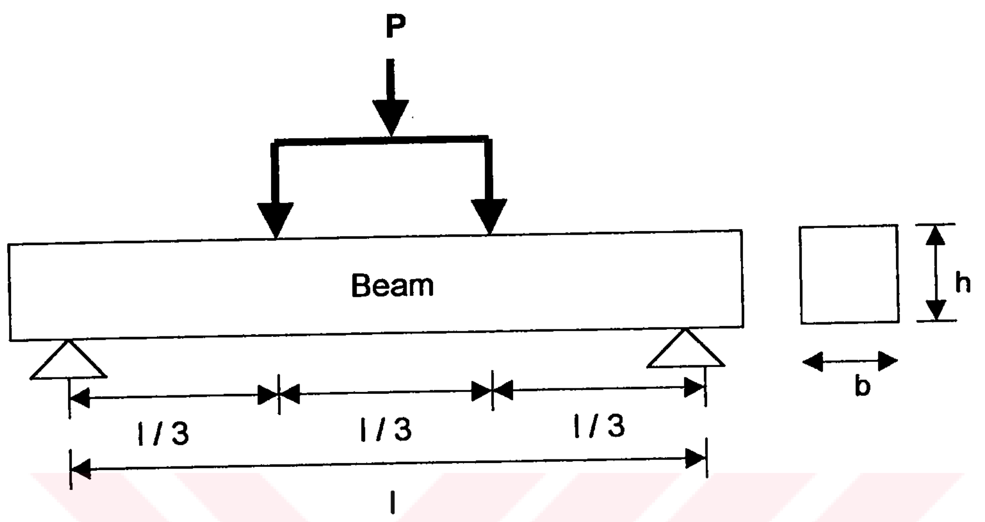


Figure 3.1 Flexural Test Set – Up

According to Banthia and Trottier [44,46], there are many concerns with the ASTM C 1018 and JSCE test methods. These are briefly discussed below.

3.1.3.1 Concerns with the ASTM C 1018 Test Method

3.1.3.1.1 Measuring true specimen deflections

An accurate measurement of deflection is very important to characterize toughness of FRC. In a flexural specimen under a transverse load, however, the biggest source of error is the settlement of the specimen supports themselves, such that the measured displacement of the load points comprises not only the true displacement due to the response of the beam material to the applied stress but also those arising from seating and the downward movement of the beam as a rigid body. If not properly considered, the settlement in the supports can lead to a gross overestimation of the first-crack energy and, hence, to erroneous indexes. The calculation of toughness indexes requires an accurate assessment of the first-crack energy, which constitutes the denominator in the definition of the various indexes. In addition, it is mentioned that the identification of first-crack deflection is not so simple, due to the substantial non-linearity of load deflection curves even prior to attaining the peak load.

3.1.3.1.2 Instability after peak load

The point of peak load occurrence, however, is also the point of instability for the loading machine, which, if not stiff enough, will undergo sudden unloading and release large amount of energy. This sudden release of energy has major effects on the load – deflection curves immediately following the peak load. The problem associated with instability can be remedied by using a closed-loop servo controlled test system. The commercial laboratories, unfortunately, do not commonly use this kind of sophisticated equipment.

3.1.3.2 JSCE Standard SF – 4 Test Method

In this technique [47], the area under the load – deflection plot up to a deflection of span/150 is obtained. From this measure of flexural toughness, a flexural toughness factor (FT) is calculated. It may be noted that FT has the unit of stress such that its value indicates, in a way, the post – matrix cracking residual strength of the material when loaded to a deflection of span/150. The chosen deflection of span/150 for its calculation is purely arbitrary and is not based on serviceability considerations.

3.1.3.2.1 Concerns with the JSCE SF-4 Test Method

Identifying the correct occurrence location of the first crack, which is crucial and one of the main problems with the ASTM method, is not a concern with the JSCE method. Unlike the ASTM method, the instability in the load – deflection plot right after the first crack is not of major concern in the JSCE method, since the end point deflection of span/150 is too far out in the curve to be affected by the instability in the initial portion. However, there are other limitations and concerns. First of all, FTs are specimen geometry – dependent, which makes an exact correlation with the field performance of FRC rather difficult. In addition, the end point chosen on the curve at a deflection of span/150 is often criticized for being much greater than the acceptable deflection/serviceability limits. The behavior immediately following the first crack, which may be of importance in many applications, is not indicated in FT in any way. Finally, the technique may be criticized for failing to distinguish between the pre – peak and post – peak behaviors by adopting the smeared approach of using the total area under the curve to calculate FTs.

3.1.3.3 Comparison of Beam Tests with Slab Test

According to explanations, the tests mentioned above can be generalised as beam tests. In fact, there have been mainly two tests, beam and slab tests, to investigate toughness behaviour and energy absorption capacity of steel fibre–reinforced concrete/shotcrete . Although in slab – like concrete structures, effective prestressing for crack control purposes will be very difficult, especially in the two principal directions, because of the following reasons, the panel test was considered as better for examining the material properties than the beam test [4, 48].

1. A beam is statically determinate system and will be subjected to bending in the longitudinal length direction only.

2. A plate is statically indeterminate system and will be subjected to bending in two directions (x and y). A statically indeterminate system allows additive stress redistribution in another direction after the first peak – load.

3. A slab is considered to represent more realistically the two – directional bending of thin shotcrete shell structures in tunnelling and mining than the beam [48]. In addition, the slab support on the four edges simulates the continuity of the shotcrete lining.

4. Steel fibre – reinforced shotcrete/concrete and high performance polypropylene fibre – reinforced shotcrete/concrete can be compared very easily with a mesh – reinforced shotcrete, to be tested in the same way [4].

3.2 Properties of Steel Fibre – Reinforced Shotcrete/Concrete (SFRS/C) under Compression

The mechanical properties of concrete/shotcrete can be improved by the addition of steel fibres. Toughness of steel fibre reinforced concrete/shotcrete can be measured by different test methods , such as the beam test and the panel test. While most methods give an indication of the flexural energy, the compressive test should also be considered to observe the behaviour of SFRC for underground construction especially at an early age, because in many cases SFRC/S in tunnels is mainly subjected to compression.

Many researchers hold the view that steel fibres do not have a significant influence on the compressive behaviour of concrete/shotcrete due to the small volume of fibres in concrete/shotcrete mix especially at the age of 28 days [49].

In the research of Ding and Kusterle [49] compressive stress strain relationship of steel fibre reinforced concrete at early age was investigated. Experimental investigations have been carried out on laboratory concrete as well as on dry-mix shotcrete at a tunnel site. The measurements were performed at about 9 h and continued up to 81 h on 20 cm * 20 cm * 20 cm cube specimens. This study demonstrated that the use of fibre reinforcement in concrete/shotcrete can greatly enhance the compressive ductility, toughness and energy absorption at early ages.

Nataraja, Dhang and Gupta [50] also studied stress-strain curves for steel fibre reinforced concrete under compression. In this experimental investigation, an attempt has been made to generate the complete stress-strain curve experimentally for steel-fibre reinforced concrete for compressive strength ranging from 30 to 50 MPa. Round crimped fibres with three volume fractions of 0.5 %, 0.75 % and 1.0 % (39, 59, and 78 kg/m^3) and for two aspect ratios of 55 and 82 are considered. The effect of fibre addition to concrete on some of the major parameters namely peak stress, strain at peak stress, the toughness of concrete and the nature of the stress-strain curve is studied. It was concluded that addition of crimped steel-fibres to concrete increases the toughness considerably. The increase in toughness is directly proportional to the reinforcing index. Increase in toughness is marginally higher for lower grade of concrete compared to higher grade of concrete. A marginal increase in compressive strength, strain at peak stress is also observed. This increase is directly proportional to the reinforcing index.

Torrenti [51] showed that in the case of metal fibre concretes under biaxial compression, the gain strength yielded by metal fibres can be considerable. In this research, the behaviour of metal fibre concrete subjected to biaxial loading was studied. Two different types of fibres and biaxial press with brush bearing platens (to avoid lateral confinement) were used. It was concluded that the addition of fibres made the material much more ductile; there was an influence of the type of fibre on mode of failure, a gain of strength and an influence of the orientation of the fibres.

3.3 Impact and Abrasion Resistance of Steel Fibre – Reinforced Shotcrete/Concrete (SFRS/C)

Steel fibre-reinforced concrete/shotcrete in many civil engineering structures must have adequate resistance to impact and impulsively applied loads. It is is currently used to provide massive armours against the impact of projectiles in sentry boxes, arms and powder depots, and other defence buildings.

In the research of Nataraja, Dhang and Gupta [52], the variation in impact resistance of steel fibre-reinforced concrete and plain concrete as determined from a drop weight test was reported. The observed coefficients of variation are about 57 and 46% for first-crack resistance and the ultimate resistance in the case of fiber concrete and the corresponding values for plain concrete are 54 and 51%, respectively. The goodness-of-fit test indicated poor fitness of the impact-resistance test results produced in this study to normal distribution at 95% level of confidence for both fiber-reinforced and plain concrete. However, the percentage increase in the number of blows from first crack to failure for both fiber-reinforced concrete and as well as plain concrete fit to normal distribution as indicated by the goodness-of-fit test. The coefficient of variation in percentage increase in the number of blows beyond first crack for fiber-reinforced concrete and plain concrete is 51.9 and 43.1%, respectively. Minimum number of tests required to reliably measure the properties of the material can be suggested based on the observed levels of variation.

Luo, Suna and Chanb [53] studied the characteristics of high-performance steel fiber-reinforced concrete subject to high velocity impact. Targets made of high-performance steel fibre-reinforced concrete (HPSFRC), which was produced by fluidised mortar, steel fibres and casting process of mortar infiltrating and vibrating, were subjected to high velocity impact of projectile and compared with those targets made of reinforced high strength concrete (RHSC). Test results show when impacted by projectiles at high speed, the RHSC targets exhibited smash failure, while HPSFRC targets remained intact with several radial cracks in the front faces penetrated by projectiles and some minor cracks in the side faces. The projectiles were either embedded in or rebounded from HPSFRC targets.

Soil saving dam, breakwater and pavement that are located in severe wearing condition are often subjected to rapid deterioration of structure. Ultra-high strength concrete exceeding 200 MPa with or without steel fibre, has a possibility of becoming high abrasion resistance concrete.

Febrillet , Kido and Ito [54] investigated the effect of addition of steel fibres, water-binder ratio and compaction method on abrasion resistance and mechanical properties of ultra-high strength steel fibre reinforced concrete. It was concluded that, the combination of addition of steel fibres and using hot-press compaction for ultra-high strength mortar is particularly effective in improving abrasion resistance.

On the other hand, Lok and Xiao [55] studied the behaviour of steel-fibre-reinforced concrete panels exposed to air blast loading. Scaled explosive tests have been conducted to investigate the response of steel-fibre-reinforced concrete (SFRC) model structural elements. The structural elements were (a) rectangular panels, simply supported on two opposing shorter edges, (b) square panels, simply supported on all edges, and (c) fully fixed panels, in the form of an open box. Seven air blast tests were conducted. For each test, six panels were exposed simultaneously to air blast overpressure generated from the detonation of bare high explosives; charge weights ranged from 8 kg to 40 kg. The panels were fabricated with different types of steel fibre, fibre concentration and conventional wire mesh reinforcement.

Test results indicate that, as a construction material, SFRC can make an important contribution to the integrity and resistance of blast-resistant structures. Details of the experimental investigation and response of the panels are presented. A single-degree-of-freedom model, which incorporates an elastic-plastic structural resistance function for the dynamic analysis, is used to predict the response. The deformed configuration of the panels was computed at constant load steps, and the results were employed to evaluate the parameters of an equivalent dynamic model.

3.4 Fatigue Behaviour of Steel Fibre – Reinforced Shotcrete/Concrete (SFRS/C)

Most engineering components are subjected to cyclical stresses in use, i.e. to alternating stresses that recur indefinitely. This variation is either attributable to changes in the load, or else to changes in the position of the component in relation to the load. SFRS/C structures are also subjected to these cycling loads in their fatigue life.

For example, in Japan, the deterioration of reinforced concrete slabs has become a serious problem. The slab thickness increasing method using steel fibre reinforced concrete (SFRC) is frequently applied to reinforce such damaged slabs. In the study of Mutsumi and Hirotoshi [56], specimens were tested to examine the fatigue properties of SFRC, and the addition of steel fibres to concrete was found to increase the fatigue life. In particular, this tendency was marked when the steel fibre content was more than 1.0% by volume (78kg/m^3).

Ahmed, Gupta and Krishnamoorthy [57] showed the influence of steel fibres on the fatigue behaviour of concrete in direct compression. Both the S-N (strength-number of cycles) and strain behaviours have been investigated. The fibres investigated were straight (volume fraction of one percent) and hooked (volume fractions of one percent and two percent) steel fibres. The maximum stress levels ranged from 95 to 55 percent of the static compressive strength while the minimum was kept at 10 percent during the tests. The number of cycles was extended up to one million. Strains were measured at different stages of fatigue cycling. The study shows that the addition of fibres enhances the fatigue strength of concrete at all stress levels significantly though not very greatly. The higher the fibre content, the higher the fatigue strength, and hooked fibres were better than straight fibres. Fibres reduced the variability in fatigue life. The strains at failure of fibre reinforced concrete were higher than those of plain concrete and fibres increased the strain sufferance capability of concrete at the stages of dilation and failure.

Yin and Thomas [58] also investigated the fatigue behaviour of SFRC in uniaxial and biaxial compression by comparing that of plain concrete. Seventy-two steel reinforced concrete specimens, with 1% by volume 25mm long fibres, were tested under compression fatigue loading. The S-N curves were obtained under four stress ratios of 0 (uniaxial), 0.2, 0.5, and 1.0, resulting in a series of fatigue stress envelopes for fibre concrete. Deformations in all three principal directions were measured. The S-N curves, strength envelopes, failure modes, and cyclic deformations of fibre concrete are compared to those of plain concrete. It is found that addition of fibres does not increase the endurance limit but is beneficial above the endurance limit in the low-cycle region. Furthermore, adding fibres to concrete increases its ductility, and changes failure modes from splitting-type to faulting-type.

Sun, Gao and Yan [59] concluded that the effect of volume fraction and length diameter ratio of fibres on fatigue performance of concrete is extremely prominent. When silica fume, steel fibre, and their composite are added to high-strength concrete, since the effects of the two of nucleation and pozzolanic reaction of silica fume are in the cement matrix, and the effects of steel fibre on the strengthening, toughening, and crack arresting in the composite, the interfacial structure of both the fibre cement matrix and aggregate cement matrix is strengthened. The double effect of interfacial strengthening and space superimposing of the fibre-cement matrix and aggregate-cement matrix is produced and the interfacial structure and character are improved, the process of strengthening, vanishing, and restrengthening of the interface is caused, and the dimension and the amount of crack sources are reduced, thus delaying crack extension and propagation and the process of fatigue damage, evidently prolonging fatigue life.

Jun, Stang and Li [60] studied the crack bridging in steel-fiber-reinforced concrete (SFRC) materials under deformation-controlled uniaxial fatigue tension. Two types of commercially available steel fibers, straight steel fiber and hooked end steel fiber, were used separately in this experimental investigation. A total of six series of fatigue tensile tests with constant amplitude between maximum and minimum crack openings were conducted. The experimental results show that the bridging stress decreases with the number of load cycles, and this phenomenon is termed bridging degradation. The general behavior of the bridging degradation with the number of cycles in SFRCs is represented by a fast dropping stage (reduction in bridging stress within the first 10-15 cycles) with a decelerated degradation rate, followed by a stable stage with an almost constant degradation rate for straight SFRC, or by several periods with a decelerated rate in each period for hooked SFRC. Although fiber deformation, such as in hooked end fibre, can improve the monotonic crack bridging significantly, faster bridging degradation is found in hooked SFRC than in straight SFRC with the same maximum crack width (>0.1 mm) and minimum load condition.

3.5 Properties of Steel Fibre – Reinforced Shotcrete/Concrete (SFRS/C) Beams under Shear

When principal tensile stresses within the shear region of a reinforced concrete beam exceed the tensile strength of concrete, diagonal cracks develop in the beam, eventually causing failure. The brittle nature of concrete causes the collapse to occur shortly after the formation of the first crack. The addition of steel fibres aids in converting the brittle characteristics to a ductile one. The principal role of fibres is resisting the formation and growth of cracks by providing pinching forces at crack tips. In addition, a marginal improvement in tensile strength also results and fibre reinforced concrete has higher ultimate strain than plain concrete.

Lima and Ohb [61] investigated the shear of steel fibre reinforced concrete beams. The tests were carried out on concrete beams reinforcedwith stirrups and steel fibres. The main purposes of the present study were (1) to study the mechanical behaviour of reinforced concrete beams containing steel fibres under shear, (2) to study the potential use of fibres to replace the stirrups, (3) to investigate combinations of stirrups and steel fibres for improvements in ultimate and shear cracking strengths as well as ductility. The present experimental program consists of testing three series of reinforced concrete beams having identical rectangular cross sections of 100 x 180 mm. The span length of the members is 1300 mm with a shear span length of 400 mm. A total of nine beams were tested to investigate the influence of fibre reinforcement on the mechanical behaviour of reinforced concrete beams in shear. The major test variables are the volume fraction of steel fibres and the contents of shear stirrups. The volume fraction of steel fibres were varied from 0% to 2% and the ratios of stirrups from 0% to 100% of the required shear reinforcement. The beams were tested under four-point loading condition and the load was applied to the test beams as two equal concentrated loads by means of steel spreader beam.

It was concluded that the mode of failure changed from shear to flexure when the volume fraction of steel fibres used exceeds a certain amount, namely about 1% in this study. This means that the addition of fibre reinforcement increases shear capacity greatly. Cracking shear strength increased significantly, about twofold, due to the addition of fibres when fibre con-tents used was 1%. Thus, the addition of fibres is effective in controlling shear cracks. Also, the use of fibre reinforcement can reduce the amount of shear stirrups required and a combination of fibres and stirrups may satisfy strength and ductility requirements.

In the research of Khaloo and Kim [62], results of an experimental investigation carried out to assess the effect of various concrete strength levels on strength and ductility behaviour of steel fibre reinforced concrete (SFRC) under direct shear was reported. The principal variables of the testing program were: (a) compressive strength of concrete, (b) volume of steel fibres, and (c) the aspect ratio of steel fibres. The concrete strengths investigated include 28 MPa for low strength (LC), 44 MPa for normal strength (NC), 54 MPa for medium strength (MC), and 72 MPa representing high-strength concrete (HC). Fibre content ranges from zero to 1.5 percent by volume of matrix. In total, twenty-eight push-off type specimens were tested. Formulations are proposed to predict the shear response of the test specimens. Addition of fibres regardless of concrete strength led to shear strength, ductility, and toughness enhancement of SFRC; however, the improvement for higher strength concrete was more pronounced than that for lower strength concrete. This is attributed to the improved bond characteristics associated with the use of fibres in conjunction with high-strength concrete. Fibres with larger aspect ratio provided higher toughness and higher ultimate shear strength concrete. The influence of fibre volume on shear behaviour of concrete was much higher for high-strength concrete. In general, good agreement between the shear behaviour predictions and the test results was found.

On the other hand, Tan and Paramasivam [63] studied punching shear strength of steel fibre reinforced concrete slabs. Each of 14 square slabs was simply supported along four edges and loaded to failure under a concentrated load over a square volume fraction of steel fibres p integra, slab thickness h, concrete strength fc, and size of loading -bearing plate r. Test results indicate that the load-deflection curve of slabs exhibit four distinct regions that may be characterised by first cracking, steel yielding, and ultimate load. Within the scope of the test program, an increase in the values of p integral, h, or r was found to lead to an increase in both the punching shear strength and the ductility of the slab. The ultimate punching shear strength of the slabs was compared with the predictions of equations available in the literature and code equations for reinforced concrete.

3.6 Durability Properties of Steel Fibre – Reinforced Shotcrete/Concrete (SFRS/C)

The corrosion resistance of SFRS is governed by the same factors that influence the corrosion resistance of conventionally reinforced concrete or shotcrete. As long as the matrix retains its inherent alkalinity and remains uncracked, deterioration of SFRS is not likely to occur. It has been found that good quality SFRC/S, when exposed to conditions conducive to reduced alkalinity, such as atmospheric pollution, deicing chemicals or a marine environment, will only carbonate to a depth of a couple of milimeters over a period of many years.

Krishnamoorthy, Bharatkumar, Balasubramanian, and Gopalakrishnan [64] carried out investigations to find the influence of corrosion of steel fibres on the strength and toughness characteristics of steel fibre reinforced concrete (SFRC). The specimens were subjected to accelerated corrosion by continuous wetting in salt solution and subsequent drying. It is found that there was no corrosion of steel fibres embedded in concrete even after exposure to 250 cycles of corrosion.

