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Optimized Energy Based Design of Tunnel Lining with Macro Synthetic Fiber Composites

Massoumeh Farjadmand and Mohammad Safi

***Abstract*—Energy absorption potential of fiber composites can be utilized for various applications especially where considerable deformations may be imposed to a structure. For underground structures such as tunnels where the media can impose such deformations, more flexibility of the support structure will result in less volume of the material requires or say a thinner structure. In order to provide higher energy absorption capacity in fiber reinforced composites, it is normally required to use more fiber content. However more use of fibers results in more cost and this leads to economical limitations. This research aims to introduce an optimized mix design with minimum possible fiber content while having the maximum possible energy absorption capacity. A series of laboratory tests were conducted with various additive and fiber contents to reach this goal. General recommendations for achieving the optimized results were proposed based on experimental results. Beam and panel tests were used to account for energy absorption capacity. The results of the optimized mixes were used to propose corresponding design chart for energy based design of tunnel lining.**

***Index Terms*—Energy based design, fiber reinforced composite, panel test, high performance concrete.**

I. INTRODUCTION

The uses of fiber reinforced composites, FRC, are being extended to various structural applications. Improved performance and durability of these materials make them an effective alternative for many designs. From a structural viewpoint, the main reason for incorporating fibers is to improve the fracture characteristics and structural behavior through the fibers' ability to bridge cracks. This mechanism influences both the serviceability and ultimate limit states. The effects on the service load behavior are controlled crack propagation, which primarily reduces the crack spacing and crack width, and increased flexural stiffness. The effect on the behavior in the ultimate limit state is increased load resistance and, for shear and punching failures, fibers also improve the ductility.

The concrete property most benefited by fiber reinforcement is the energy absorption capacity. Adding the amount of fibers used in current applications of FRC, the concrete compression, tensile, shear and torsional strength are increased by various degrees depending on the fiber type and the structure characteristics. In structures with redundant supports, like slabs on soil and tunnel lining, the increment on the material energy absorption capacity, provided by fiber reinforcement, enhances the cracking behavior and increases the load bearing capacity of the structure [1].

Due to the relevance of the energy absorption capacity of fibrous concrete, several entities have been proposed for evaluating this property, namely, the toughness indices, the equivalent flexural strength and the fracture energy. Among these entities, the fracture energy is the most used in the constitutive models for characterizing the concrete tensile post-cracking behavior. The other entities have not been used widely in numerical simulation of the behavior of FRC structures. Compared to other composite materials such as fiber-reinforced polymers, fiber reinforced cement-based composites are different [2], [3]. An obvious difference is that the reinforcing effect primarily occurs after the brittle matrix has cracked, either at the microscopic level or with visible cracks through the composites.

This paper discusses various parameters which affect the ductility of the fiber concrete and presents the results of experimental analyses performed to fine the most sensitive parameters affecting energy absorption and the optimized mix design considering the test limitations [4]. The required energy classes for tunnel lining in various rock situations were used as bench mark and it was tried to reach those levels by producing the most economic mix design. Discussion about the effect of additives on the ductility of the composite material has also been presented in this paper.

II. ENERGY ABSORPTION EVALUATION

European Standard EN 14487 includes two different ways of specifying the ductility of Fiber Reinforced Concrete (FRC) in terms of residual strength and energy absorption capacity [5]. It also indicates that both ways are not exactly comparable. The residual strength approach can be adopted when the concrete characteristics are used in a structural design model. The energy absorption value measured for a panel can be adopted when, in the case of ground support, emphasis is placed on the energy which has to be absorbed during the deformation of the ground which is especially useful for primary sprayed concrete linings.

In order to assess the structural behavior of FRC in a tunnel lining, a test program was developed in Turkey by UK Construction Technologies Corporation. The test method described in EN 14488 is intended to determine the energy absorbed under the load/deflection curve. Panels intended for this flexural-punching test were made in forms measuring 600×600×100 mm.

If the capacity for energy absorption of FRC is specified, it must be determined using a panel specimen as per standard

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M. F. is Senior Lecturer at University of Creative Energy, Westminster, London, U.K (e-mail: m.farjadmand1@westminster.ac.uk).