In the research of Abdullah and Saeki [65] corrosion-protection behaviour of galvanized steel fibers in reinforced concrete specimens was studied under accelerated artificial aggressive conditions. The results showed that in the galvanized steel fiber reinforced concrete matrix, although the amount of chloride ion was 10 times more than the threshold limit to initiate corrosion, the embedded steel bars were not corroded. However, in the same conditions the bars which were not incorporated by galvanized steel fibers in the concrete matrix were seriously corroded. On the other hand, galvanized steel fibers had a sacrificial anode role to protect the corrosion of reinforced concrete and also could tolerate a higher chloride concentration than the non-fiber concrete matrix.

Cantin and Pigeon [66] made investigations to determine if the use of steel fibres can have a significant influence on the deicer salt scaling resistance of concrete exposed to severe winter conditions. Sixteen steel-fibre-reinforced concrete mixtures were investigated. The test variables were the water/binder ratio, the use of silica fume, the type of fibre and the quality of the air-void network. The results of the tests show that the fibres have no apparent influence on the deicer salt scaling resistance of concrete. Furthermore, it has been observed that a very small difference in the minimal freezing temperature could have a great influence on the deicer salt scaling resistance.

3.7 Comparison of SFRS/C with Steel Mesh Reinforced Concrete/Shotcrete (SMRC/S)

Recently it has become more and more common to replace steel reinforcement with steel-fibre reinforced concrete/shotcrete especially in underground constructions. It is therefore of great importance to compare the behaviour of steel-fibre reinforced concrete and conventional steel-reinforced concrete. In cases of shotcrete at the tunnel face, it is important to obtain a fast stabilizing effect. To avoid damage to the shotcrete caused by blasting or drilling for bolts, it is also important to obtain high early strength. Compared to the actual strength, the tunnel shell is loaded to the highest degree during the first advance rounds after spraying, and therefore most failures occur at early ages.

Although the fibre influence on concrete/shotcrete at later ages is well known, at present, there are few research results comparing the properties of steel fibre-reinforced concrete (SFRC) with various fibre contents and steel-reinforced concrete (SRC), especially at ages of 10 h to 2 days. At the laboratory of the Institute of Building Materials and Material Testing, University of Innsbruck, preliminary tests on fibre-reinforced concrete with a shotcrete mix design and on conventional steel mesh-reinforced concrete at early age has been performed [48].

Ding and Kusterle [48] also studied steel-fibre reinforced concrete and steel mesh reinforced concrete at early ages in panel tests. To evaluate the development of punching shear and flexural ductility for panels, experimental investigations were preformed on laboratory concrete in accordance with EFNARC. The measurements were taken at the earliest age of the specimen possible, about 10h. and continued up to 48 h.

This study demonstrated that the use of fibre reinforcement in concrete/shotcrete can greatly enhance the punching shear capacity, flexural ductility, toughness, and therefore possibly replace the conventional steel mesh reinforcement.

In fact, the main difference between SFRC and SMRC is showing different failure mechanisms. Steel fibres, which are regularly distributed two-or three dimensionally in the panel, can work partly as shear reinforcement. Therefore fibre reinforcement greatly increases the shear capacity. In this way, the punching shear as the cause for failure in conventional steel reinforced concrete/shotcrete panels changes to flexural failure of steel fibre reinforced concrete/shotcrete panels especially when the fibre content exceeds 20 kg/m^3.

3.8 Usage of Steel Fibre with Polypropylene Fibre in Shotcrete/Concrete

Steel fibres have a considerably larger length and higher Young's modulus as compared to the polypropylene (PP) fibre. This leads to an improved potential for crack control. But volumetric density is high, and steel is conductive in electric and magnetic fields. So, steel fibre content has to be reduced to below certain level in structures such as tunnels. Optimization of mechanical and conductivity properties can be achieved by combining different kinds, types, and sizes of fibres [15].

For this purpose, in the research of Qian and Stroeven [15] it was investigated the optimization of fibre size, fibre content, and fly ash content in hybrid polypropylene-steel fibre concrete with low fibre content based on general mechanical properties. The research results show that a certain content of fine particles such as fly ash is necessary to evenly disperse fibres. The different sizes of steel fibres contributed to different mechanical properties at least to different degree. Additions of small fibre type had a significant influence on the compressive strength but the splitting tensile strength was only slightly affected. A large fibre type gave rise to opposite mechanical effects, which were further fortified by optimization of the aspect ratio. There is a synergy effect in the hybrid fibres system.

Qian and Stroven [23] also investigated the fracture properties of concrete reinforced with steel-polypropylene. This research discussed polypropylene fibres and three sizes of steel fibres reinforced concrete. The total fibre content ranges from 0% to 0.95% by volume of concrete. A four-point bending test is adopted on the notched prisms with the size of 100 x 100 x 500 mm^3 to investigate the effect of hybrid fibres on crack arresting. The research results show that there is a positive synergy effect between large steel fibres and polypropylene fibres on the load-bearing capacity and fracture toughness in the small displacement range. But this synergy effect disappears in the large displacement range. The large and strong steel fibre is better than soft polypropylene fibre and small steel fibre in the aspect of energy absorption capacity in the large displacement range. The K_{IC} (Critical stress intensity factor) and fracture toughness of proper hybrid fibre system can be higher than that of mono-fibre system.

CHAPTER 4

EXPERIMENTAL STUDY

4.1 Experimental Program

Seventeen different shotcrete/concrete mixes having different reinforcements in different amounts were produced to be used in the tests for the purpose of evaluating the performance characteristics such as toughness, flexural ductility, energy absorption and load – carrying capacities of mesh and fibre reinforced shotcrete/concrete. Reinforcement types and amounts of these different shotcrete/concrete mixes can be seen in Table 4.1.

The first nine mixes were steel fibre–reinforced shotcrete/concrete (SFRS/C) also tenth and eleventh mixes were high performance polypropylene fibre – reinforced shotcrete (HPPRS). In addition, the twelfth mix was hybrid polypropylene – steel fibre – reinforced (HPP+SF) RS and the mixes from thirteenth to fifteenth were hybrid steel – different type of steel fibre – reinforced (SF+SF)RS shotcretes. Finally, the last two mixes were steel – mesh reinforced shotcrete/concrete (SMRS/C).

The shotcrete mixes were produced by dry – shotcrete method. For this method, cement, slightly dampened sand and aggregates were thoroughly mixed in ready mix concrete central and then transported to the dry shotcreting machine by ready mix truck. Also the fibres were introduced into the mixture during mixing. Then, the mix is added to the delivery equipment, and compressed air conveyed the shotcrete from the gun down the hose at high velocity. Water was added under pressure through a water ring at the nozzle. Finally, the shotcrete mixes were sprayed into the forms dimensions of 50 cm * 50 cm * 20 cm and 60 cm * 60 cm * 10 cm at an angle with respect to the vertical and from the distance of between 0.60 m and 1.80 m to decrease the rebound. The cores for tests were taken from the first type of these panels and the second ones were used for plate test.

Besides the tests conducted on cement, cement paste, mortar, and aggregates to be able to determine physical and chemical properties, tests were performed to find out the effect of different reinforcements on compressive strength, energy absorption capacity, ductility and toughness of hardened shotcrete/concrete mixes. Also rebound characteristics, specific gravity, boiled absorption and permeable voids of shotcrete mixes were determined.

Table 4.1 Shotcrete/Concrete Mixes Produced for the Experimental Study

Mix No.	Designation*	Reinforcement Types and Amounts for 1 m^3 shotcrete/concrete
I	SF-1RS 35	Steel Fibre (SF-1)Type-1; 35 kg/m^3
II	SF-1RS 50	Steel Fibre (SF-1)Type-1; 50 kg/m^3
III	SF-2RC 40	Steel Fibre (SF-2)Type-2; 40 kg/m^3
IV	SF-2RC 50	Steel Fibre (SF-2)Type-2; 50 kg/m^3
V	SF-2RC 60	Steel Fibre (SF-2)Type-2; 60 kg/m^3
VI	SF-3RC 30	Steel Fibre (SF-3)Type-3; 30 kg/m^3
VII	SF-3RC 40	Steel Fibre (SF-3)Type-3; 40 kg/m^3
VIII	SF-4RC 30	Steel Fibre (SF-4)Type-4; 30 kg/m^3
IX	SF-4RC 40	Steel Fibre (SF-4)Type-4; 40 kg/m^3
X	HPPRS 7	High Performance Polypropylene Fibre (HPPF); 7 kg/m^3
XI	HPPRS 10	HPPF; 10 kg/m^3
XII	(HPPF+SF-1)$_{5,30}$ RS 35	Mix of HPPF+SF-1; 5 and 30 kg/m^3 respectively; totally 35 kg/m^3
XIII	(SF-2+SF-5)$_{40,10}$ RS 50	Mix of SF-2+SF-5; 40 and 10 kg/m^3 respectively; totally 50kg/m^3
XIV	(SF-2+SF-5)$_{35,15}$ RS 50	SF-2+SF-5; 35 and 15 kg/m^3
XV	(SF-2+SF-5)$_{30,20}$ RS 50	SF-2+SF-5; 30 and 20 kg/m^3
XVI	SMRS	Steel Mesh (Ø8*150*150 mm) diameter:8 mm and interval 150mm 23,5kg/m^3
XVII	SMRC	

* "S", "C" and "R" are the abbreviations for "Shotcrete Mix", "Concrete Mix" and "Reinforced" respectively.

All of the tests, except plate test which is realized by French Railway Company (SNCF) together with the Alpes Essais Laboratory of Grenoble (a slab test developed to characterize SFRC) [67] in accordance with EFNARC [68] were made according to ASTM Standard Specifications [69], and the experimental works were conducted in the Materials of Construction Laboratory at M.E.T.U. and at the site of Bolu tunnels of the Gümüşova – Gerede Motorway.

Tables 4.2.a, 4.2.b and 4.2.c show the relevant standards followed for performing the tests on cement, cement paste, cement mortar, aggregates, fresh and hardened shotcrete/concrete.

Table 4.2.a Tests Performed on Cement, Paste and Mortar

Tests	Relevant Standards
For Cement:	
Chemical Analysis	ASTM C 114, C 150
Density	ASTM C 188
Fineness	ASTM C 204
For Cement Paste:	
Normal Consistency	ASTM C 187
Time of Setting	ASTM C 191, C 150
For Cement Mortar:	
Compressive Strength	ASTM C 109, C 150

Table 4.2.b Tests Performed on Aggregates

Tests	Relevant Standards
Specific Gravity and Absorption	ASTM C 127, C 128
Sieve Analysis	ASTM C 136

Table 4.2.c Tests Performed on Shotcrete/Concrete

Tests	Relevant Standards
For Fresh Shotcrete/Concrete:	
Slump	ASTM C 143
Unit Weight	ASTM C 138
Air Content	ASTM C 231
For Hardened Shotcrete/Concrete:	
Compressive Strength	ASTM C 31, C39
Specific Gravity, Absorption And Permeable Void	ASTM C 642-90
Rebound Characteristics of Fibres	
Energy Absorption, Toughness	SNCF, EFNARC

4.2 Materials Used

4.2.1 Portland Cement

An ordinary Turkish portland cement, PÇ 42.5, was used (This type of cement corresponds to ASTM Type 1 cement.) for the preparation of paste, mortar and shotcrete/concrete.

The chemical and physical properties of this cement are shown in Tables 4.3 and 4.4, respectively

Table 4.3 Chemical Composition of Portland Cement

Oxides	(%)	ASTM C150 Limits
CaO	61.88	-
SiO_2	19.83	-
Al_2O_3	5.32	-
Fe_2O_3	3.47	-
MgO	1.40	max. 6.0 %
SO_3	2.26	max. 3.5 %
K_2O	0.82	-
Na_2O	0.20	-
LOI	1.42	max. 3.0 %

Table 4.4 Physical Properties of Portland Cement

Property		ASTM C150 Limits
Specific Gravity	3.11	-
Specific Surface Area (cm^2/g)	3633	min. 2800
Time of Setting (min)		
Initial	130	min.45
Final	185	max.375
Compressive Strength (MPa)		
3 days	23.5	min.12.4
7 days	31.6	min.19.3
28 days	44.7	-

4.2.2 Aggregates

4.2.2.1 Aggregates in Shotcrete

A natural river sand having a particle size between (0-1 mm) in 13% and a crushed stone having particle size between (0-5 mm) in 57% were used as fine aggregates. Sieve analysis of the fine aggregates in shotcrete is shown in Table 4.5.a.

Table 4.5.a Sieve Analysis of Fine Aggregates in Shotcrete

Sieve No	Cumulative Percent Passing	
	Fine Aggregate (0-1)	Fine Aggregate (0-5)
3/8" (9.5 mm)	100	100
No.4 (4.75 mm)	100	95.7
No.8 (2.36 mm)	98.4	62.7
No.16 (1.18 mm)	95.3	37.5
No.30 (600 µm)	87.8	24.8
No.50 (300 µm)	34.3	2.8
No.100 (150 µm)	11.3	2.0

Also the crushed stone having particle size between (5-12 mm) was used as coarse aggregate in 30%. Table 4.5.b shows the sieve analysis of the coarse aggregates.

Table 4.5.b Sieve Analysis of Coarse Aggregate in Shotcrete

Sieve No	Cumulative Percent Passing Coarse Aggregate
1 ½" (37.5 mm)	100
1" (25.0 mm)	100
3/4" (19.0 mm)	100
1/2" (12.5 mm)	98.1
3/8" (9.5 mm)	64.9
No.4 (4.75 mm)	2.7
No.8 (2.36 mm)	0

After the sieve analysis of the fine aggregates and coarse aggregate, a total mixture of aggregates were prepared consisting of 70% of the fine aggregate and 30% of the coarse aggregate. Maximum aggregate size was 12 mm which is smaller than 16 mm. Because, experience with aggregates over 16 mm has shown that the rebound increases drastically.

Figure 4.1 displays the gradation curve of this combined aggregate representing all the size groups and the gradation curve meets the gradations specified in ACI 506.

Table 4.6 gives the results of the specific gravity and absorption tests conducted on aggregates.

Table 4.6 Specific Gravity, and Absorption of Aggregates in Shotcrete

Specific Gravity	
Fine Aggregate (0-1mm) (Dry)	2.69
Fine Aggregate (0-1mm) (SSD)	2.76
Fine Aggregate (0-5mm) (Dry)	2.53
Fine Aggregate (0-5mm) (SSD)	2.61
Coarse Aggregate (5-12mm) (Dry)	2.65
Coarse Aggregate (5-12mm) (SSD)	2.68
Absorption, (%)	
Fine Aggregate (0-1mm)	2.60
Fine Aggregate (0-5mm)	2.90
Coarse Aggregate (5-12mm)	1.60

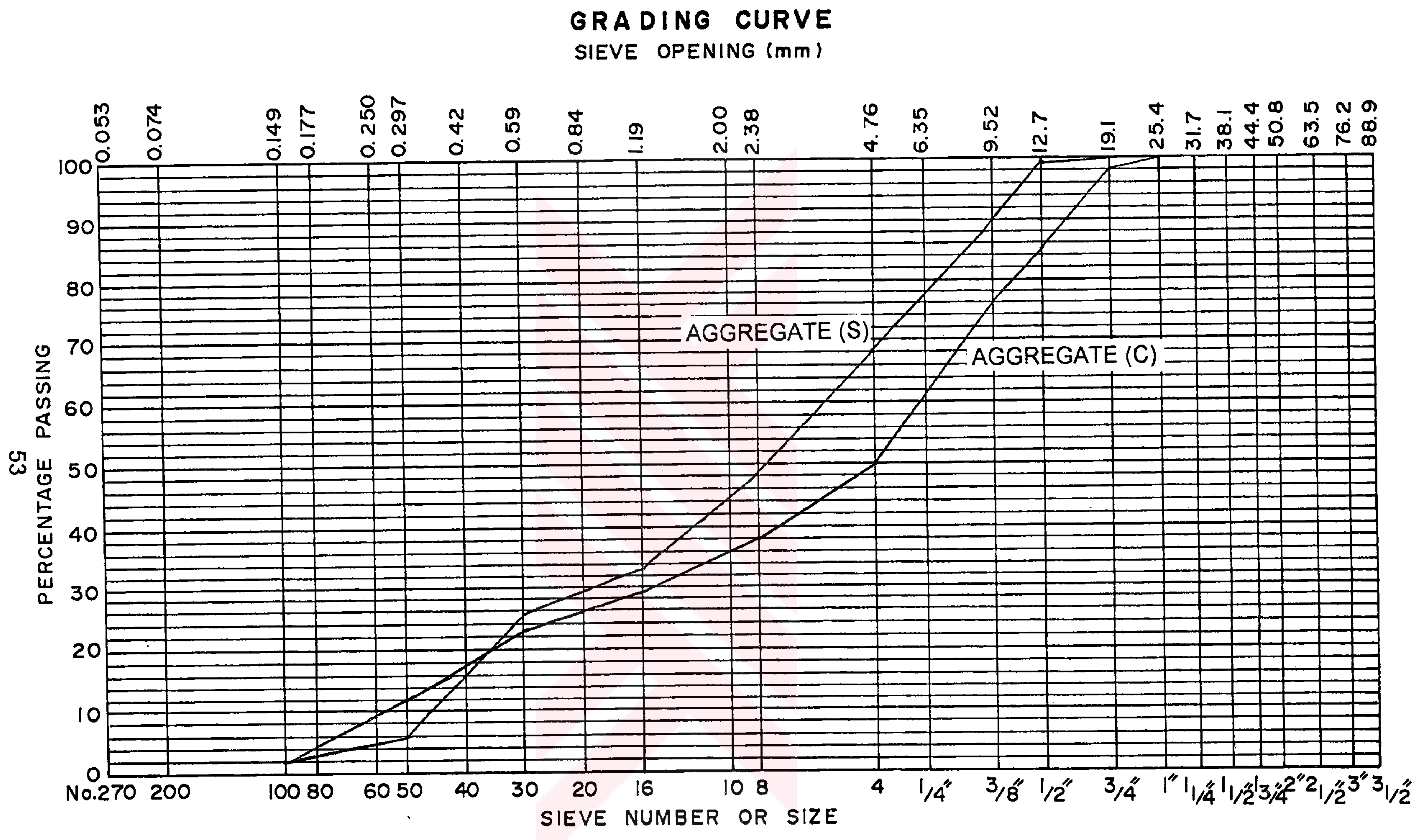


Figure 4.1 Comparison of gradation curves of the combined Shotcrete Aggregate(S) with Concrete Aggregate (C) for all sizes.

4.2.2.2 Aggregates in Concrete

A natural river sand having a particle size between (0-1 mm) in 16% and a crushed stone having particle size between (0-5 mm) in 36% were used as fine aggregates. Sieve analysis of the fine aggregates in concrete is shown in Table 4.7.a.

Table 4.7.a Sieve Analysis of Fine Aggregates in Concrete

Sieve No	Cumulative Percent Passing	
	Fine Aggregate (0-1)	Fine Aggregate (0-5)
3/8" (9.5 mm)	100	100
No.4 (4.75 mm)	100	91.5
No.8 (2.36 mm)	100	62.0
No.16 (1.18 mm)	100	37.1
No.30 (600 μm)	98.3	21.7
No.50 (300 μm)	56.2	9.6
No.100 (150 μm)	3.2	3.4

Also the crushed stone having particle size between (5-12 mm) and (12-20 mm) were used as coarse aggregates in 30% and 18% respectively. Table 4.7.b shows the sieve analysis of the coarse aggregates.

Table 4.7.b Sieve Analysis of Coarse Aggregates in Concrete

Sieve No		Cumulative Percent Passing	
		Coarse Aggregate (5-12)	Coarse Aggregate (12-20)
1 ½"	(37.5 mm)	100	100
1"	(25.0 mm)	100	100
3/4"	(19.0 mm)	100	92.3
1/2"	(12.5 mm)	100	25.3
3/8"	(9.5 mm)	78.1	2.1
No.4	(4.75 mm)	2.4	0
No.8	(2.36 mm)	0	0

After the sieve analysis of the fine aggregates and coarse aggregate, a total mixture of aggregates were prepared consisting of 52% of the fine aggregate and 48% of the coarse aggregate. Maximum aggregate size was 20 mm.

Figure 4.1 displays the gradation curve of this combined aggregate representing all the size groups.

Table 4.8 gives the results of the specific gravity and absorption tests conducted on aggregates.

Table 4.8 Specific Gravity, and Absorption of Aggregates in Concrete

Specific Gravity	
Fine Aggregate (0-1mm) (Dry)	2.60
Fine Aggregate (0-1mm) (SSD)	2.63
Fine Aggregate (0-5mm) (Dry)	2.52
Fine Aggregate (0-5mm) (SSD)	2.58
Coarse Aggregate (5-12mm) (Dry)	2.58
Coarse Aggregate (5-12mm) (SSD)	2.62
Coarse Aggregate (12-20mm) (Dry)	2.62
Coarse Aggregate (12-20mm) (SSD)	2.65
Absorption, (%)	
Fine Aggregate (0-1mm)	1.40
Fine Aggregate (0-5mm)	2.80
Coarse Aggregate (5-12mm)	2.20
Coarse Aggregate (12-20mm)	1.60

4.2.3 Mixing Water and Admixtures

Normal, drinkable tap water that was assumed to be free from oil, organic matter and alkalies, was used as mixing water.

The following commercially available admixtures were used in shotcrete:

- A commercial pozzolanic admixture (Microsilica), which was in powder form and having gray color and a density of approximately 0.55-0.7gr/cm^3, was used for the purposes of increasing strength, obtaining concrete with a low cement content and greater layer thicknesses sprayable. It was introduced into the shotcrete as a part of the cement during batching.
- A commercial high range water reducing admixture (Rheobuild 716), which was in liquid form and having no color and a density of approximately 1.18-1.25 gr/cm^3, was used to impart rheoplastic qualities to concrete. It was introduced into the shotcrete together with mixing water.
- A commercial accelerating admixture (MeycoSA 160) which was a high performance alkali – free set accelerator for use in the dry – mix spraying processes. It was in liquid form and having white color and a density of 1.44 gr/cm^3. It was sprayed from the nozzle with shotcrete also mixed with water.

The following commercially available admixture was used in concrete:

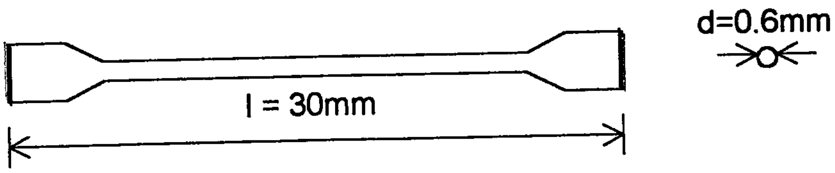
- A super plasticiser (CV-1), polynaphtalene based synthetic polymer, conforming to ASTM C 494 Type F standard, in liquid form and having brown color and a density of approximately 1.16 gr/cm^3, was used to get high performance concrete which was obtained that had a low water/cement ratio, reduced segregation and possessed good cohesive qualities. It was introduced into the concrete as a part of the mixing water.

4.2.4. Reinforcements

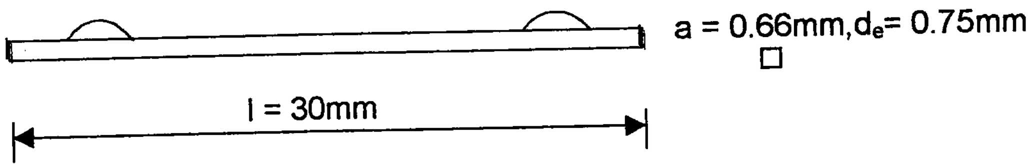
In fibre reinforced shotcrete/concrete (FRS/C), six types of commercially available fibres were investigated as a reinforcement in this research:

- The first type of steel fibre was called SF-1 (Steel fibre type-1) having flattened ends with round shaft has l(length) of 30mm, d(diameter) of 0.5mm and aspect ratio of 50.They were cold drawn fibres (Figure 4.2.a).
- The second one was called SF-2 (Steel fibre type-2) having rectangular cross-section and deformed at the ends. It has l(length) of 30mm, d_e(effective diameter) of 0.75 mm and aspect ratio of 40.They were cut from plate fibres (Figure 4.2.b).
- The third one was called SF-3 (Steel fibre type-3) having hooked ends, l(length) of 35 mm, d(diameter) of 0.55 mm and aspect ratio of 64. They were cold drawn fibres (Figure 4.2.c).
- The fourth one was called SF-4 (Steel fibre type-4) having hooked ends, l(length) of 50 mm, d(diameter) of 0.62 mm and aspect ratio of 81. They were cold drawn fibres (Figure 4.2.d).
- The fifth type of steel fibre was called SF-5 (Steel fibre type-5) having also hooked ends has l(length) of 30 mm, d(diameter) of 0.55 mm and aspect ratio of 50.They were cold drawn fibres (Figure 4.2.e).
- The sixth type of fibre was called HPPF (High performance polypropylene fibre) having engineering shaped has l(length) of 30 mm, d(nominal diameter) of 0.9 mm. They were polymer based materials having specific gravity of 0.91.(Figure 4.2.f).

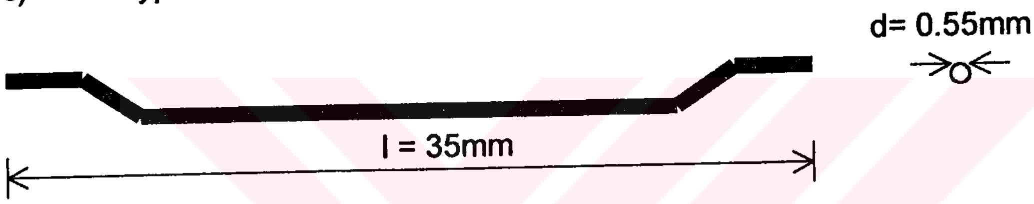
a) SF-1 type l/d=50.



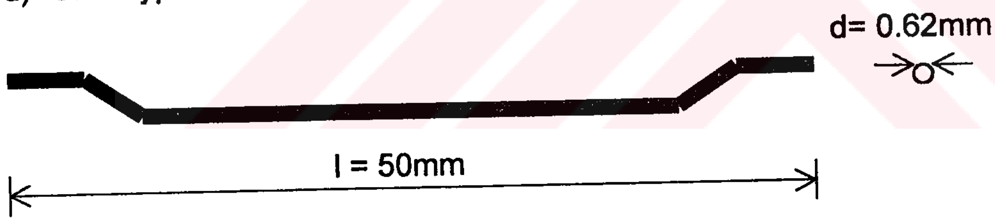
b) SF-2 type l/d=40.



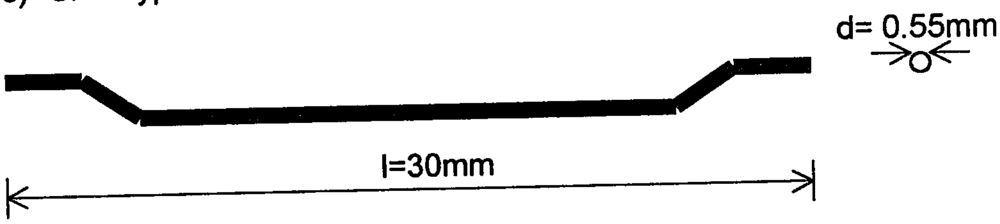
c) SF-3 type l/d=64.



d) SF-4 type l/d=81.



e) SF-5 type l/d=55.



f) HPPF type.

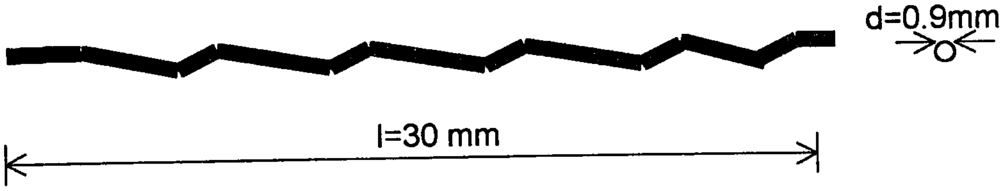


Figure 4.2 Fibre Types Used in FRS/C.

In addition, in the design of steel mesh – reinforced shotcrete/concrete panels (SMRS/C), the mesh (diameter 8 mm, intervals 150 mm and the weight of the steel mesh in the panel 0.846 kg) was placed centrally. While it could more ideally be positioned in the tension face, it is more common in underground support for the bars / meshes to be pinned directly to the excavated face [70].

4.3 Shotcrete/Concrete Mixtures

The procedure given by the American Concrete Institute, ACI 211, was followed to calculate the mix design proportions.

In shotcrete mix design, the aggregate gradation and the cementitious content were different from that of concrete mix design. A total mixture of aggregates were prepared consisting of 70% of the fine aggregate and 30% of the coarse aggregate and total cementitious material including microsilica was 525 kg/m^3. For shotcrete mix designs, it is generally agreed that a suitable base mix contents about 20 % of cementitious material, together with 15-20 % coarse aggregate, and a sand content lies normally between 60 and 65 % of the total aggregate weight. Also, the cement content of the in-place shotcrete should always be higher than the as batched cement content because of the higher degree of rebound of coarse aggregates and sand particles than that of cement [3].

Shotcrete/concrete mix proportions were designed for saturated surface dry (SSD) conditions of aggregates and moisture corrections were made when necessary.

Shotcrete and concrete mix proportions used in this experimental study are given in Table 4.9.

Table 4.9 Shotcrete and Concrete Mix Proportions

		Shotcrete (C30)*	Concrete(C40)*
Cement (kg/m^3)		500	410
Water (kg/m^3)		205	201
F.A. (0-1 mm) (kg)		219	273
F.A. (0-5 mm) (kg)		907	602
C.A. (5-12 mm) (kg)		490	509
C.A. (12-20 mm) (kg)		-	308
Admixtures			
Microsilica	content (%)	5	-
	amount (kg)	25	-
Rheobuild	content (%)	2	-
	amount (kg)	10	-
CV-1	content (%)	-	1.5
	amount (kg)	-	6.15
Total Weight (kg)		2345	2309

* The numbers of this concrete classes show the minimum critical cube (15*15*15 cm) compressive strengths at 28 days in terms of N/mm^2)

** For shotcrete at nozzle 7.0% MeycoSA160 Accelerator was also sprayed.

Table 4.10 gives a summary of the information given in Table 4.9 and the unit weights of shotcrete and concrete mixes as determined experimentally. The slump of shotcrete mixes were adjusted to 16 mm because for the slumps above 15 cm to 17.5 cm, the cohesion is lost and coarse aggregates may tend to separate out [3]. Also, the water / cement ratio of shotcrete mixes was 0.41 which generally lies between 0.40 and 0.45.

Table 4.10 Characteristics of Fresh Shotcrete and Concrete

Mixes	W/C	Slump (cm)	Air Content (%)	Unit Weight (kg/m^3)
Shotcrete (C30)	0.41	16	2.5	2356
Concrete (C40)	0.49	20	2.0	2395

4.4 Tests on Fresh Shotcrete/Concrete

Slump, unit weight and air content tests were the types of tests performed on shotcrete/concrete

4.4.1 Slump Test

While shotcrete and concrete mixes were being prepared, a strict slump control was made for batches, and slumps of shotcrete and concrete mixes were adjusted to the exact values given in Table 4.10.

4.4.2 Unit Weight of Fresh Shotcrete/Concrete

Unit weight tests of shotcrete and concrete mixes were performed according to ASTM C 138. The results were given in Table 4.10.

4.4.3 Determination of Air Content

Air contents of shotcrete and concrete mixes were determined by Pressure Method according to ASTM C 231 and the results were given in Table 4.10.

4.5 Tests on Hardened Shotcrete/Concrete

Compressive strength tests and plate tests were conducted on shotcrete and concrete specimens. Also, fibre amounts after shooting to evaluate the fibre rebound characteristics, specific gravity, boiled absorption and permeable voids of shotcrete mixes were determined according to relative standard.

4.5.1 Compressive Strength Tests

Compressive strength tests of plain or fibre reinforced shotcrete/concrete specimens at the ages of 3, 7 and 28 days were performed according to ASTM C 39. Cubic steel molds having nominal dimensions of 15cm * 15cm * 15cm also cylindrical cores 10 cm in diameter and 10 cm height were used for tests. The results are tabulated and discussed in Chapter 5.7.

4.5.2 Specific Gravity, Absorption and Permeable Voids Tests

Twenty eight days after shooting, specific gravity, boiled absorption and permeable voids tests were conducted on shotcrete core specimens in dimensions of 10 cm in diameter and 10 cm height according to ASTM C 642-90. The results are tabulated and discussed in Chapter 5.4.

4.5.3 Determination of Rebound Characteristics of FRS Mixes

The rebound characteristics of the fibre – reinforced shotcrete (FRS) panels i.e. their actual fibre amounts were determined according to the following procedure which was improved at the shooting site: Firstly, the cores in dimensions of 10 cm * 10 cm in diameter and height were taken from the shotcrete panels having dimensions of 50 cm * 50 cm * 20 cm. They were weighted and then, crushed under huge load. Subsequently, steel fibres and PP fibres in crushed core specimens were accumulated by magnetism and by hand relatively, after that they were weighted. Finally, the fibre content (%), fibre quantity (kg/m^3) in FRS and fibre rebound by mass (%) were calculated as follows. The results are tabulated and discussed in Chapter 5.5.

- Calculation of the fibre content (%):
  D = (B/C)*100
- Calculation of the actual fibre amount (kg/m^3):
  F = B/E
- Calculation of the fibre rebound (%)
  For example; for SF-1RS 35, the theoretical fibre amount is 35 kg/m^3.
  The actual fibre quantity F =18.60 kg/m^3 from Table 5.2,
  The fibre rebound (%), $G = \frac{35 - 18.60}{35}$ = 46.86 %

Where,
A = Core weight (gr)
E = Core volume (cm^3)
B = Fibre weight in core (gr)
C = Concrete weight (gr), C=A-B
D = Fibre content (%)

4.5.4 Plate Tests

The plate test which is realised by French Railway Company (SNCF) together with the Alpes Essais Laboratory of Grenoble (a slab test developed to characterise SFRS/C) [67] in accordance with EFNARC [68] was performed to investigate the toughness, ductility, load carrying and energy absorption capacities of reinforced shotcrete/concrete mixes. The results are tabulated, graphed and discussed in Chapter 5.

Firstly, the plates having dimensions of 600 x 600 x 100 mm were prepared according to specification. Then, the specimens were allowed to be cured and stored in water for 28 days immediately before testing and kept moist during testing according to EFNARC which specifies that the prepared plates shall be stored in water for a minimum of 3 days.

As can be seen from Figure 4.3, the prepared test panels for each shotcrete mix were supported on its four edges by a rigid metallic frame and center point load applied by using 40 t Universal Testing Machine through a contact surface of 100 x 100 mm. The rough side of the panel was on the bottom during the test, i.e. the load was applied to the spraying direction The rate of deformation at the mid-point was nearly 1.5 mm per minute. Tests continued until a deflection of 25 mm was achieved at the center point of the slab.

After that, the load-deformation curves were drawn for all mixes having three plates each and comparative load – deflection curves were obtained as average results of the tests.

Then, the energy - deflection curves were found by integrating the area under these curves giving the absorbed energy amount as a function of the plate deflection [67,68]. Figures from 5.1 to 5.26 show the comparative load – deflection and energy – deflection curves of the panels.

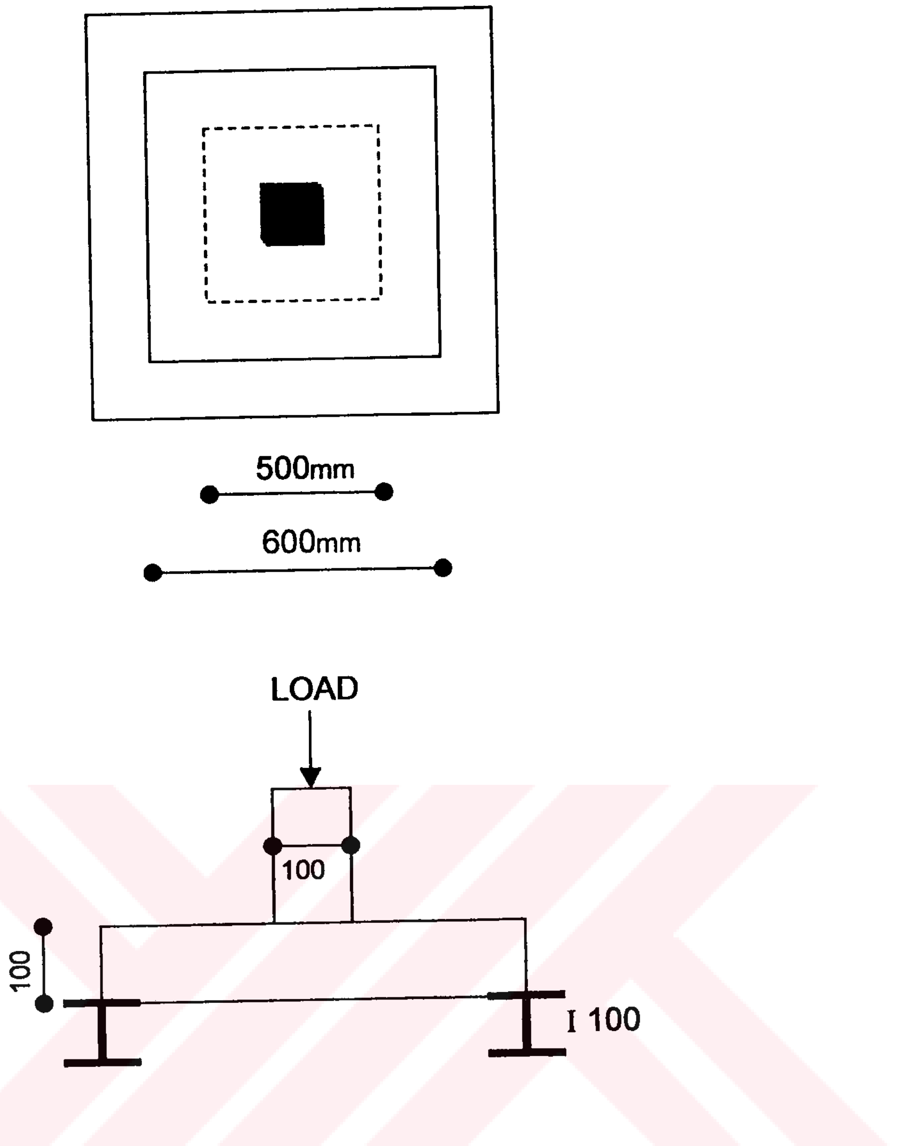


Figure 4.3 Set – Up for Plate Test

Also, the average results for the first – peak load, the maximum load and the energy absorption in joule for a deflection until 25 mm for shotcrete/concrete plates can be seen in Table 5.4.

The criterion for the evaluation of the material toughness of panel test is the energy absorption classes (Table 5.5) [48]. For tunnel repair jobs, the SNCF specifies energy absorption of 500 J till a deflection of 25mm [67].

CHAPTER 5

TEST RESULTS AND DISCUSSIONS

In this chapter, results of the tests performed on reinforced hardened shotcrete/concrete will be given and these results will be discussed extensively.

5.1 Effect of Fibre Amount on the Performance of FRC/S

For the performance point of view, the amount of fibre used in FRS/C is very important. In this section, results of panel tests were compared for different types of mixes to evaluate the effect of fibre amount on shotcrete/concrete.

It can be seen from Figures 5.1and 5.2 that the first–peak and ultimate loads of SF-1RS 50 are more than that of SF-1RS 35 and after the peak load, both shotcrete types having decrease in load–carrying capacities show unstable zone. On the other hand, up to 25mm deflection, the area under the load–deflection curve of the SF-1RS 50 is much higher than that of SF-1RS 35 causing SF-1RS 50 having also higher energy absorption capacity.

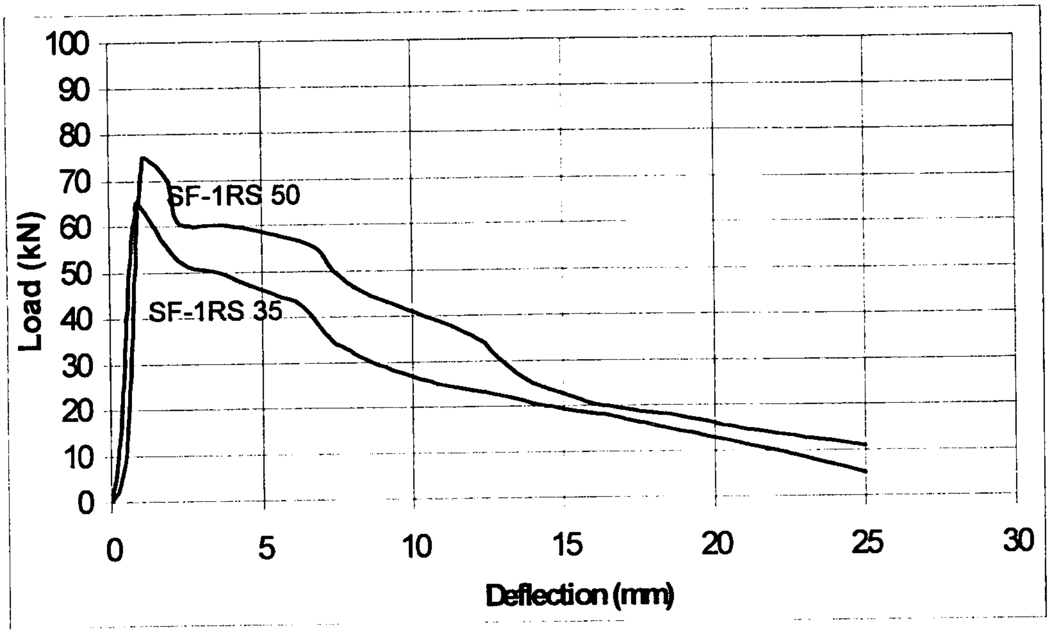


Figure 5.1 Comparison of Load–Deflection Curves of SF-1RS 35 and SF-1RS 50.