M. S. is Assistant Professor at Power & Water University of Technology, Tehran, I.R. Iran (e-mail: msafi@pwut.ac.ir).

EN 14488-5. Based on this panel test, three FRC classes (E500, E700, and E1000) are defined as follows [5]:

- 500 Joules for sound ground/rock conditions.
- 700 Joules for medium ground/rock conditions.
- 1000 Joules for difficult ground/rock conditions.

When dealing with aspects of structural application of FRC materials it is important to realize that three situations can be achieved including tension softening response which is so significant that it can be allowed to be taken into account in structural design, the strain hardening portion that is significant enough that it can be taking into account in structural contexts and both the hardening and the softening regimes which are significant enough to be taken into account in structural design.

The generic mechanical response contains a linear regime in which very little permanent micro-structural changes and deformation take place and a nonlinear regime in which permanent micro-structural changes take place in a stable manner. In this range a certain permanent deformation is typically introduced. If the micro-structural change is formation of frictionless micro-cracks, the corresponding mechanical response would only show decreasing stiffness and virtually no permanent deformation [6].

III. EXPERIMENTAL STUDY

In order to obtain the most appropriate mix characteristics with highest energy absorption an experimental study were performed including 33 beam and rectangular panels all by the authors. Test setup and general information have been shown in figure 1. First the general mix proportion has been introduced and then the results have been presented briefly and discussed.

For fibers, black colored, 48mm long modified polyolefin type synthetic fibers (SHOGUN) were used. For preparing the concrete test specimens, CEM-I 42.5 type Portland cement was used. According to the mixture design, the cement content was selected as 450 kg per cubic meter. A new generation poly-carboxylate based high range water reducer (HRWR), Adva Flow 501, was used. The amount of the HRWR has been changed between the range of 1.6% and 2.1% by weight of total cement content. An air entraining admixture, Sika ACR, was also used. According to the mixture design, the amount of the air entraining agent was selected as 0.1 kg per cubic meter.

According to the mixture design, the amount of the fiber reinforcement was selected to vary as 4.0, 6.0 and 8.0 kg per cubic meter. The fibers should be added simultaneously with other HRWR additive in order to facilitate the mixing process and uniform propagation of fibers.

For preparing the concrete mixtures, different aggregate group was used: (0-5) mm Sand, (5-12) mm Crushed Limestone and (12-22) mm Crushed Limestone. According to the mixture design, the amount of aggregates per cubic meter were used as 837 kg (0-5) mm Sand, 500 kg (5-12) mm Coarse Aggregate and 335 kg (12-22) mm Coarse Aggregate. The amount of tap water per cubic meter of concrete was selected as 160 kg. Consequently, for all mixtures, water to cement ratio (w/c) by weight was fixed to 0.356.

The average cylindrical compressive strength of the samples was 50 MPa. The presence of fiber had little effect on compressive strength compared to plain concrete. The splitting tensile strength was also obtained with average of 4.5 MPa for fiber samples which was at least 35 percents higher than that of plain concrete.

The first series of test were conducted using various fiber contents. These tests were performed by 4, 6 and 8 kg of fibers per cubic meter to account for fiber dosage effect on energy absorption capacity. The obtained specific energy obtained from theses samples has been shown in table 1.

TABLE I: EFFECT OF FIBER CONTENT AND ADDITIVES ON SPECIFIC ABSORBED ENERGY

Sample	#	A	B	C	D	E	F	G
Fiber Content	Kg/m^3	0	4	4	6	6	8	8
Specific Absorbed Energy	Joule/m^2	244	640	911	1478	1925	2790	1656
Comment	Additive	None	Air	HRWR Added	Air	HRWR Added	HRWR Added	Air

As shown in the table, the specific absorbed energy will increase by increasing fiber content. The increase does not have a linear relationship with dosage as shown in Fig. 1. The poly-carboxylate based high range water reducer has increased the effectiveness of the fibers and improved the energy absorption capacity. The minimum increase in the energy absorption value has been observed to be 50 percents. Note that this additive will lead to self compacting concrete with minimum slump of 20 millimeters. The results showed that 20 percents increase in this additive value will result in more than 55 percents decrease in energy absorption.

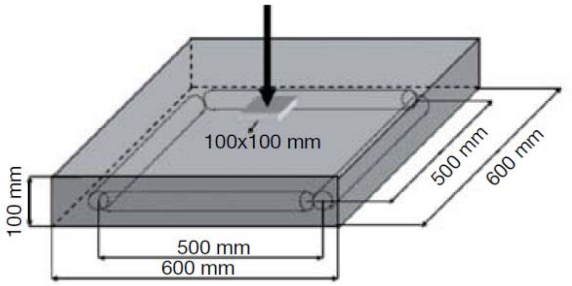

Fig. 1. Test setup geometry and loading pattern and definition of energy absorption capacity until 25 mm deflection as noted in EFNARC [5].