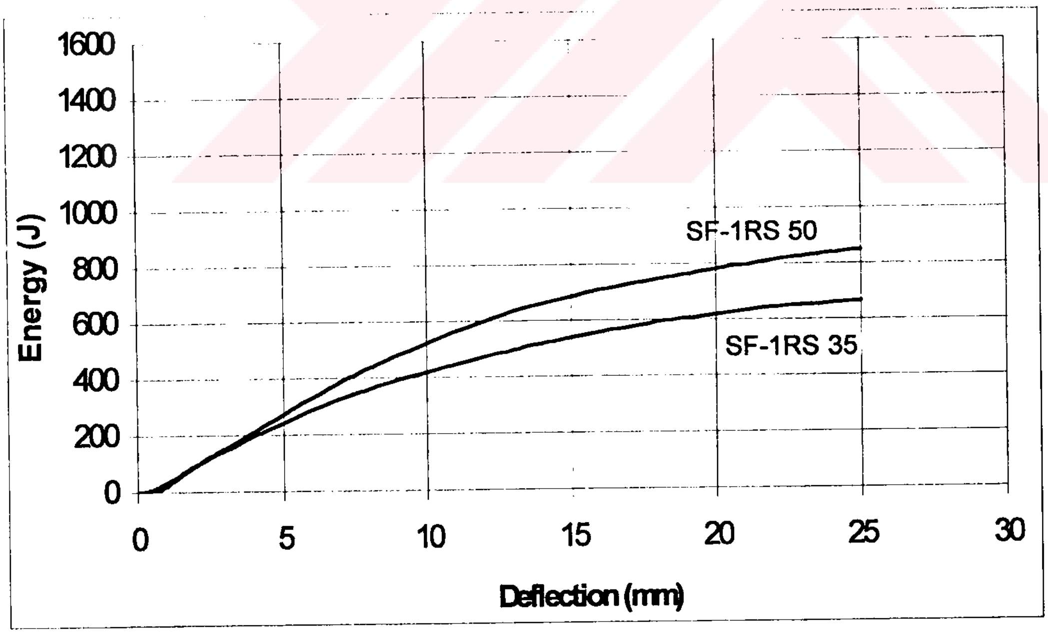


Figure 5.2 Comparison of Energy–Deflection Curves of SF-1RS 35 and SF-1RS 50.

Figures 5.3 and 5.4 represent that the first–peak and ultimate loads of SF-2RC 50 are the highest loads but after the peak load, the load carrying capacity of SF-2RC 50 drops faster than that of SF-2RC 60 and all concrete types indicate very unstable zone. On the other hand, in the unstable zone, SF-2RC 60 showing relatively more ductile behaviour has better load carrying and energy absorption capacity up to 25mm deflection than other panels although its first-cracking and ultimate loads are the lowest ones.

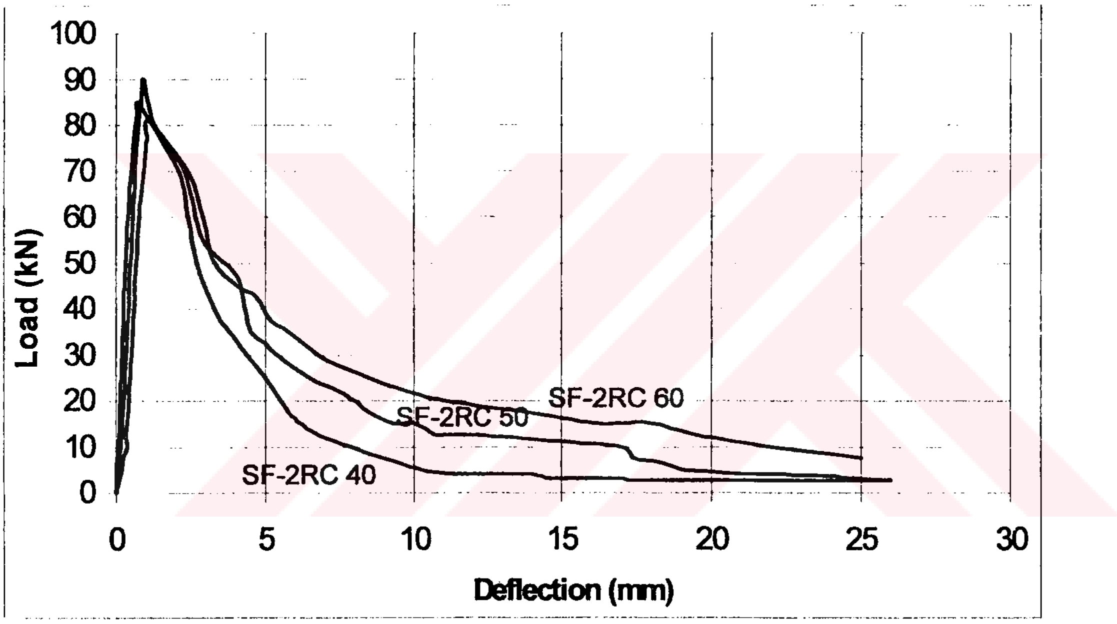


Figure 5.3 Comparison of Load–Deflection Curves of SF-2RC 40, SF-2RC 50 and SF-2RC 60.

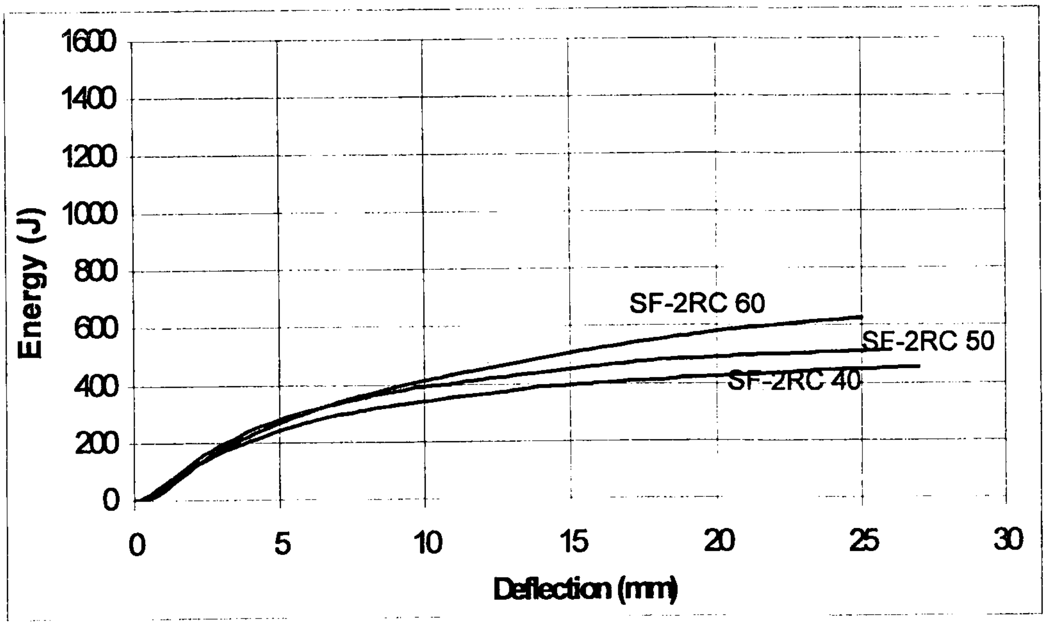


Figure 5.4 Comparison of Energy–Deflection Curves of SF-2RC 40, SF-2RC 50 and SF-2RC 60.

Figures 5.5 and 5.6 show that the first–peak and ultimate loads of SF-3RC 40 are more than that of SF-3RC 30 and after the peak load, SF-3RC 40 represents a stable zone between the deflections of 2 mm and 4 mm but then, the load–carrying capacities of both concrete types decrease although they are more ductile than other concrete/shotcrete types. At the end, up to 25mm deflection, the area under the load–deflection curve of the SF-3RC 40 is higher than that of SF-3RC 30 causing SF-3RC 40 having also higher energy absorption capacity.

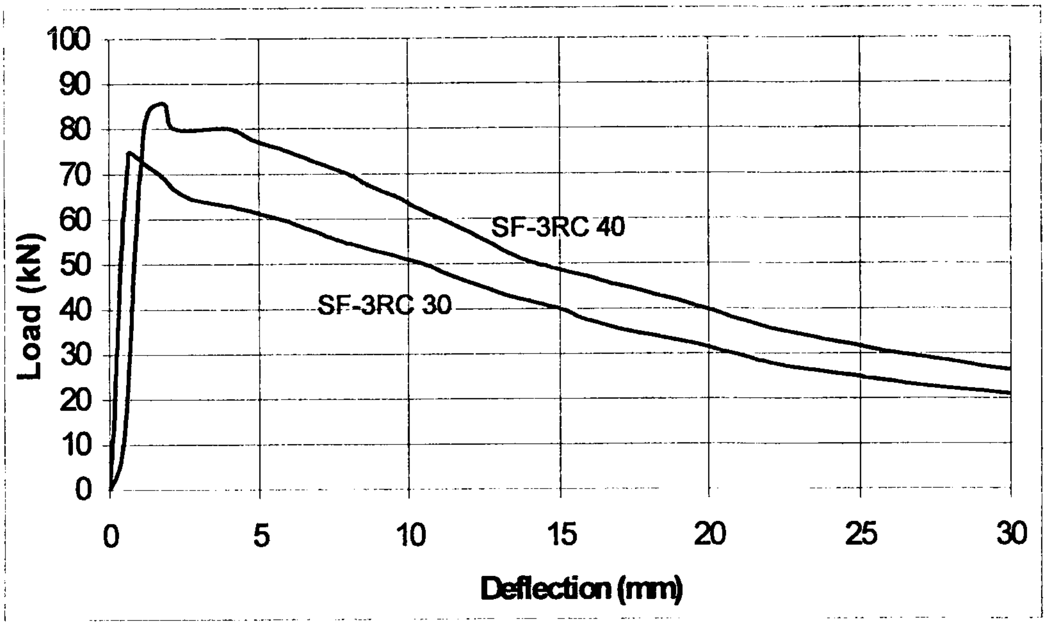


Figure 5.5 Comparison of Load–Deflection Curves of SF-3RC 30 and SF-3RC 40.

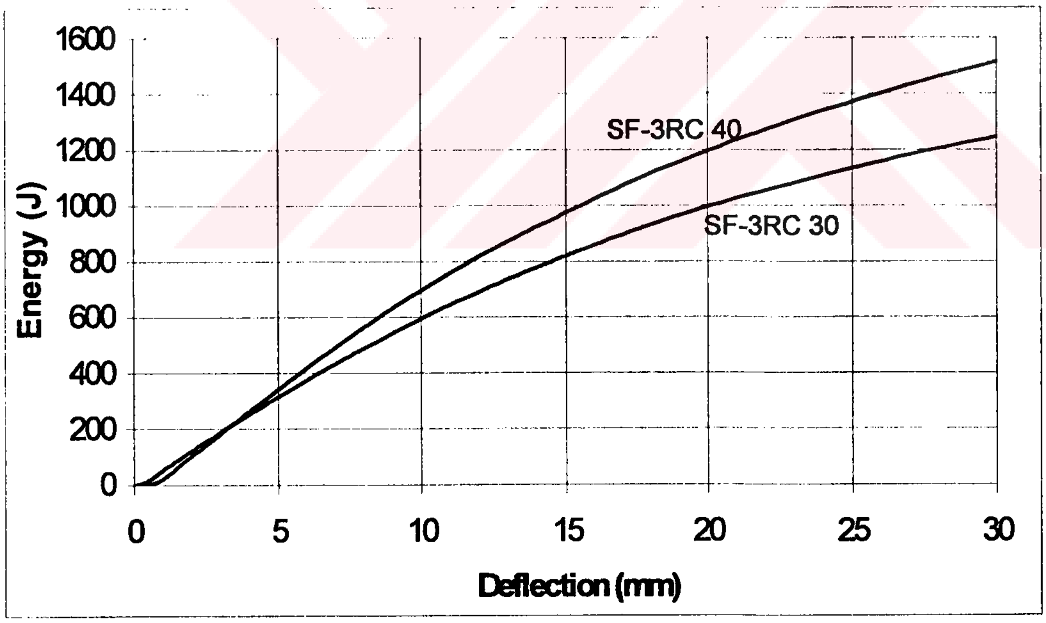


Figure 5.6 Comparison of Energy–Deflection Curves of SF-3RC 30 and SF-3RC 40.

Similarly, it could be seen from Figure 5.7 and 5.8, the first–peak and ultimate loads of SF-4RC 40 are more than that of SF-4RC 30 and after the peak load, both concrete types having decrease in load–carrying capacities show unstable zone though they are more ductile than concrete mixes having the same fibre content. Up to 15mm deflection, the area under the load–deflection curve of the SF-4RC 40 higher than that of SF-4RC 30 causing SF-4RC 40 having also higher energy absorption capacity till 25mm deflection but they have the similar load carrying capacities between the deflections of 15mm and 25mm.

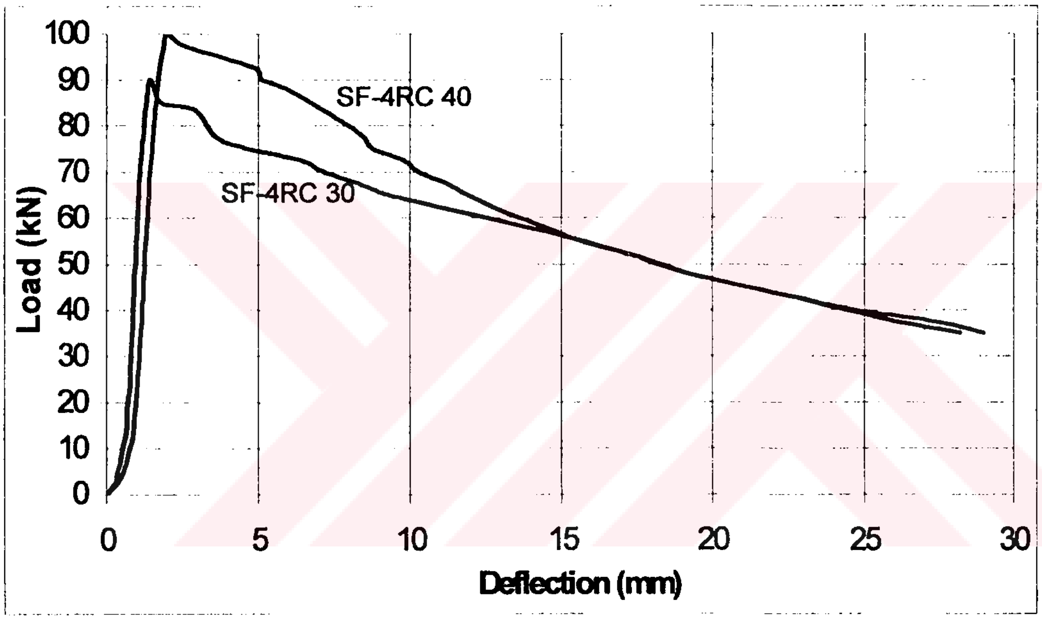


Figure 5.7 Comparison of Load–Deflection Curves of SF-4RC 30 and SF-4RC 40.

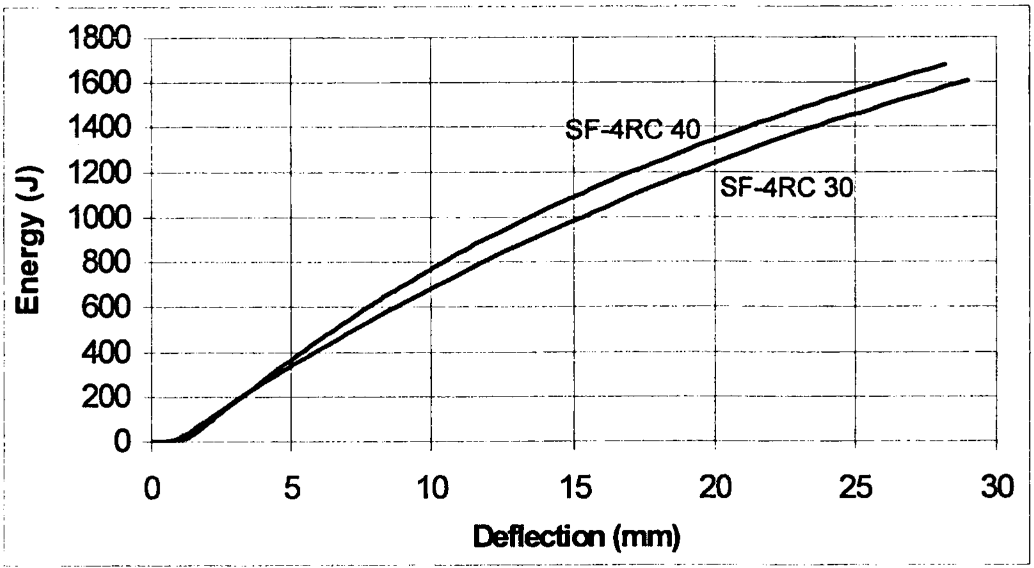


Figure 5.8 Comparison of Energy–Deflection Curves of SF-4RC 30 and SF-4RC 40.

As far as Figures 5.9 and 5.10 concerned, the first–peak and ultimate loads of HPPRS 7 are more than that of HPPRS 10, but after the peak load, the load–carrying capacity of HPPRS 7 falls significantly compared to that of HPPRS 10. On the other hand, HPPRS 10 shows a small decrease in load carrying capacity between the deflections of 1mm and 2mm after it's peak load, but then it preserves it's load–carrying capacity representing the stable and ductile behaviour. At the end, up to 25mm deflection, the area under the load–deflection curve of the HPPRS 10 is higher than that of HPPRS 7 causing HPPRS 10 having also higher energy absorption capacity.

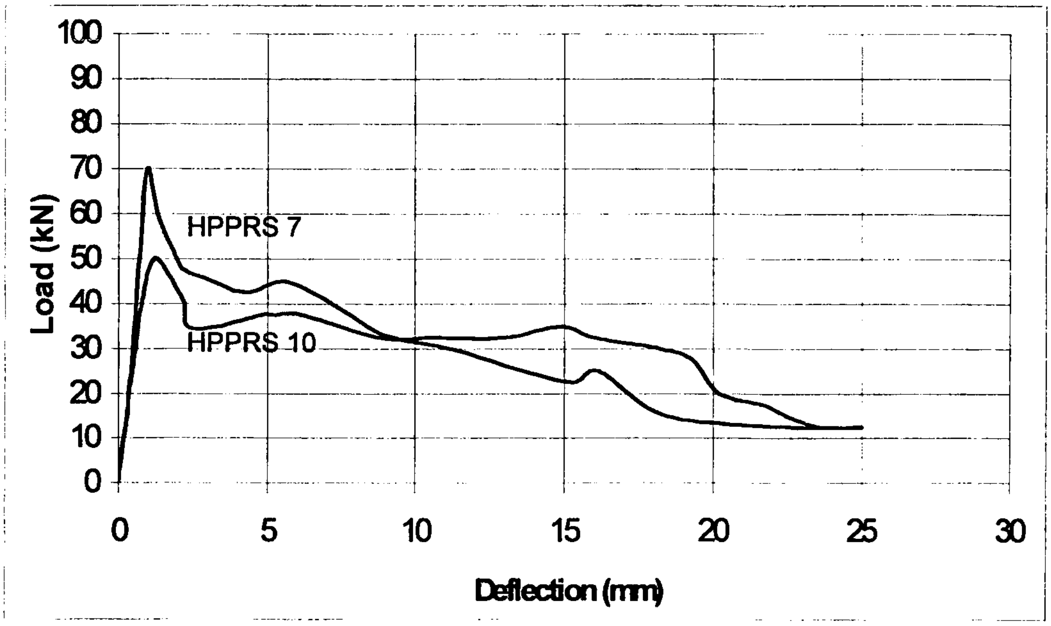


Figure 5.9 Comparison of Load–Deflection Curves of HPPRS 7 and HPPRS 10.