Fig. 2 shows the sample failure mechanism of plain concrete rectangular panel and the objective load – deflection curve and specific absorbed energy definition. This result can be compared with failure mechanism of fiber composite rectangular panels shown in figure 3 and shows a more flexible failure mechanism for fiber composite panels.

As can be seen from the figure, the failure mechanisms follow a uniform pattern with maximum number of cracks which leads to higher energy absorption. This also shows the uniform distribution of fibers in different samples. Sample load deflection and energy absorption curves have also been shown in figures 3 and 4. The required energy absorption for tunneling application can be extracted by reading energy capacity at 25 mm displacements of the panels.

The microstructure of concrete, and its development with time, plays a significant role in controlling the performance of a fiber-reinforced concrete. For plain concrete there are a number of complex mechanisms involved in the fracture process, and the major toughening mechanism is the aggregate bridging but that increased toughness also can be achieved by air voids.

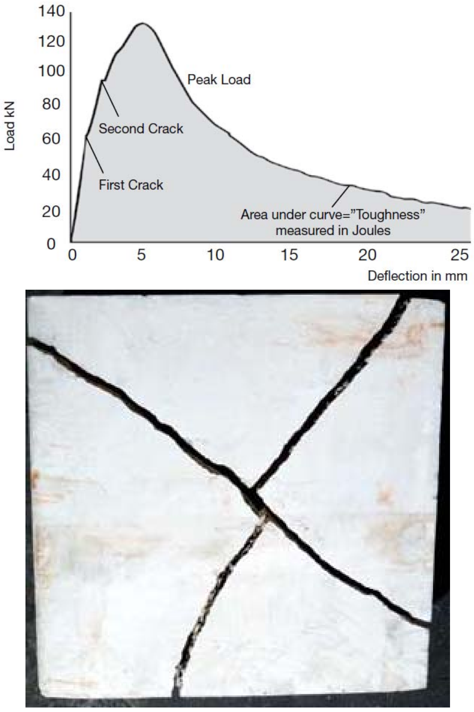

Fig. 2. Failure mechanism of plain concrete rectangular panel.

Tests were conducted for various fiber contents and the maximum specific absorbed energy was measured. The small amount of energy absorbed by plain concrete panel was ignored. Fig. 4 shows the variation of specific absorbed energy with fiber content. Load – deflection curve for optimized samples have been presented in figure 5. The corresponding energy-deflection curves have also been shown in Fig. 6.

An investigation on the broken samples showed that the additive will give a better orientation to the fibers. This issue will increase the effect of the fibers and decrease the need for more fiber content. Normally the fibers are located in the mix randomly. But this would not be an optimum condition for structural members.

In structural members such as slabs or shells, the load path inside the member has a governing or specific orientation so that the orientations of maximum tensile stress and strain are predetermined. In such cases the best orientation for fibers can be determined and if we can put most of them in these directions, then the most effective load carrying system will be obtained. The additive introduced above can help to reach this goal. HRWR polarize the fibers so that they stand parallel to each other. This characteristic accompanied by changes in concrete purring pattern can result in the expected pattern of fibers for the most effective load carrying and energy absorption capacity.

Another parameter used for specifying the energy absorption capacity of the fiber reinforced concrete is characteristic length. The characteristic length, l_{ch}, is an indication of the material's brittleness which depends on fracture energy, modulus of elasticity and tensile strength and is defined as:

$$l_{ch} = \frac{E_c . G_F}{f_t^2} \tag{1}$$

where f_t the tensile strength; E_c is the modulus of elasticity and G_F is the fracture energy. For the current tests this parameter ranges between 25000 to 31000 for 6 kg fiber content per cubic meter. The value for mesh reinforced concrete is around 5000. This shows the higher ductility of fiber reinforcement compared to concrete reinforced with welded wire mesh which is widely used in conventional tunneling works.

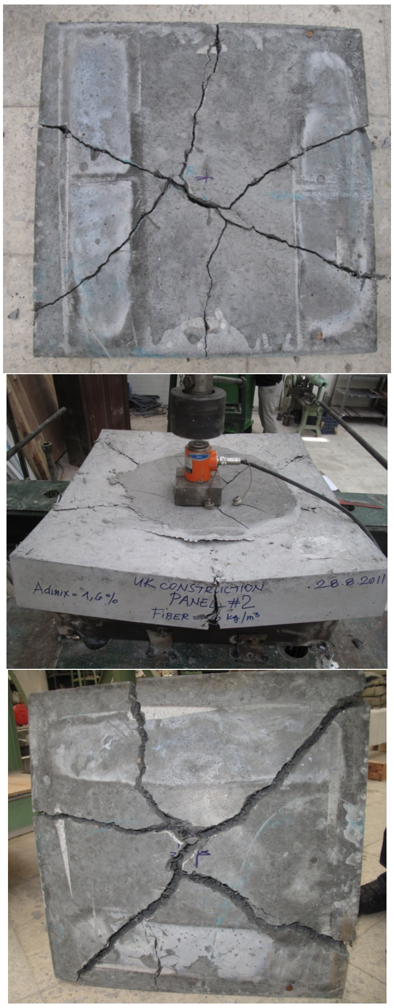

Fig. 3. Failure mechanism of fiber reinforced concrete rectangular panels with 6 kg/m3 synthetic fibers.

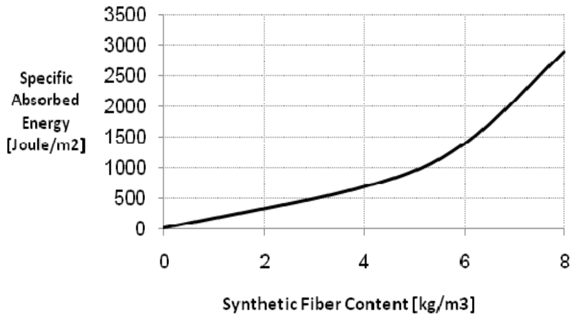

Fig. 4. Variation of specific absorbed energy with fiber content.

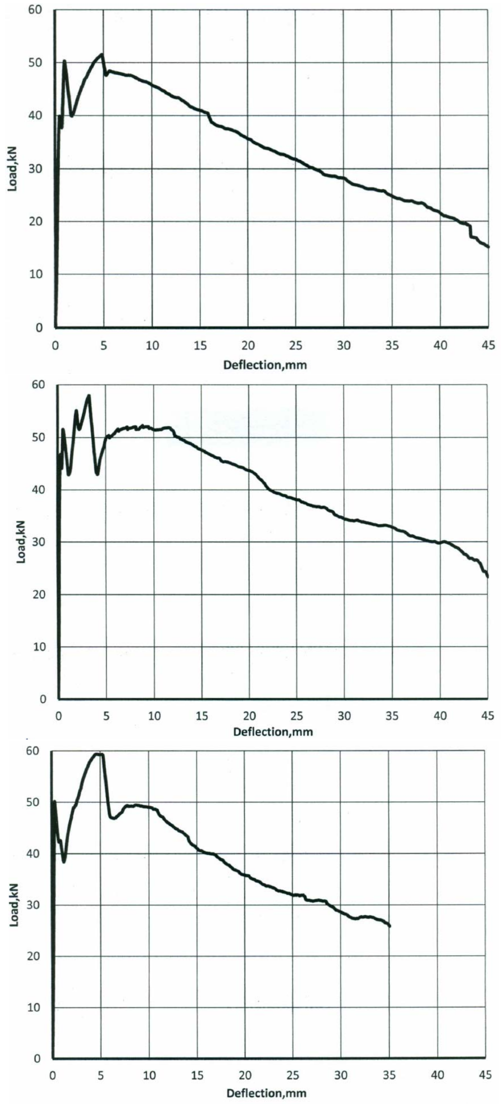

Fig. 5. Load-deflection curve from rectangular slab test with modified mix design for samples C, E and F respectively from top.

Besides the minimum energy absorption capacity required for the structure, the other limitation for fiber dosage is the amount required for shrinkage cracking control. The minimum fiber amount to be used for shrinkage control, ρ_f, can be estimated from the following equation:

$$\rho_f = \frac{\pi . d_f^2 . l_f}{4s^3} \qquad (2)$$

where d_f is the diameter of fiber, lf is the length of the fiber and s is the average required distance between the fibers which can conservatively be assumed as 45 percents of the fiber length as shown in Fig. 7.