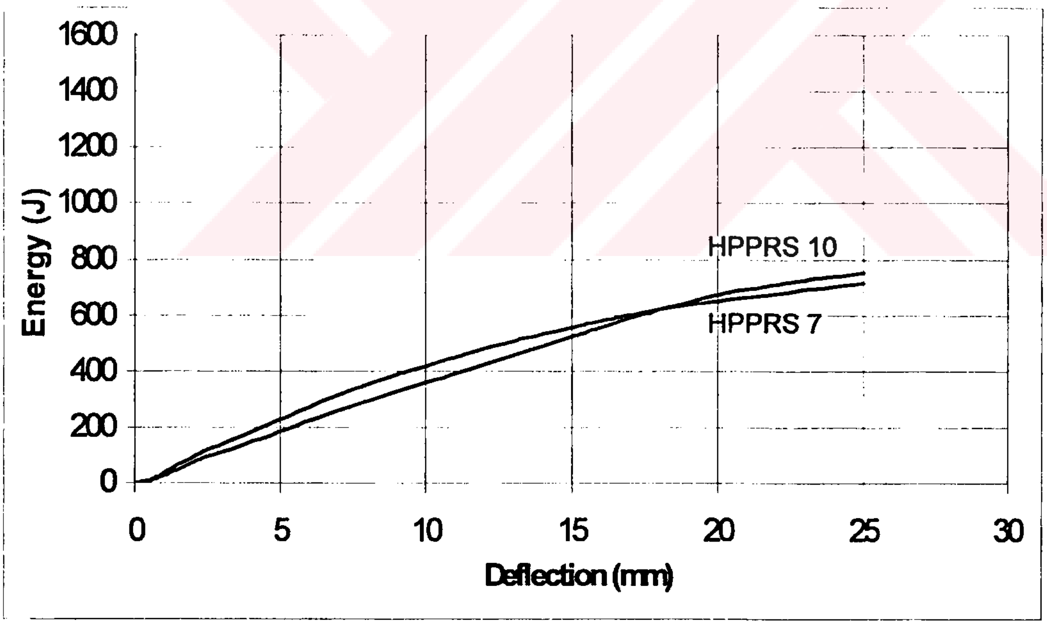


Figure 5.10 Comparison of Energy–Deflection Curves of HPPRS 7 and HPPRS 10.

By comparing Figures from 5.1 to 5.10 it can be seen that the increase in fibre content enhanced the load carrying and energy absorption capacities for all types of panels.

On the other hand, as can be seen from Figures 5.3, 5.4, 5.9 and 5.10, for SF-2RC and HPPRS panels, increase in the fibre content decreased the first–cracking and ultimate load capacities of them causing not so much increase in toughness and energy absorption capacities especially for HPPRS panels. Therefore, it must be stated for the fibre amount used in the concrete/shotcrete that, there is an optimum point to get the best efficiency from the composite. Because, an excess of fibres also may have adverse effects on strength due to the introduction of additional defects during the processing stage [71,72] and also strengthening and weakening effects are the opposite results of adding fibres to concrete [71,73]. Additionally, it must be stated that, to obtain the exact optimum point for fibre content is very difficult.

Also, by comparing Figures 5.7 and 5.8 with Figures 5.5 and 5.6 it can be said that for the panels having fibres with high aspect ratios, increase in fibre content causes not so much increase in the performance of the panels relative to panels having the fibres with lower aspect ratios but the same fibre content due to the fact that the increase in aspect ratio of the fibres may cause additional defects in the panels.

5.2 Effect of Fibre Geometry on the Performance of FRC/S

The geometrical properties of the fibres play an important role on the performance of the FRS/C like the effect of fibre amount. That is why the influence of fibre geometry was discussed in this study.

Figures 5.11 and 5.12 represent that the first–peak and ultimate loads of SF-2RC 50 are the highest loads and that of SF-3RC 30 are the least ones. However, after the peak load, the load carrying capacities of all SF-2RC panels drop much faster than that of SF-3RC panels do and they indicate very unstable zone. On the other hand, in the unstable zone, SF-3RC panels showing more ductile behaviour have much better load carrying and energy absorption capacities than others. At the end, up to 25mm deflection, the area under the load–deflection curves of the SF-3RC panels are much higher than that of all SF-2RC panels causing SF-3RC panels having also higher energy absorption capacity.

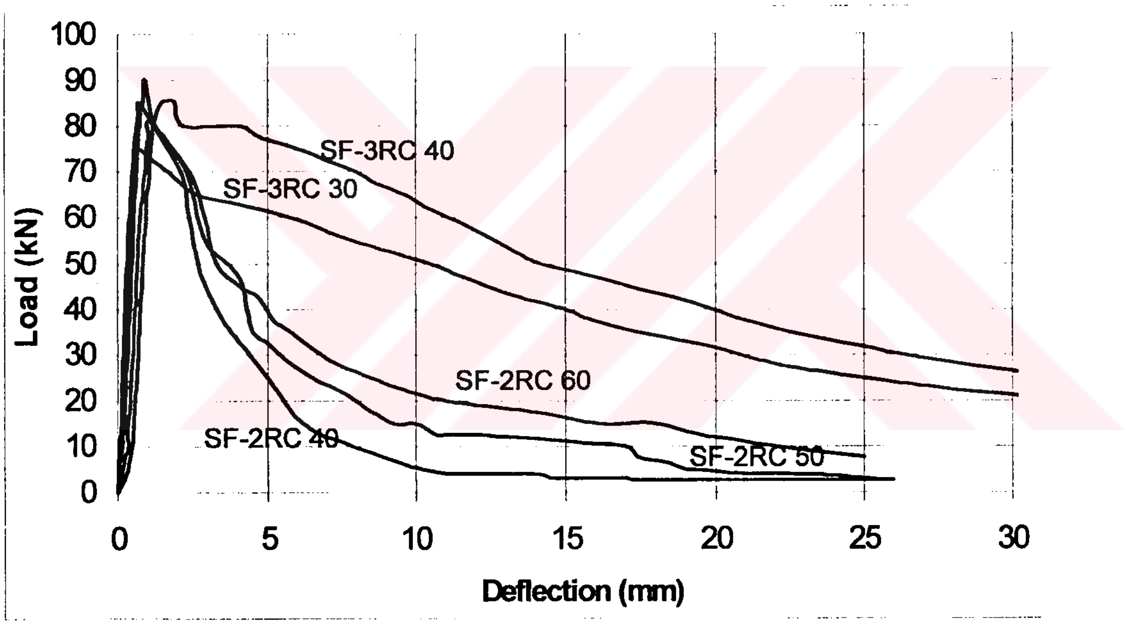


Figure 5.11 Comparison of Load–Deflection Curves of SF-2RC 40, SF-2RC 50, SF-2RC 60,and SF-3RC 30, SF-3RC 40.

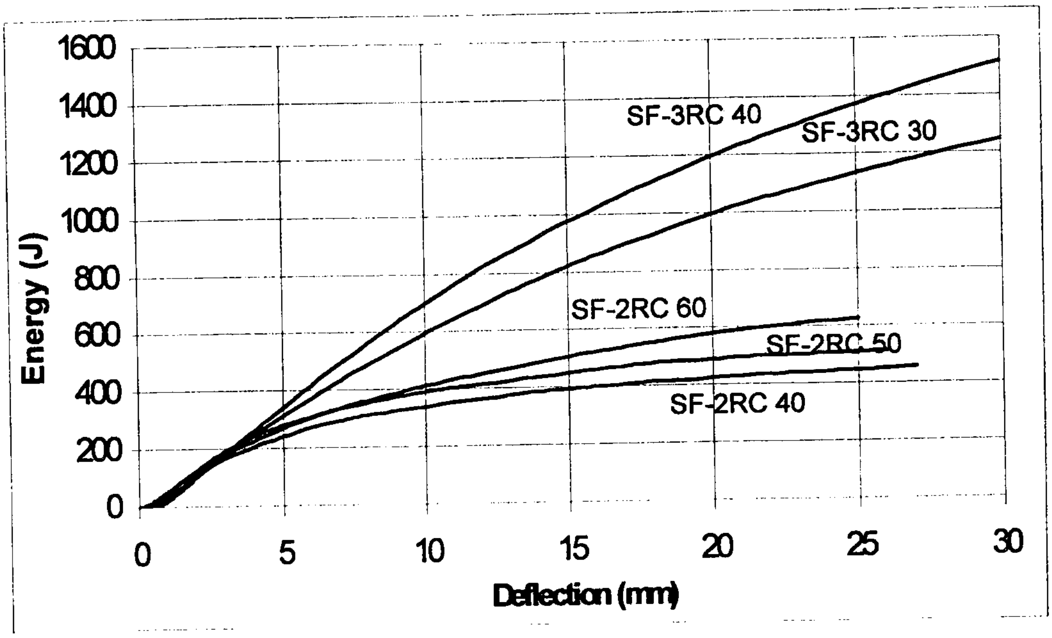


Figure 5.12 Comparison of Energy–Deflection Curves of SF-2RC 40, SF-2RC 50, SF-2RC 60,and SF-3RC 30, SF-3RC 40.

It can be seen from Figures 5.13 and 5.14, although all panels have the same fibre content totally, the first–peak and ultimate loads of $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50 are more than that of $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50 and $(SF\text{-}2+SF\text{-}5)_{40,10}$RS 50 has the lowest ones. After the peak load, the load–carrying capacities of all concrete types decrease but starting from the deflection of 7,5mm, $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50 shows better load–carrying capacity than other types. At the end, up to 25mm deflection, the area under the load–deflection curve of the $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50 is higher than others causing $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50 having also higher energy absorption capacity.

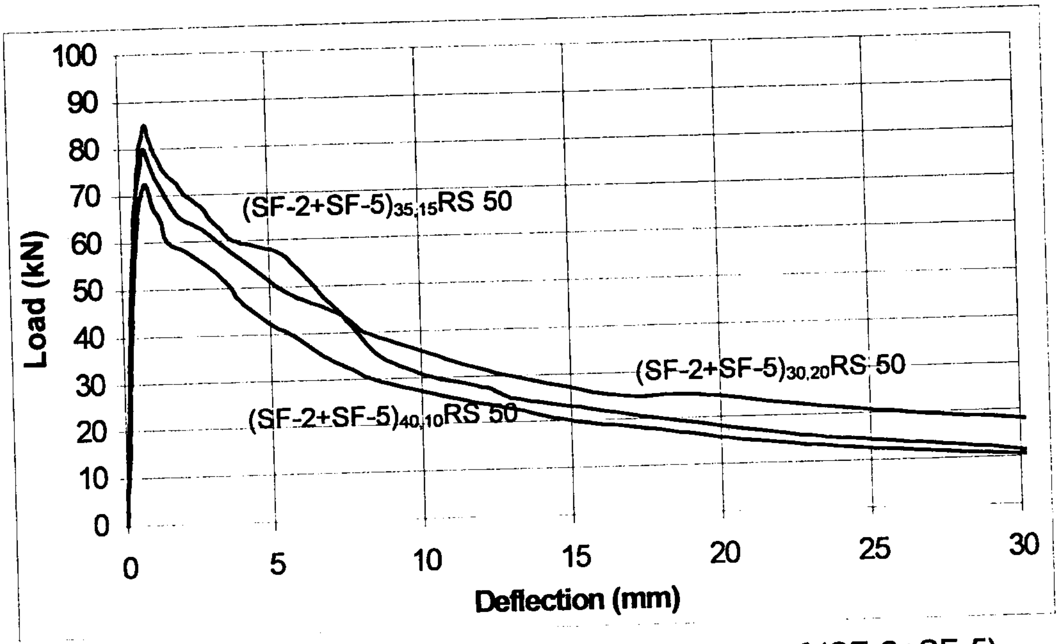


Figure 5.13 Comparison of Load–Deflection Curves of $(SF\text{-}2+SF\text{-}5)_{40,10}$ RS 50, $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50 and $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50.

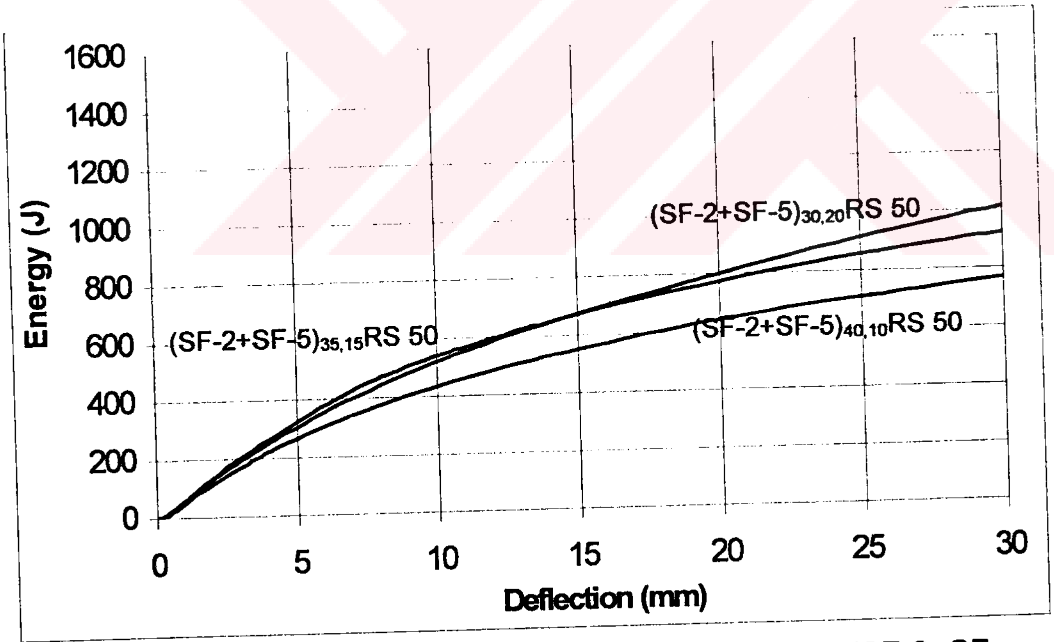


Figure 5.14 Comparison of Energy–Deflection Curves of $(SF\text{-}2+SF\text{-}5)_{40,10}$RS 50, $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50 and $(SF\text{-}2+SF\text{-}5)_{30,20}$ RS 50.

From Figures 5.11 and 5.12, it can be seen that there is a huge difference between the load carrying capacities of SF-2 panels and SF-3 panels having equal or even less fibre content than that of SF-2 panels. For example, the energy absorption capacity of SF-3RC 30 up to 25 mm is nearly two times that of SF-2RC 60 the fibre content of which is twice as much as that of SF-3RC 30. One of the reason of this event is that fibres used have different aspect ratios, but the main reason is the difference between the geometries i.e. end shapes of SF-2 and SF-3. SF-2 is deformed at the ends (Figure 4.3.b). On the other hand, SF-3 has hooked end (Figure 4.3.c).

It must be stated that while plain shotcrete/concrete panels fails in a brittle manner, fibres in fibre reinforced shotcrete/concrete bridge matrix cracks and undergo pull-out processes giving the material a high post–crack ductility. In order to improve the bond of fibres with the surrounding matrix such that their overall pull–out resistance and ductility of composite are improved, the commercial fibres are mostly deformed in geometry along their lengths [7] or their ends can be hooked.

According to results, it could be said that using steel fibres with hooked ends contributed significantly to the increase in the bond between the fibre and the matrix because of the anchored hooked ends of the fibres, which made it possible to use the whole length of the fibre to transmit the maximum amount of force and prevented any splitting force from being exerted on the concrete.

Also, Figure 5.13 and 5.14 show that for the panels having the same constant fibre content totally, increase in hooked end fibre amount increased the performance of panels. This also proves that using hooked end fibres in shotcrete/concrete applications is very advantageous in performance point of view.

5.3 Effect of Aspect Ratio (l/d) of Fibres on the Performance of FRC/S

The effect of fibre amount and fibre geometry were discussed in Chapter 5.1 and 5.2. It is also necessary to discuss the effect of aspect ratio of fibres on shotcrete/concrete performance.

It can be seen from Figures 5.15 and 5.16 that SF-4RC panels have higher first–peak and ultimate loads than SF-3RC 30 have. In addition, after the peak load, the load carrying capacities of both SF-3RC panels decrease faster than that of SF-4RC panels and SF-4RC panels showing more ductile behaviour have much better load carrying and energy absorption capacities than SF-3RC panels have. At the end, up to 25mm deflection, the area under the load–deflection curves of the SF-4RC panels are higher than that of both SF-3RC panels causing SF-4RC panels having also higher energy absorption capacity.

The reason of the panels showing different performances for the same fibre content is that the aspect ratios of the fibres used in panels are different although they are all hooked end.

It must be stated that the geometry of the reinforcing phase is one of the major parameters in determining the effectiveness of the reinforcement; in other words, the mechanical properties of composites are a function of the shape and dimensions of the reinforcement [1]. Actually, the performance of SFRC/S especially toughness and ductility of it is greatly influenced by the properties; size, type, geometry and distribution of the fibres used in composite panels [25].

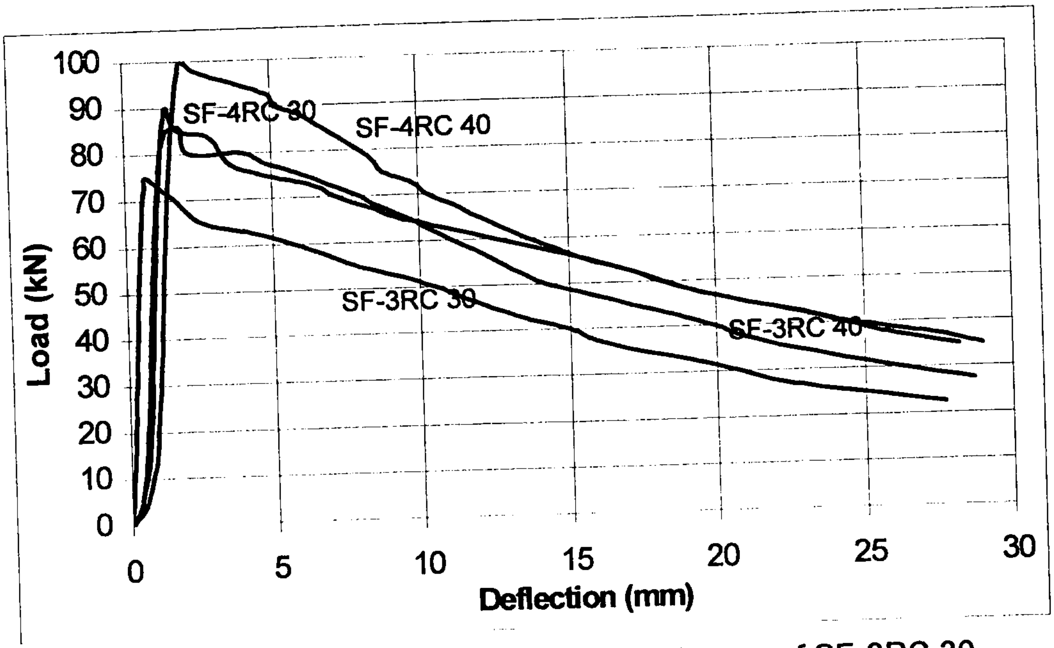


Figure 5.15 Comparison of Load–Deflection Curves of SF-3RC 30, SF-3RC 40 and SF-4RC 30, SF-4RC 40.

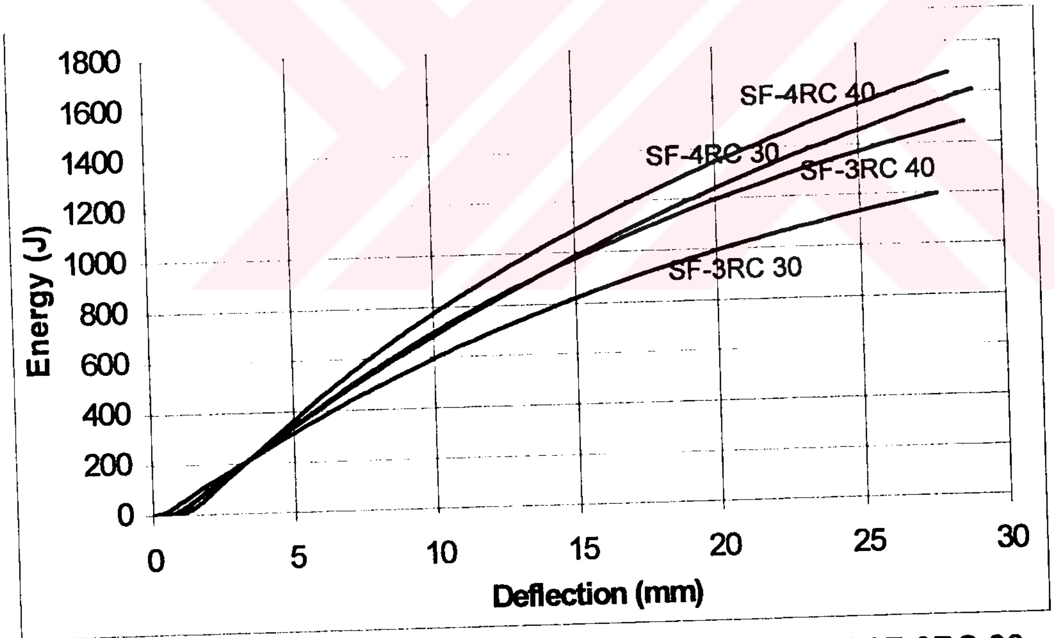


Figure 5.16 Comparison of Energy – Deflection Curves of SF-3RC 30, SF-3RC 40 and SF-4RC 30, SF-4RC 40.

From the results obtained, it can be concluded that the higher the aspect ratio of the fibre provided the better the performance of the SFRS/C with respect to flexural strength, toughness, ductility, and crack resistance. On the other hand, as the aspect ratio of the fibres decreased the end effects became progressively more significant and the efficiency of the fibres in stiffening and reinforcing the matrix decreased. Therefore, the load carrying capacity of SF-3RC panels decreased faster than that of SF-4RC panels after the peak load. However, the problem is that the higher the aspect ratio like the higher volume concentration of the fibre, the more difficult the shotcrete becomes to mix, convey and shoot. Thus there are practical limits to the amount of single fibres that can be added to SFRS/C, with the amount varying with the different geometrical characteristics of the several fibre types. Unfortunately, loose steel fibres with a high l/d aspect ratio that is essential for good reinforcement, are difficult to add to the concrete and to spread evenly in the mixture [4].

5.4 Usage of HPPF in Concrete/Shotcrete as a Reinforcement

Up to this point, the effect of fibre properties on shotcrete/concrete mixes was discussed generally based on steel fibre properties. In this section, the possibility of HPPF usage instead of steel fibre in shotcrete/concrete mixes will be discussed from the performance point of view.

As can be seen from Figures 5.17 and 5.18, the first–peak and ultimate loads of SF-1RS 50 are the highest ones and the loads of HPPRS 7 are also higher than that of both HPPRS 10 and SF-1RS 35, but after the peak load, the load carrying capacity of HPPRS 7 falls significantly just like that of SF-1RS 35 and SF-1RS 50 and indicates very unstable zone.

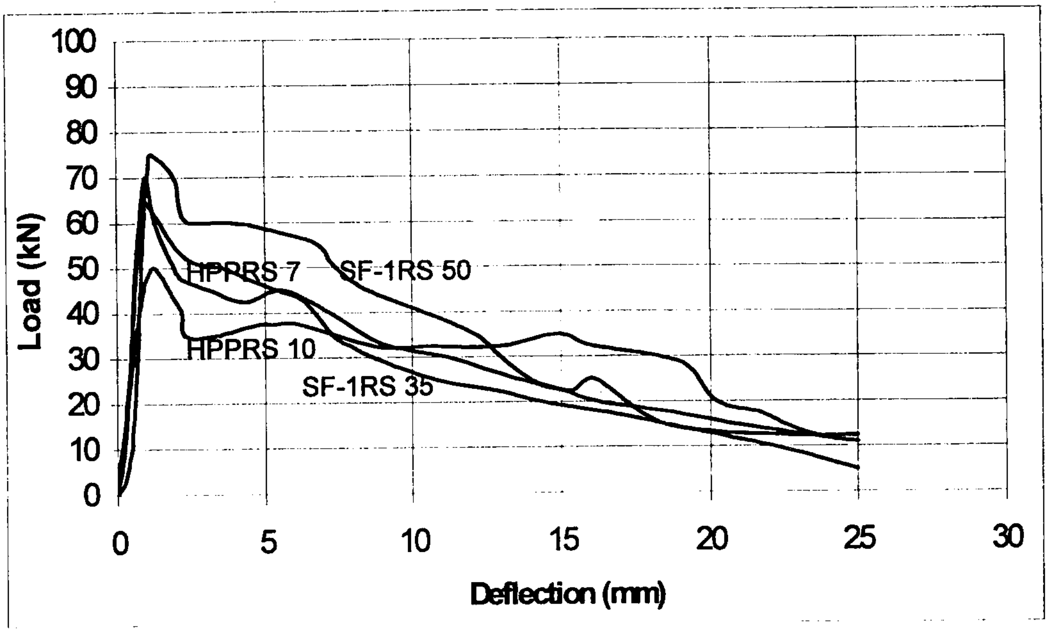


Figure 5.17 Comparison of Load–Deflection Curves of HPPRS 7, HPPRS 10 and SF-1RS 35, SF-1RS 50.

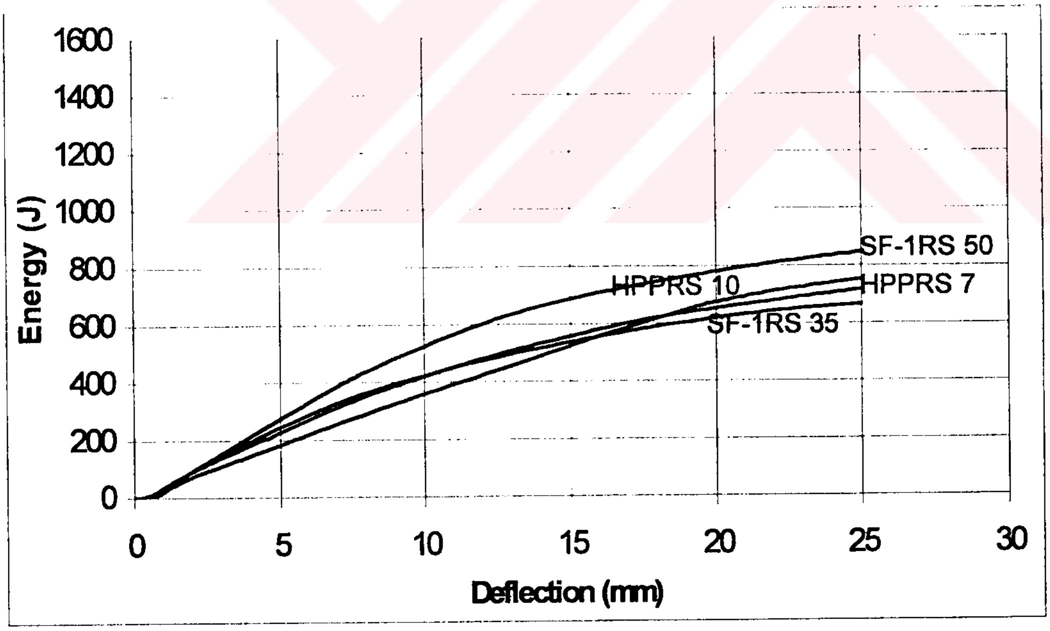


Figure 5.18 Comparison of Energy–Deflection Curves of HPPRS 7, HPPRS 10 and SF-1RS 35, SF-1RS 50.

On the other hand, in the unstable zone, HPPRS 10 shows better load carrying and energy absorption capacity although its first cracking and ultimate loads are the least ones. At the end, by comparing the panels it can be seen that the energy absorption of HPPRS 10 is slightly greater than that of HPPRS 7 and it is also higher than that of SF-1RS 35 but slightly lower than that of SF-1RS 50. Additionally, the results for HPPRS 7 are better than that of SFRS 35 and slightly worse than that of SFRS 50.

According to results of HPPRS panels, it can be said that the homogeneously distributed HPP fibres, although having low Young's modulus nearly 3500 MPa and to be expected having little effect on crack propagation, showed better adherence and bond being geometrically engineered to anchor mechanically with high friction stresses to the shotcrete than SF-1 did in some aspects. Also they were more convenient to mix and to shoot with shotcrete because of having very low specific gravity which is nearly 0.91 and relatively high specific surface area also being used much less amount in concrete compared to the usage amount of steel fibres.

In addition, by comparing the number of fibres for one kg of fibre, it can be obtained that the number of HPP fibres is 57.604 fibre/kg while the number of SF-1 is 15.038 fibre/kg; SF-2, 9.400 fibre/kg; SF-3, 14.500 fibre/kg; SF-4, 8.100 fibre/kg and SF-5, 16.750 fibre/kg. As can be seen from the number of fibres that the number of HPPF is nearly 3.5 times as much as that of SF-5 number of which is the highest in steel fibres. This may be also a factor which increases the performance of HPPRS that because of the large numbers involved, HPP fibres can be properly and three dimensionally distributed throughout the mortar matrix, around the coarse aggregate particles, and even in boundary layers of concrete elements [15].

Also, from the results about specific gravity, boiled absorption and permeable voids of mixes in Table 5.1, it can be said that the permeable void ratios of mixes are nearly equal to each other. It means that large number of HPP fibres do not increase the void ratio of shotcrete significantly. In addition, increase in fibre content caused a slight increase in permeable voids for all shotcrete types. Finally, according to classification proposed by Morgan [10], the shotcrete mixes produced in this study could be placed in fair to good category.

Table 5.1 Comparison of the Specific Gravity, Absorption and Permeable Void Ratios of Shotcrete Mixes.

Types of Mixes	Absorp. Immersion (%)	Absorp. Boiled (%)	Dry Dens. (gr/m^3)	SSD* Dens. (gr/m^3)	SSD(B)* Dens. (gr/m^3)	Apparent Dens. (gr/m^3)	Perm. Voids (%)
SF-1RS 35	8.53	8.83	2.092	2.271	2.277	2.567	18.49
SF-1RS 50	9.27	9.52	2.066	2.257	2.262	2.571	19.67
HPPRS 7	8.62	9.42	2.055	2.232	2.248	2.580	19.36
HPPRS10	9.43	10.19	2.031	2.222	2.238	2.560	20.69
MIX 35**	9.18	9.92	2.060	2.249	2.264	2.589	20.43
MIX-1 50**	7.07	7.99	2.110	2.260	2.270	2.530	16.80
MIX-2 50**	6.82	7.77	2.150	2.300	2.320	2.580	16.70
MIX-3 50**	7.47	8.23	2.130	2.290	2.310	2.580	17.50

*SSD = Saturated Surface Dry, SSD(B) = Saturated Surface Dry (Boiled)

** MIX 35 = $(HPPF+SF\text{-}1)_{5,30}$ RS 35, MIX-1 50 = $(SF\text{-}2+SF\text{-}5)_{40,10}$RS 50

MIX-2 50 = $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50, MIX-3 50 = $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50

5.5 Comparison of Rebound Characteristics of FRS Mixes

In fact, shotcrete was applied traditionally using dry–mix process in this study, that is, all ingredients except water were pre–mixed in the dry state and water was added at the nozzle. The drawbacks of this process include a dusty shooting environment and excessively high material rebounds, which in the case of fibrous mixes consists essentially of coarse aggregates and fibres.

Accordingly, rebound of fibres during shooting of dry-mix SFRS and HPPRS at the tunnel site decreased the fibre content in them causing adverse effects on mechanical and economical properties. The results can be seen in Table 5.2.

From this table, by comparing the fibre rebound percentages, it can be said that rebound percentages of SFs are nearly four times greater than HPP fibres have. Also the fibre rebound percentage of (HPPF+SF-1)$_{5,30}$RS 35 is lower than that of SF-1RS 35 due to usage of HPPF instead of SF although they have the same fibre amount. This is an evidence that HPP fibre usage highly reduces rebound in shotcrete applications. Because, they are more convenient to mix and to shoot with shotcrete having very low specific gravity which is nearly 0.91 and relatively high specific surface area.

As a result, it can be said that using HPP fibre in shotcrete is very advantageous because of not only causing increase in performance of shotcrete but also reducing the decrease in amount of fibres due to rebound of them during shooting. Also reduction in rebound has significant financial implications. Particularly fibre loss reduction (fibres as the most expensive component of the shotcrete mix) improves the economical attractiveness of FRS.

Table 5.2 Comparison of Average Fibre Quantities after Shooting for Shotcrete Mixes.

Types	Core wt. (A) (gr)	Fibre wt. (B) (gr)	Core vol. (E) (cm^3)	Conc. wt. (C) (gr)	Fibre cont. (D) (%)	Fibre amount (F) (kg/m^3)	Fibre rebound (G) (%)
SF-1RS 35	1745	14.6	785.4	1730.4	0.84	18.6	46.86
SF-1RS 50	1785	22.2	785.4	1762.8	1.26	28.3	43.40
HPPRS 7	1758	4.8	785.4	1753.2	0.27	6.1	12.86
HPPRS10	1748	7.0	785.4	1740.9	0.40	9.0	10.30
MIX 35 *	1755	18.2	785.4	1736.8	1.04	23.2**	33.86
MIX-1 50 *	1845	34.0	785.4	1811.0	1.88	43.3	13.40
MIX-2 50 *	1813	35.6	785.4	1777.4	2.00	45.4	9.20
MIX-3 50 *	1826	37.6	785.4	1788.4	2.10	47.9	4.20

* MIX 35 = $(HPPF+SF\text{-}1)_{5,30}$ RS 35, MIX-1 50 = $(SF\text{-}2+SF\text{-}5)_{40,10}$RS 50, MIX-2 50 = $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50, MIX-3 50 = $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50

**(4.1 kg/m^3 (HPPF) + 19.1 kg/m^3 (SF-1)) = 23.2kg/m^3

Also, from the table, it can be seen that the rebound percentages of (SF-2+SF-5)RS mixes are the lowest ones. The reason of this may be that they have better shotcrete matrix according to Table 5.1 or they have hooked end fibres and confirming with an early study [6], rebound appears to be related to fibre geometry.

5.6 Evaluation of Hybrid Fibre–Reinforced Shotcrete/Concrete Performance

The effects of mono–fibre usage on shotcrete/concrete performance were discussed in previous sections. In this chapter, the effect of hybrid fibre usage not only for SF with different type of SF but also for HPPF with SF as reinforcement in shotcrete/concrete mixes will be discussed from performance point of view.

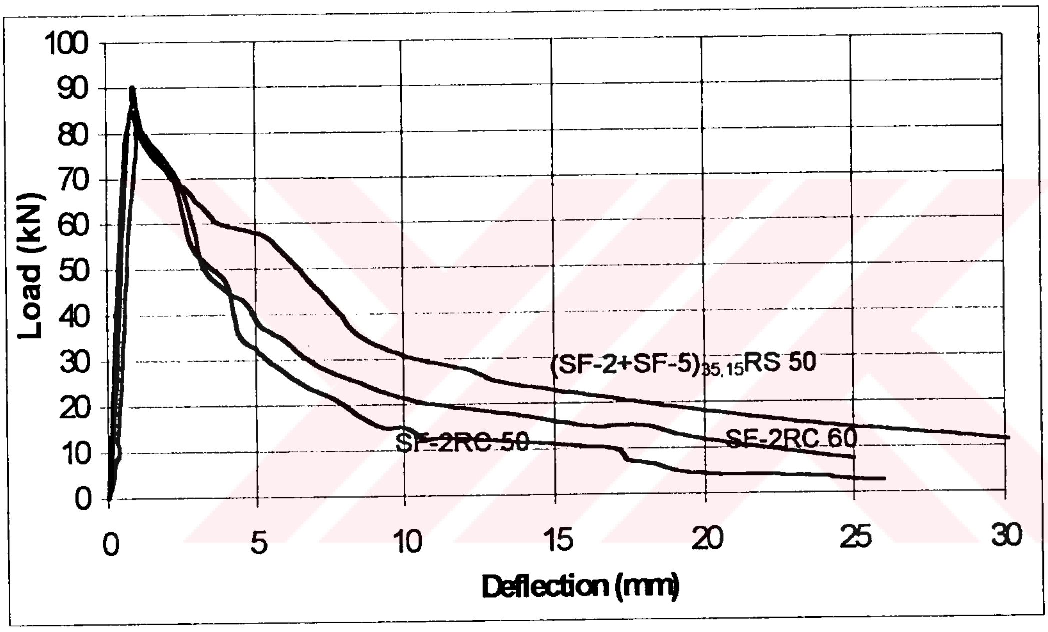


Figure 5.19 Comparison of Load–Deflection Curves of $(SF\text{-}2+SF\text{-}5)_{35,15}$ RS 50 and SF-2RC 50, SF-2RC 60.

It can be seen from Figure 5.19 and 5.20 that the first–peak and ultimate loads of SF-2RC 50 are the highest loads and that of SF-2RC 60 are the least ones. However, after the peak load, the load carrying capacities of all SF-2RC panels drop much faster than that of $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50 panel and they indicate very unstable zone. On the other hand, in the unstable zone, $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50 panel showing more ductile behaviour has much better load carrying and energy absorption capacity than others. At the end, up to 25 mm deflection, the area under the load –deflection curves of the $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50 panel is much higher than that of all SF-2RC panels causing $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50 panel having also higher energy absorption capacity.

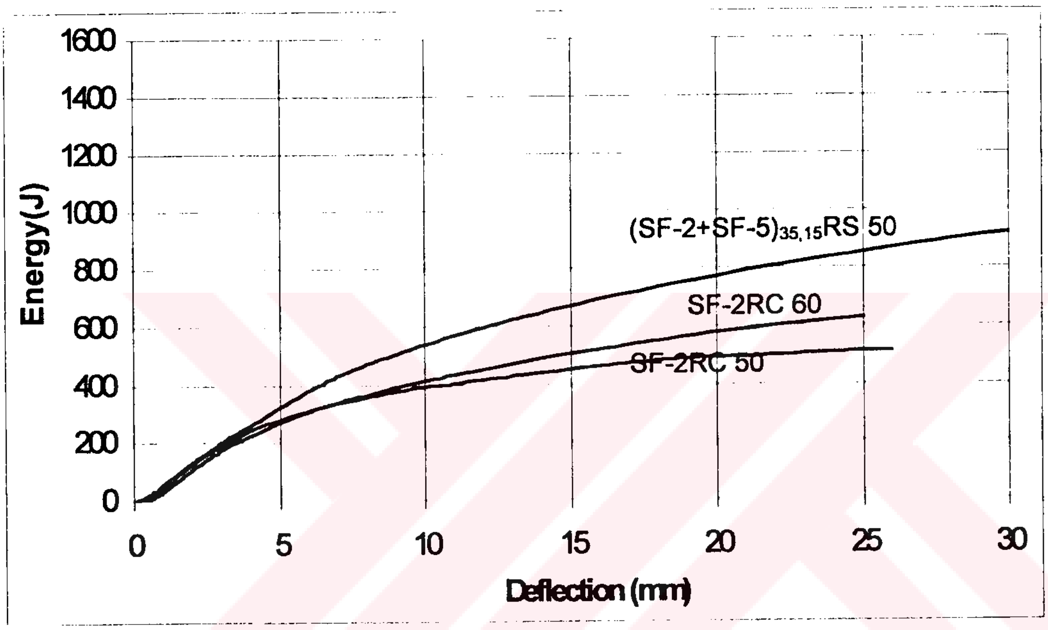


Figure 5.20 Comparison of Energy–Deflection Curves of (SF-2+ SF-5)$_{35,15}$RS 50 and SF-2RC 50, SF-2RC 60.

Also, the fibre amount of $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50 is not the same as that of SF-2RC 50. Because, the first one is a shotcrete and the second one is a laboratory concrete. As expressed in previous section, in shotcrete the actual fibre content was different than the fibre amount which should be due to rebound of fibres during shooting but also the matrix strength was higher in shotcrete providing greater influence of the properties of added fibres on the performance of it [25]. The actual fibre amount of $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50 can be seen in Table 5.2. Although the fibre content of $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50 is much lower than SF-2RC 50 and SF-2RC 60, it's performance is much better than that of others as mentioned in previous paragraph. This means that by using the mix of SF-2 and SF-5 that are different types and sizes of steel fibres, the mechanical properties of shotcrete/concrete panels could be improved significantly.

On the other hand, as can be seen from Figures 5.21 and 5.22, the first–peak and ultimate loads of SF-1RS 50 are higher than the loads of others and after the peak load, the load carrying capacity of SF-1RS 50 is also better than other panels up to deflection of 7 mm, but then $(HPPF+SF\text{-}1)_{5,30}$RS 35 shows better load carrying and energy absorption capacity while the load carrying capacities of SF-1RS 35 and SF-1RS 50 fall significantly. At the end, up to deflection of 25 mm, by comparing the panels, it can be seen that the energy absorption of $(HPPF+SF\text{-}1)_{5,30}$RS 35 panel is greater than that of both SF-1RS 35 and SF-1RS 50 although it's fibre content is equal to that of SF-1RS 35 and lower than SF-1RS 50's. This means that using HPP fibres with steel fibres in FRS/C greatly enhanced the performance of it.

It can be concluded that the optimisation of mechanical properties of panels were able to be achieved by combining HPP fibres having large numbers in less amounts with steel fibres which have larger aspect ratio, density and higher Young's modulus as compared to HPP fibres.