For the high performance polyolefin modified fibers, this value is less than 0.3 percents. Shrinkage tests performed by the authors for the current fiber dosage, 0.67 percents, showed that this amount of fibers completely controls the plastic and drying shrinkage cracks. This value corresponds to the 6 kg dosage of fiber in one cubic meter of fresh concrete.

The modulus of elasticity was also measured in this study as shown in figure 8. As could be expected the fibers reduce the modulus of elasticity up to an average of 10 to 15 percents for initial tangent modulus and 15 to 20 percents for reduced modulus. Test results showed that more increase in the fiber content will not result in the same reduction of elasticity modulus. Thus the fiber contents of 6 and 8 kilograms per cubic meter have nearly same ductility and the optimum fiber content in this case can be fixed on 6 kilos.

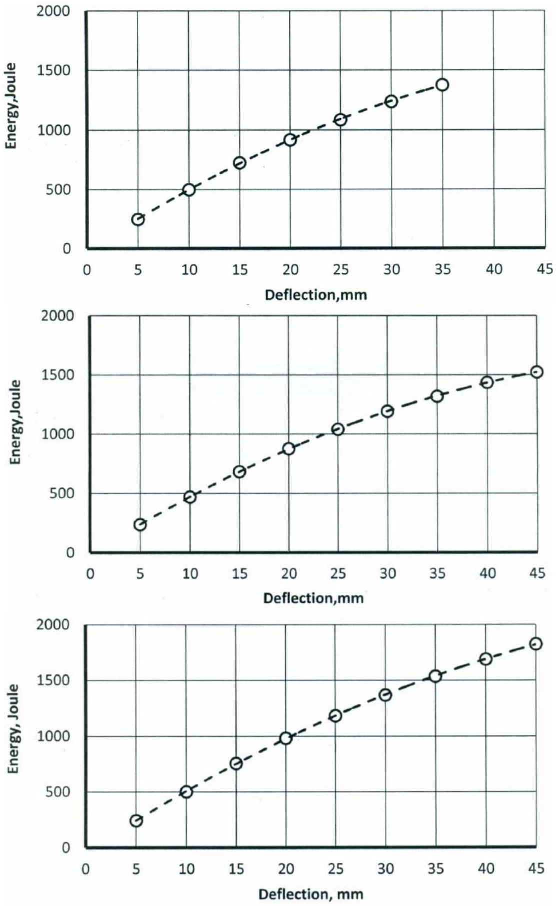

Fig. 6. Energy absorption-deflection curve from rectangular slab test for modified mix design for samples C, E and F respectively from top.

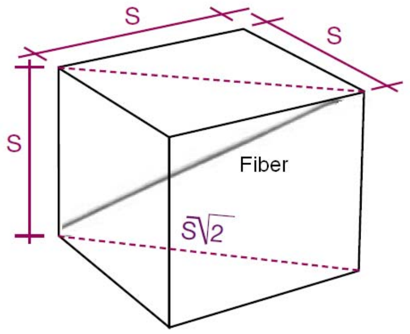

Fig. 7. Definition of average required distance between the fibers.

Reduction of elasticity modulus with constant compressive strength generally results in more ductile concrete with same resistant. This ductility can reduce stress concentration and crack width and totally a better behavior compared to steel reinforced concrete. For conventional steel mesh reinforced concrete the equivalent modulus of elasticity increases and less number of cracks with more width has normally been observed form panel tests.

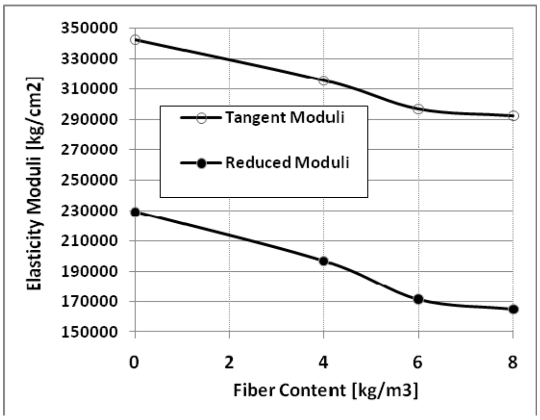

Fig. 8. Tangent and reduced modulus of elasticity for concrete samples with different fiber contents.