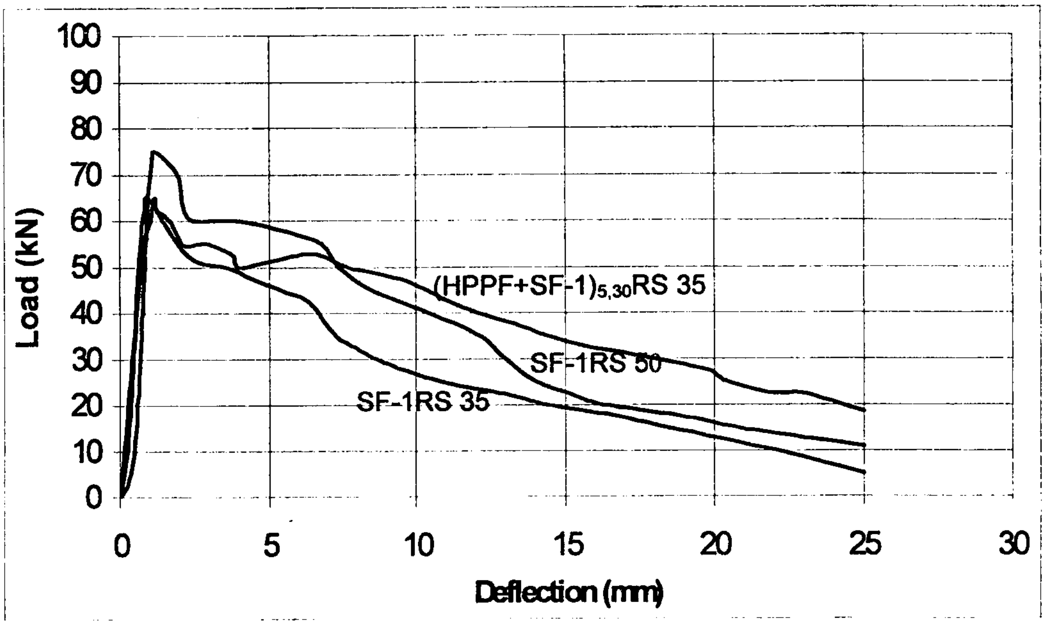


Figure 5.21 Comparison of Load–Deflection Curves of (HPPF+ SF-1)$_{5,30}$RS 35 and SF-1RS 35, SF-1RS 50.

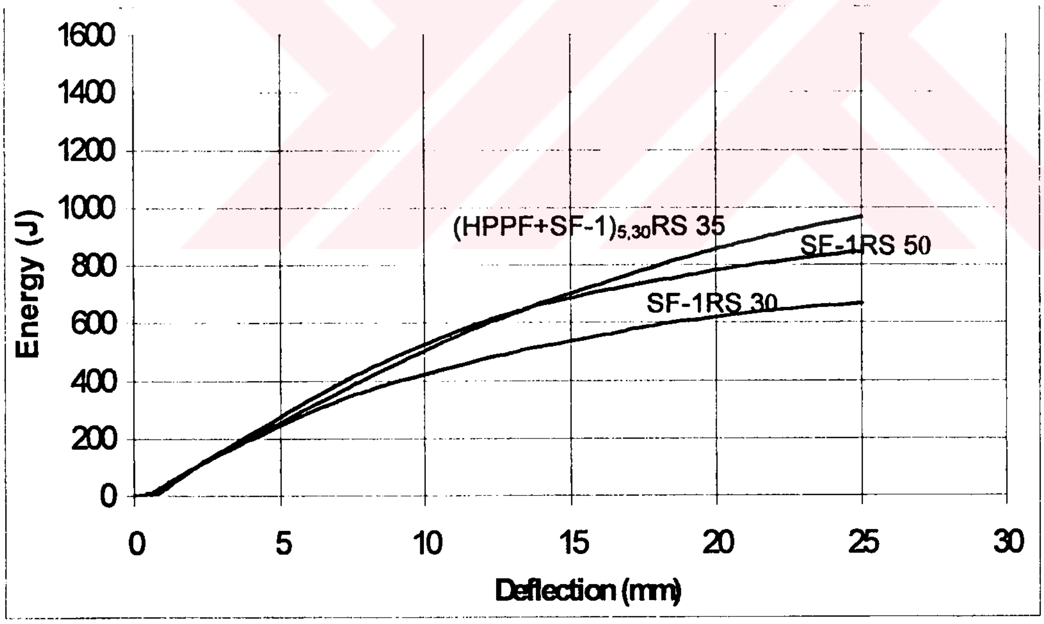


Figure 5.22 Comparison of Energy–Deflection Curves of (HPPF+ SF-1)$_{5,30}$RS 35 and SF-1RS 35, SF-1RS 50.

5.7 Effect of Fibre Addition on Compressive Strengths of Shotcrete/Concrete Mixes

In previous sections, the effect of fibre addition on FRS/C mixes was evaluated according to flexural behaviour. Additionally, in this section, the compressive strengths of mixes will be compared to evaluate the effect of fibre addition on compressive behaviour of FRS/C.

The compressive strength results can be seen in Table 5.3. From this table, it can be said that compressive strengths were little influenced by fibre addition for both shotcrete and concrete mixes. Many researchers hold the view that steel fibres do not have a significant influence on the compressive behaviour of concrete/shotcrete due to the small volume of fibres in concrete/shotcrete mix [50]. Accordingly, this research showed that not only for steel fibres but also HPP fibres and hybrid fibres had no important effect on compressive strengths of shotcrete/concrete mixes at the ages of 3,7,28 days.

Therefore it can be concluded that for shotcrete/concrete mixes compressive strength is mainly controlled by the shotcrete/concrete matrix design.

Also, seven day compressive strengths of 40 MPa and 28 day compressive strengths in the range of 50 to 60 MPa are quite common in dry mix shotcretes [4] and in this research, as can be seen from Table 5.3 this values were reached for shotcrete mixes. Because, particularly in dry-mix shotcretes, leaner shotcrete mixes with low compressive strengths tend to have substantially increased rebound and poorer adhesion characteristics causing decreases in performances [4].

Table 5.3 Compressive Strengths of Shotcrete/Concrete Mixes.

Mixes	Cube Comp. Strength* (MPa)			Core Comp. Strength** (MPa)		
	3 days	7 days	28 days	3 days	7 days	28 days
Plain Shotcrete	30.9	45.4	65.3	25.7	34.6	47.7
Plain Concrete	28.3	35.2	45.7	-	-	-
SF-1RS 35	31.8	46.7	70.4	25.9	34.8	47.0
SF-1RS 50	33.2	47.5	67.4	27.9	34.6	43.6
SF-2RC 40	21.6	37.0	44.8	-	-	-
SF-2RC 50	22.7	37.2	45.3	-	-	-
SF-2RC 60	21.5	32.7	43.0	-	-	-
SF-3RC 30	22.7	33.4	45.5	-	-	-
SF-3RC 40	23.2	36.5	47.3	-	-	-
SF-4RC 30	23.0	33.9	45.2	-	-	-
SF-4RC 40	22.5	34.6	43.4	-	-	-
HPPRS 7	33.9	49.9	66.7	26.3	30.6	44.9
HPPRS 10	30.2	43.1	59.6	26.3	29.8	46.1
$(HPPF+SF\text{-}1)_{5,30}$ RS 35	32.4	45.6	65.3	25.8	30.2	45.4
$(SF\text{-}2+SF\text{-}5)_{40,10}$ RS 50	37.6	54.4	69.0	31.7	40.4	50.3
$(SF\text{-}2+SF\text{-}5)_{35,15}$ RS 50	37.2	53.4	72.3	29.9	37.2	49.6
$(SF\text{-}2+SF\text{-}5)_{30,20}$ RS 50	35.3	52.5	67.3	30.7	41.5	52.2

* 15x15x15 cm^3 cube compressive strength at 3,7,28 days in MPa.

**10x10(dxh) cylindrical core compressive strength at 3,7,28 days in MPa.

5.8 Comparison of Performances of FRS/C with SMRS/C

In previous sections, the performances of shotcrete/concrete mixes having different fibre reinforcements were discussed. In this section the comparison of FRS/C mixes with SMRS/C mixes will be made from performance point of view.

It can be seen from Figure 5.23 and 5.24 that the first–peak and ultimate loads of $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50 are the highest loads but after the first–cracking load, the load carrying capacities of all panels drop. On the other hand, for SF-1RS 50, HPPRS 10 and SMRS, these decreases in load carrying capacities is up to a deflection of nearly 2.5 mm and then, the load capacity of SF-1RS 50 after showing small stability continues to decrease and HPPRS showing small increase remains stable till 19 mm deflection and decreases after this point, but SMRS indicating different behaviour increases it's load–carrying capacity and reaches its ultimate value at the deflection of nearly 9 mm and it shows much better load carrying and energy absorption capacity than others although it's load capacity decreases after it's ultimate load. Also, its energy absorption up to the deflection of 25 mm is nearly 1.5 times that of others.

As could be seen from Figure 5.25 and 5.26 that the first–peak load of SF-4RC 50 is the highest load and that of SMRC is the lowest one but after the first–cracking load, the load carrying capacities of all SFRC panels drop. In fact, SF-2RC 40 more sharply and others slowly decrease. But SMRC, like SMRS, after having decrease in load capacity up to a deflection of nearly 2.5 mm, it increases it's load–carrying capacity and reaches its ultimate load at the deflection of nearly 7.5 mm which is the highest ultimate load and it shows better load carrying and energy absorption capacity than others. However, its energy absorption capacity up to the deflection of 25 mm is nearly equal to that of SF-4RC 50 and higher than others.

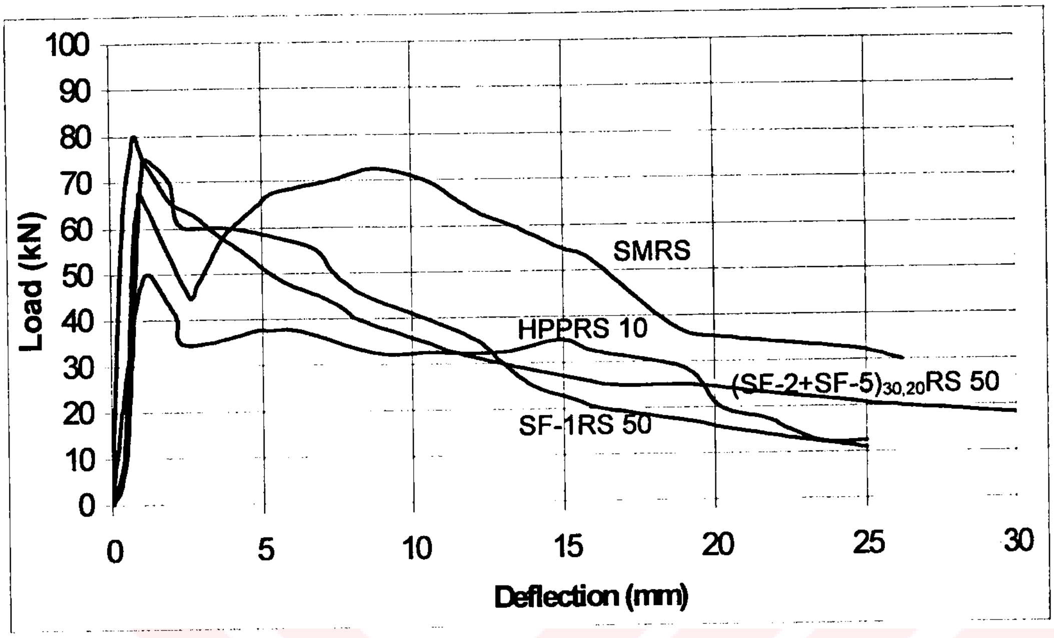


Figure 5.23 Comparison of Load–Deflection Curves of SMRS and $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50, SF-1RS 50, HPPRS 10.

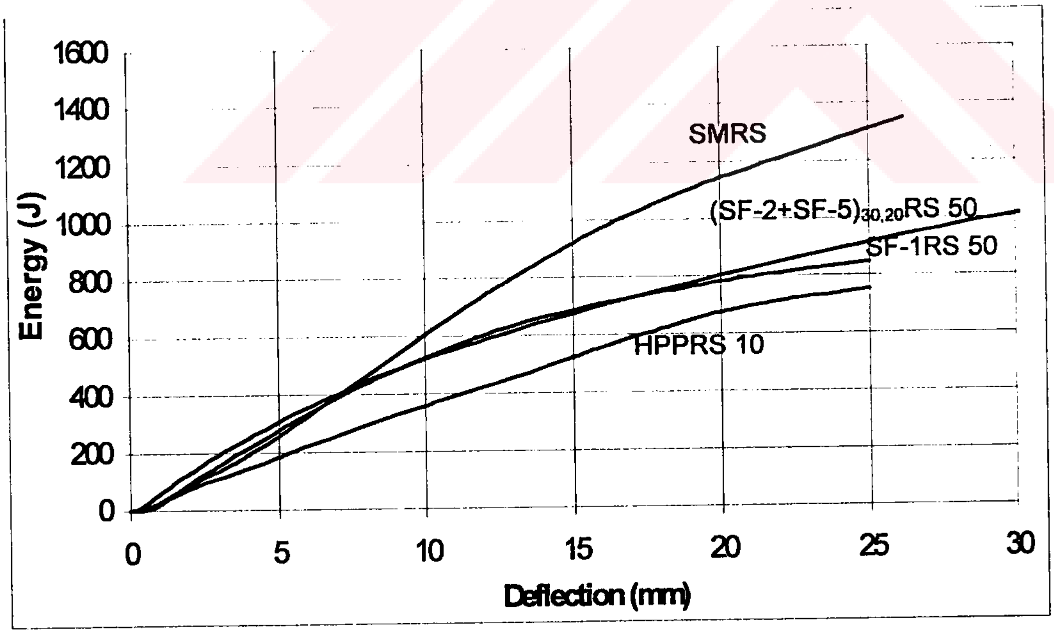


Figure 5.24 Comparison of Energy–Deflection Curves of SMRS and $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50, SF-1RS 50, HPPRS 10.

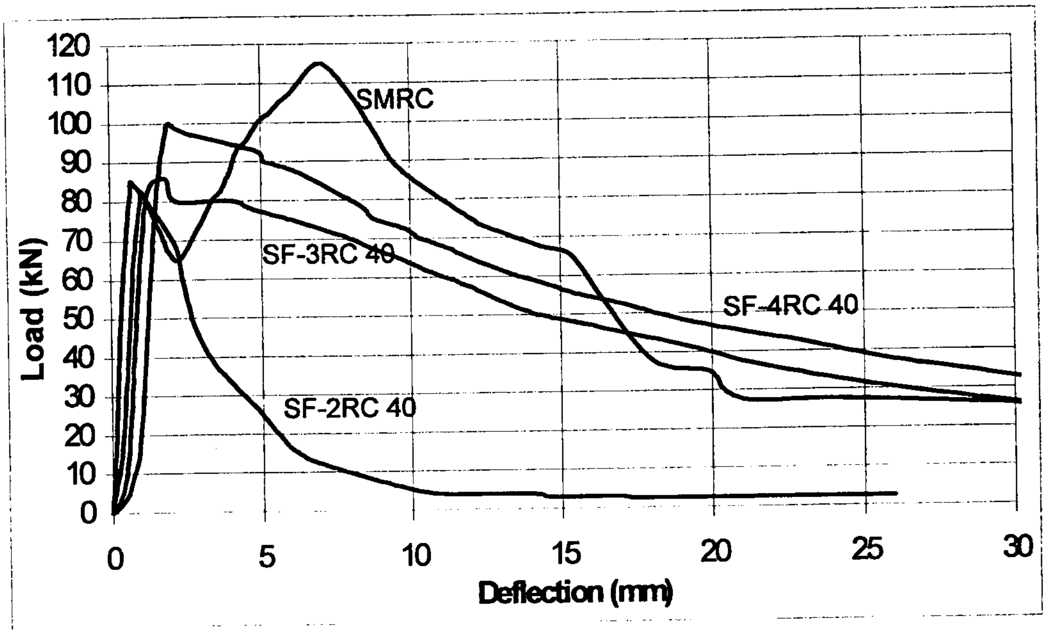


Figure 5.25 Comparison of Load–Deflection Curves of SMRC and SF-2RC 40, SF-3RC 40, SF-4RC 40.

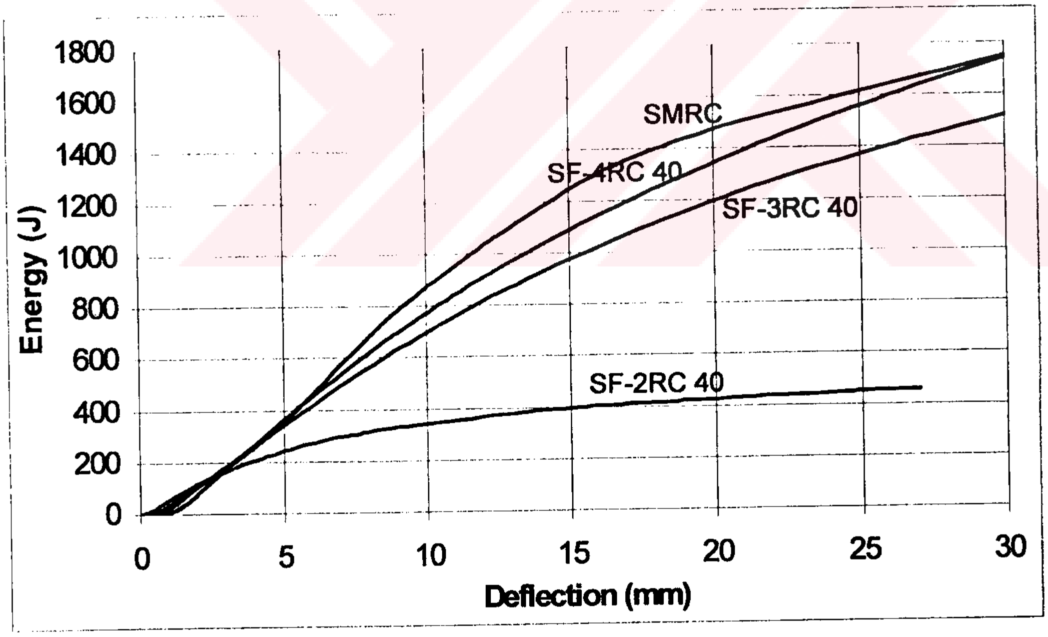


Figure 5.26 Comparison of Energy–Deflection Curves of SMRC and SF-2RC 40, SF-3RC 40, SF-4RC 40.

The main reason of SMRS and SMRC panels having higher energy absorption capacity than SFRS/C panels is that the bond and the friction stresses between the steel mesh and the shotcrete/concrete matrix are greater and the steel mesh has enough bond length which provides yielding and plastic deformation of it also increasing of the load–carrying and energy absorption capacity. In addition, the diameter of mesh is high as 8 mm.

On the other hand, for SFRS/C panels except panels having hooked steel fibres, after reaching their ultimate load capacities, it can be seen significant decreases in load carrying capacities due to having relatively not enough bond length and not enough bond with the shotcrete/concrete matrix, the fibres start to slip off from the shotcrete/concrete.

In addition, it should be pointed that there was almost no slipping off fibres from matrix in SFRS/C panels having hooked end steel fibres because of the hooked ends contributing significantly to the increase in the bond. The quality of steel fibres having hooked end was fully revealed when the cracks were in the concrete and they absorbed the tensile forces present. This process is related to the hooks of the fibres that are fixed in the concrete and continues until a high maximum pulling–out force is reached [74]. After the ultimate load, while the fibres not hooked were starting to slip from matrix, for hooked end steel fibre reinforced panels, the width of the cracks increased causing the hooks of the fibre showing plastic deformation and this plastic deformation allowed steel fibres shotcrete/concrete to achieve a high degree of toughness and ductility. In the case of further loading, when the embedded length to be pulled out was greater than the critical length, the tensile stress in the fibres reached the fracture stresses and the fibres were broken but did not slip.

According to results, it can be said that using steel fibres which is hooked and having high aspect ratio or hybrid steel-polypropylene fibres in shotcrete/concrete is considerably more advantageous than using steel mesh in performance point of view especially for tunnel applications where there are also many difficulties in application of steel mesh as mentioned before.

5.9 Failure Mechanisms of SMRS/C and FRS/C Panels

There are differences between FRS/C and SMRS/C from performance point of view as mentioned in previous sections. It was seen in this study that there were also differences between failure mechanisms of the mixes and these will be discussed in this section.

Figures 5.27, 5.28, 5.29, 5.30, 5.31 and 5.32 show the failure patterns of the panels. According to figures it can be seen that the SMRS /C panels failed mainly in punching shear modes and showed also evidence of flexural failure modes due to the hardened concrete matrix having some tensile strength. Also friction stresses and bond present between steel mesh and concrete matrix increased the punching shear capacity relatively in little amount although not having shear reinforcement.

On the other hand, according to earlier experiments, steel fibres in concrete are capable of converting the brittle failure by shear forces into a more controlled flexural failure [75,76] and a high punching resistance which can be obtained by using steel fibres may be a solution for the problem of high shear stresses in concrete slabs [77].

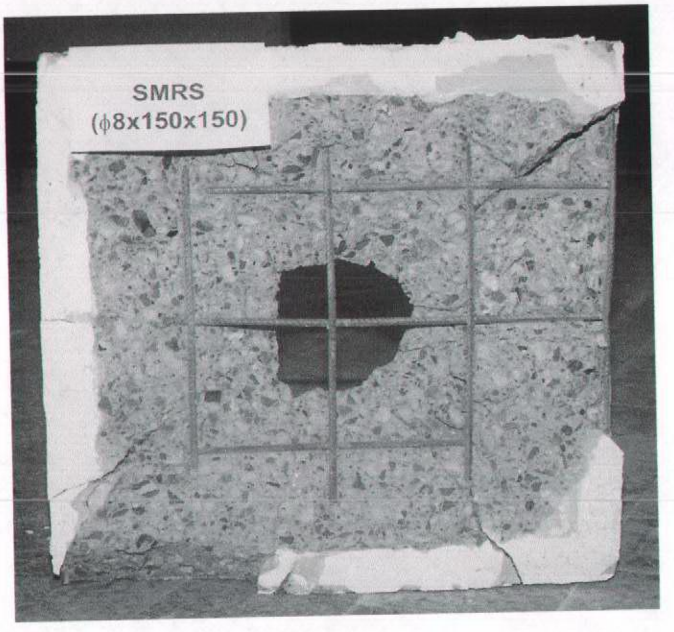


Figure 5.27 Failure Pattern of SMRS.

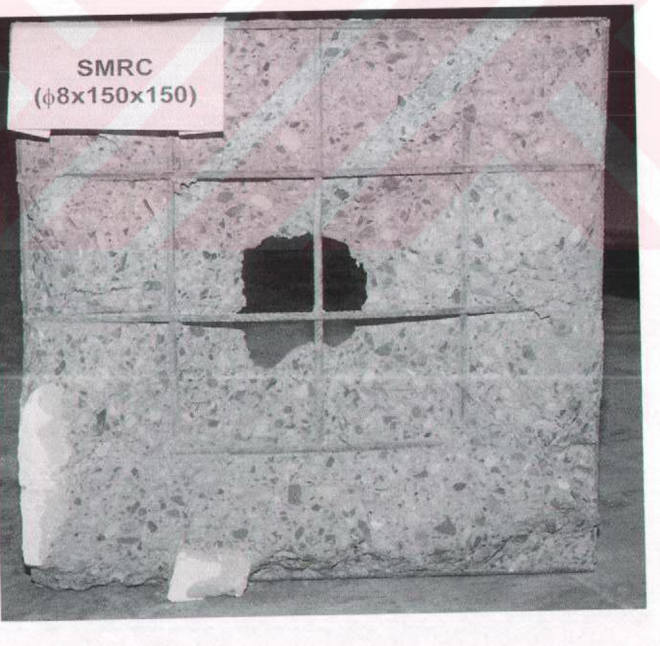


Figure 5.28 Failure Pattern of SMRC.

Confirming with the earlier studies, this investigation also proved that using fibres steel or polypropylene in shotcrete/concrete prevented cracks by punching shear and as could be seen from Figures, FRS/C panels failed mainly in flexural modes with some punching shear. As the load increased, the underside of the panels developed a series of cracks radiating outward to the edges from the centrally loaded area and the failure is caused dominantly by the damage from these radial cracks.

For FRS/C panels, the mode of failure changed from punching shear to flexure because the fibres that are regularly distributed mainly two or three dimensionally in the SFRS/C and HPPRS panels worked partly as shear reinforcement by increasing the shear capacity also enhancing the ductility greatly.

In fact, for shotcrete panel, the fibre distribution can be only defined as mainly two dimensional due to the unevenness of different aggregate, technology and other building site factors. It means that the fibres have negligible effect on vertical (splitting) cracks and have only effect on oblique shear cracks. On the other hand, the fibre distribution is mainly three-dimensional in laboratory concrete panel and this means that the fibres can reinforce both shear and vertical cracks [50]. But this difference between the fibre distribution in shotcrete and concrete panel had no important effect on the failure mechanisms of them where mainly flexural failure also some punching shear failure were effective because of fibres in both matrix types working partly as shear reinforcement.

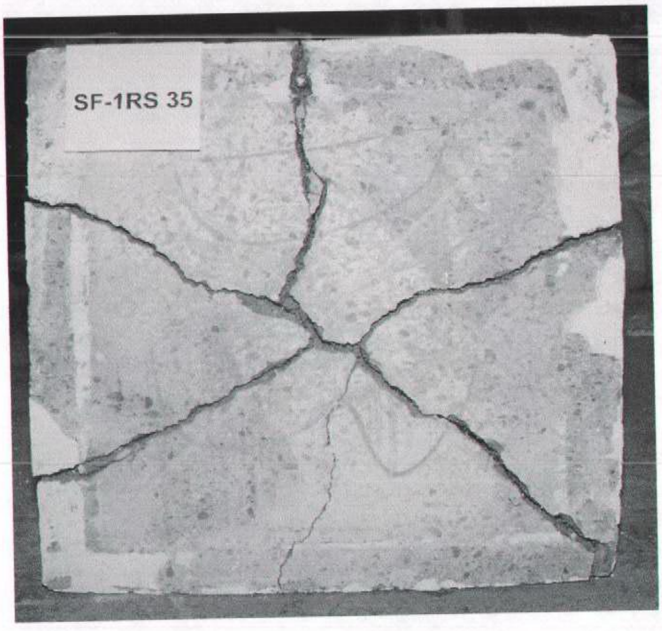


Figure 5.29 Failure Pattern of SF-1RS 35.

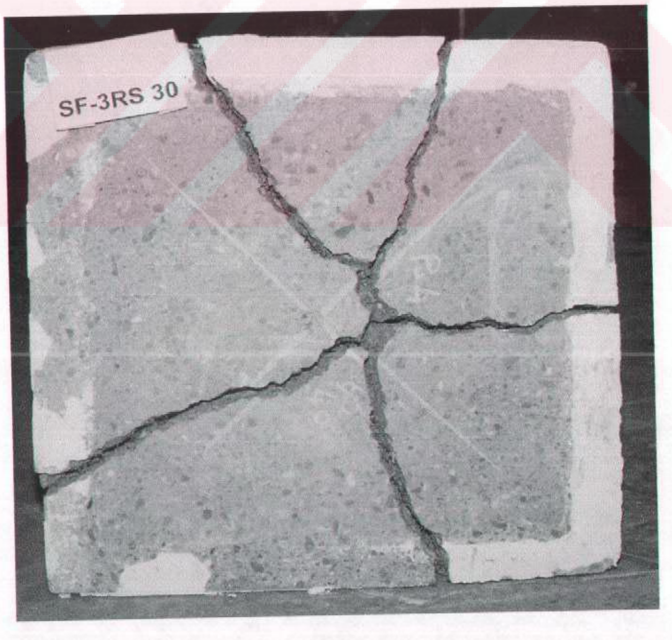


Figure 5.30 Failure Pattern of SF-3RC 30.

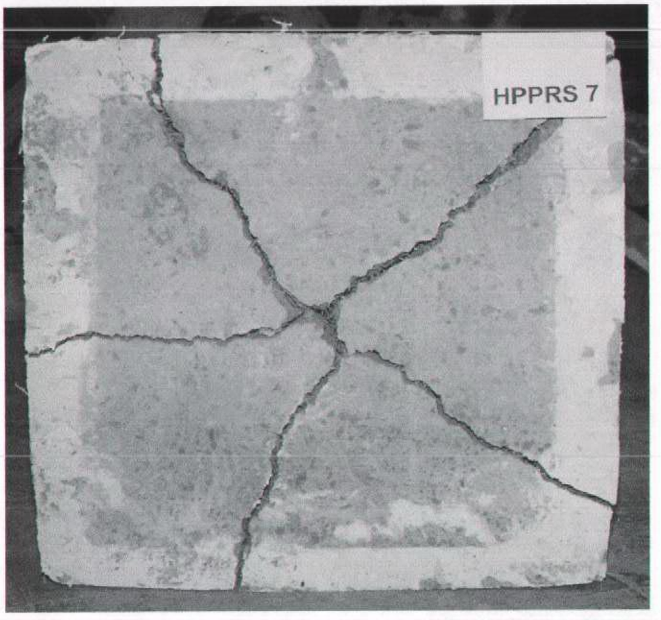


Figure 5.31 Failure Pattern of HPPRS 7.

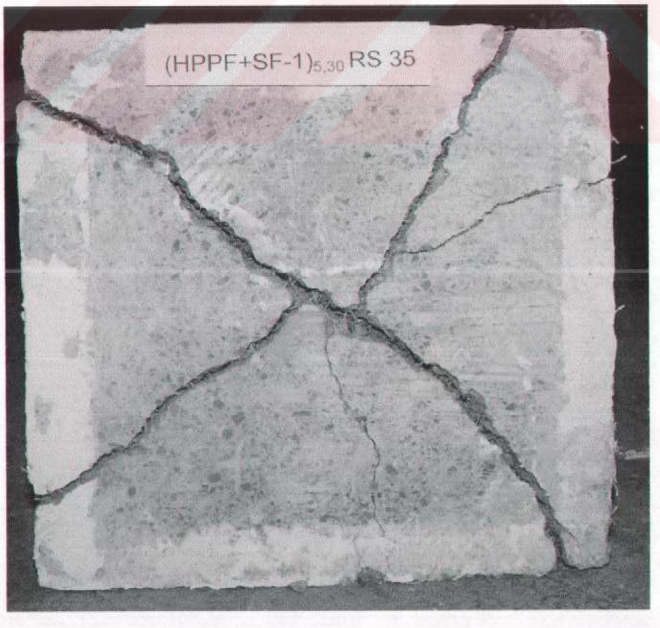


Figure 5.32 Failure Pattern of (HPPF+SF-1)$_{5,30}$RS 35.

5.10 Comparison of Panel Test Results for Shotcrete and Concrete Mixes According to Toughness Classes

In this section panel test results for all concrete/shotcrete mixes which was presented in graphical form in previous sections were tabulated and discussed according to energy absorption classes.

The average results for the first – peak load, the maximum load and the energy absorption in joule for a deflection until 25 mm for shotcrete/concrete plates can be seen in Table 5.4.

From Table 5.4, it can be seen that SF-4RC 40 has the maximum first-peak load and its ultimate load is also one of the highest loads with that of SMRC. Also, its energy absorption capacity with that of SMRC up to 25 mm are the highest ones. On the other hand, HPPRS 10 has the lowest first-peak load and its ultimate load is also the lowest one. In addition, SF-2RC 40 has the lowest energy absorption capacity up to deflection of 25 mm.

The criterion for the evaluation of the material toughness of panel test is the energy absorption classes (Table 5.5) [48]. For tunnel repair jobs, the SNCF specifies energy absorption of 500 J till a deflection of 25mm [67].

Also, by comparing Figures from 5.1 to 5.26 with Table 5.5, the results of achieving of energy absorption classes according to related deflections can be obtained and it can be seen in Table 5.6.

Table 5.4 Comparison of the Average Values of First–Peak Load (kN), Ultimate Load (kN) and Energy Absorption Till Deflection of 25 mm (J) for Shotcrete/ Concrete Plates.

Mixes	First–Peak Load (kN)	Ultimate Load (kN)	Energy Absorption at 25 mm (J)
SMRC	82.5	115.0	1615.30
SMRS	67.5	72.5	1308.40
SF-1RS 35	65.0	65.0	664.11
SF-1RS 50	75.0	75.0	846.48
SF-2RC 40	85.0	85.0	406.73
SF-2RC 50	90.0	90.0	525.05
SF-2RC 60	81.0	81.0	626.37
SF-3RC 30	75.0	75.0	1130.60
SF-3RC 40	86.5	86.5	1369.84
SF-4RC 30	90.0	90.0	1440.56
SF-4RC 40	100.0	100.0	1559.80
HPPRS 7	70.0	70.0	716.17
HPPRS 10	50.0	50.0	751.35
MIX 35*	65.0	65.0	965.45
MIX-1 50**	73.0	73.0	710.55
MIX-2 50**	85.0	85.0	855.45
MIX-3 50**	80.0	80.0	912.30

* MIX 35 = $(HPPF+SF\text{-}1)_{5,30}$RS 35

** MIX-1 50 = $(SF\text{-}2+SF\text{-}5)_{40,10}$RS 50, MIX-2 50 = $(SF\text{-}2+SF\text{-}5)_{35,15}$RS 50, MIX-3 50 = $(SF\text{-}2+SF\text{-}5)_{30,20}$RS 50

Table 5.6 Energy Absorption Classes with respect to Deflections for Shotcrete/Concrete Mixes.

Mixes	Deflection(mm) achieved class (a)	Deflection(mm) achieved class(b)	Deflection(mm) achieved class (c)
SMRC	6.25	8.05	11.50
SMRS	8.32	11.33	16.32
SF-1RS 35	14.50	-	-
SF-1RS 50	9.50	15.65	-
SF-2RC 40	-	-	-
SF-2RC 50	23.50	-	-
SF-2RC 60	15.00	-	-
SF-3RC 30	8.25	12.00	20.00
SF-3RC 40	7.00	10.00	15.50
SF-4RC 30	7.00	10.00	15.00
SF-4RC 40	6.50	8.75	13.50
HPPRS 7	12.75	23.90	-
HPPRS 10	14.50	21.75	-
MIX 35*	10.00	15.35	-
MIX-1 50**	13.15	24.50	-
MIX-2 50**	9.25	16.50	-
MIX-3 50**	9.50	16.50	29.00

* MIX 35 = $(\text{HPPF+SF-1})_{5,30}$ RS 35

** MIX-1 50 = $(\text{SF-2+SF-5})_{40,10}$RS 50, MIX-2 50 = $(\text{SF-2+SF-5})_{35,15}$RS 50, MIX-3 50 = $(\text{SF-2+SF-5})_{30,20}$RS 50.

Table 5.5 Energy Absorption Requirements.

Toughness Class	Energy Absorption for Deflection up to 25mm in Joule
a	500
b	700
c	1000

From Table 5.6, it can be seen that SMRC and SF-4RC 40 panels firstly achieved the energy absorption class of (a), (b), and also (c). On the contrary, SF-2RC panels lastly achieved the energy classes. Generally, it can be said that panels having steel fibres that had hooked end and high aspect ratio showed the best performances in steel fibres and they achieved the all energy classes. On the other hand, neither of other types of steel fibres achieved the energy class of (c).

Apart from these, HPPRS panels also showed good performances. Especially, hybrid usage of HPP with SF in panels provided earlier achievement of energy classes and also increased the energy absorption capacities significantly compared to that of SF-1RS panels having the same fibre content. Similarly, (SF-2+SF-5) panels gave much better results than SF-2 panels had. These are the evidences of positive synergy effect between hybrid fibres on panels.

CHAPTER 6

CONCLUSIONS

The experimental investigations were performed on steel mesh (SM), steel fibre (SF), high performance polypropylene fibre (HPPF) and hybrid fibre (SF-HPP and SF-SF) – reinforced shotcrete/concrete mixes to evaluate their performance characteristics such as toughness, flexural ductility, energy absorption and load carrying capacities etc. Also their compressive behaviour and rebound characteristics of FRS mixes were investigated.

As a result of this study, the following conclusions can be drawn:

1- All types of fibres, including HPPFs that are low – modulus fibres have the ability to strengthen brittle shotcrete/concrete.

   The addition of fibres improved toughness, flexural ductility, punching shear, energy absorption capacity and load carrying capacity of shotcrete/concrete significantly. On the other hand, no significant increases were seen in compressive strengths of mixes with the addition of fibres.

2- The increase in fibre content enhanced the load carrying and energy absorption capacities for all types of panels.

On the other hand, for some panel types, like SF-2RC and HPPRS, increase in fibre content decreased the first – cracking and ultimate load-carrying capacities of them causing not so much increase in toughness and energy absorption capacities. Therefore, it must be stated for fibre amount used in the concrete/shotcrete that, there is an optimum point to get the best efficiency from the composite. Because, an excess of fibres may also have adverse effects on strength due to the introduction of additional defects during the processing stage.

3- The size, shape and geometry of the fibres are very important for fibre – reinforced shotcrete/concrete from performance point of view.

Among the four types of steel fibres SF-1, SF-2, SF-3 and SF-4, SF-4 is the best one from the mechanical property point of view. Because it is hooked and it has high length/diameter ratio.

Accordingly, it could be said that using steel fibres with hooked ends in shotcrete/concrete contribute significantly to the increase in bond between the fibre and the matrix because of the anchored hooked ends of the fibres, which make it possible to use the whole length of the fibre to transmit the maximum amount of force.

Also, the higher the aspect ratio of the fibres provide the better the performance of the FRS/C with respect to flexural strength, toughness, ductility and load carrying capacity. However, the problem is that the higher the aspect ratio like the higher content of the fibre, the more difficult the shotcrete becomes to mix, convey and shoot. Thus, there should also be practical limits to the geometrical characteristics of the fibre types.

Finally, it must be stated that the most important aspects controlling the performance of fibres in shotcrete/concrete are:

- the amount of fibres
- the aspect ratio of fibres
- the geometrical shape of fibres

4- The homogeneously distributed HPP fibres, although having low Young's modulus and to be expected having little effect on crack propagation, showed better performances than SFs did in some aspects. Also, they were more convenient to mix and to shoot with shotcrete due to their very low specific gravity and being used much less amount in concrete compared to the usage amount of steel fibres.

Additionally, by comparing the rebound characteristics of fibres it can be said that using HPP fibre in shotcrete is very advantageous because of not only causing increase in performance of shotcrete but also reducing the decrease in volume concentration of fibres due to rebound of them during shooting. Reduction in rebound has also significant financial implications. By increasing the fibre loss reduction, (fibres as the most expensive component of the shotcrete mix) HPPFs also improve the economical attractiveness of FRS.

5- This research showed that there was a positive synergy effect between different type, kind and geometry of steel fibres and between steel – polypropylene fibres on load carrying capacity, ductility and toughness.

Using HPP fibres with steel fibres and steel fibres with different type of steel fibres in FRS/C greatly enhanced the performance. It can be said that the hybrid fibre system is more efficient than mono-fibre system from performance point of view if proper types of fibres are used in proper amounts and hybrid polypropylene–steel fibres particularly hooked end can be used alternatively instead of steel mesh and mono steel fibre as reinforcement in shotcrete/concrete applications to get better efficiency.

6- It can be concluded that compressive strengths were little influenced by fibre addition for all hardened shotcrete and concrete mixes.

Therefore it can be said that compressive strength is mainly controlled by the shotcrete/concrete matrix design and the compressive strength of FRS/C depends on the compressive strength of the matrix.

7- By comparing the performances of SMRS/C with FRS/C, it can be concluded that using steel fibres which is hooked and having high aspect ratio or using hybrid steel-polypropylene fibres is considerably more advantageous than using steel mesh in shotcrete/concrete especially for tunnel applications where there are also many difficulties in application of steel mesh.

8- This investigation also proved that using fibres steel or polypropylene in shotcrete/concrete prevented cracks by punching shear and the fibre usage greatly improved the punching shear capacity with ductility due to working of fibres which are distributed mainly two or three dimensionally in the FRS/C as shear reinforcement. Accordingly, it must be stated that while FRS/C panels failed mainly in flexural modes with some punching shear SMRS/C panels failed mainly in punching shear modes and showed also evidence of flexural failure modes.

9- Finally, according to toughness classes, it can be said that all shotcrete/concrete panels except SF-2RC 40 reached the toughness class of a (500 J) till a deflection of 25 mm which is specified by SNCF for tunnel repair jobs. This is an evidence that using steel or polypropylene fibres in shotcrete/concrete provide a certain level of energy absorption capacity and toughness for brittle matrix.

CHAPTER 7

RECOMMENDATIONS

The main purpose to apply panel tests is to evaluate the performances of reinforced shotcrete/concrete mixes such as toughness, ductility, energy absorption and load capacity etc. Compressive strengths and rebound characteristics were the other characteristics of mixes discussed in this study. Based on the results obtained from the present study the following recommendations are made for further investigations.

1- In this experimental study, the experimental investigations were performed on steel mesh, steel fibre and high performance polypropylene fibre – reinforced shotcrete/concrete panels cured for 28 days. Further studies should be performed on the specimens at early age. In this way, the evaluation of the performances can be made for early strength developments, which is important especially for tunnel applications.

2- The energy absorption capacity and flexural toughness of the specimens were obtained in this investigation by integrating the area under load – deflection curve of them. Additional tests can be performed to investigate the compressive behaviour of the same composites by using stress-strain relationships. In this way, compressive toughness of the mixes can be obtained.

3- In this study to evaluate the toughness behaviour, panel test according to EFNARC was performed on the specimens. A more thorough study can be made to characterise toughness behaviour by using also other approaches.

4- Further studies should cover different types of reinforcements other than steel mesh, steel and polypropylene fibre to get the best efficiency from shotcrete/concrete. For example, tire rubber particles can be used to investigate toughness behaviour.

5- Shotcrete panels reinforced with steel – polypropylene and steel – steel hybrid fibres were also tested in this research to investigate the effect of using hybrid fibres in shotcrete/concrete panels on performance of them. Additional tests can be made for hybrid steel-polypropylene fibre reinforced shotcrete/concrete containing hooked steel fibres having high aspect ratio to improve the performance.

6- Also in this study, it can be observed that increase in HPP fibre content from 7kg/m^3 to 10 kg/m^3 did not impart a significant increase in toughness but caused decrease in first – peak load. Additionally, by comparing the results of HPPRS 7 with SFRS 35, it can be said that there may be a probable economical amount for performance characteristics point of view near the 7 kg/m^3 at which it is possible to use HPP fibres instead of steel fibre and it can be more efficient. Therefore, another investigation can be made on HPPRS containing HPP 8 or 9 kg/m^3.

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