For fiber-reinforced concrete, with a low volume fraction of fibers (V_f <1.0%), the fibers have a little effect on the strength both in tension and compression and that the primary effect of fibers is their ability to improve the post-cracking behavior and the toughness or the capacity of transferring stresses after matrix cracking and the tensile strains at rupture. The fiber pull-out depends on the characteristics of the fiber and the matrix, the mechanical properties of the interface between fiber and matrix, and the angle of inclination of the fiber with respect to the direction of loading.

Previous literature shows that, in order to achieve structural benefits such as high energy absorption from conventional fibers the amount of fiber used in the concrete mix should be at around 1.5 to 2.0 percents. This study introduced a new mix proportion with long synthetic fibers which has the same characteristics by using half of the conventional fiber dosage. The highest energy absorption class, 1000J, defined by EFNARC [5] was achieved with a more economic concrete mix.

IV. CONCLUSIONS AND DESIGN RECOMMENDATIONS

The experimental study performed for finding optimized mix design of fiber reinforced concrete showed that by applying some changes to the mix design the amount of fiber can be reduced while keeping the energy absorption capacity constant. The changes in the mix should have two major effects namely preordination of fibers in the mix and reducing the water to cement ration to less than 0.4. This totally results in a high performance self compacting fiber reinforced concrete with rather high strength and high energy absorption capacity. Such composite shows high resistance and ductility and can be very fantastic for both normal and special structural applications.

Regarding the application, the required energy absorption capacity is different for different structures and thus the mix design can be adjusted or optimized to fit the requirements. For long macro synthetic fibers used in this study, medium strength concrete will require at least 0.6 percent fibers with presented changes in the mix to give the required 1000 Joule energy capacity for tunneling in weak rock media. Normal applications of structural fibers present an average of 1.0 percent which is at least 50 percents more fibers. Note that this average changes slightly based on the type of the fiber. For Better condition of rock, fewer amounts of fibers can be used. For this level which is equivalent to 700 Joule energy absorption capacity, the test results propose 0.45 percent fibers.

Barton *et al.* [7], [8] have proposed the energy based design graph for conventional fiber composites. The graph presents the relation between tunnel characteristics such as length or span, the rock media type from poor to good rock or the rock mass quality index [7] and the proposed type of support required. The fiber composite linings proposed in this graph does not characterize the properties of fiber and the only way to find the composite mix design will be the energy absorption capacity. Thus by correlating the panel test results directly to other design demand parameter we can select the appropriate composite liner for tunnel support. The energy absorption level for each mix and its corresponding panel will be appropriate for a range of quality of the rock and thus design ranges for can be defined for each composite mix.

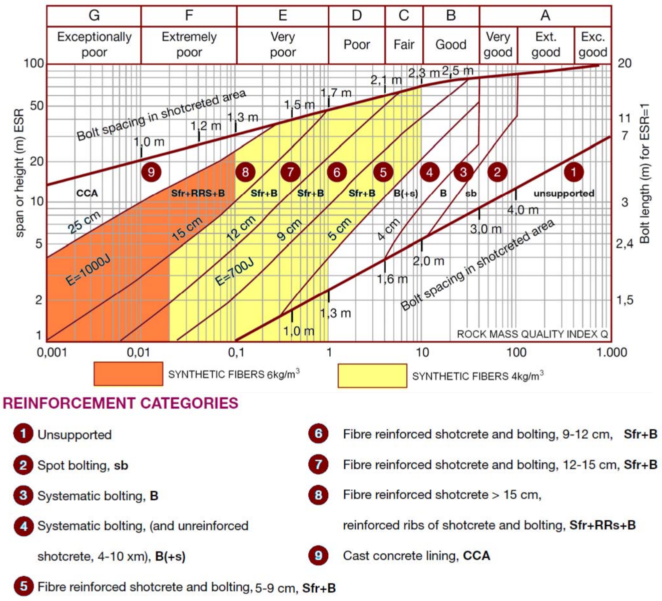

Fig. 9. Recommended application of tested mix designs with 4 and 6 kg fibers for tunnel support based on energy absorption capacity classes introduced by EFNARC [5] for rectangular panel test shown on modified experimental design charts [7], [8].

The series of test results obtained in this study can be used to introduce three levels of energy absorption capacities as noted by EFNARC [5] with corresponding mix designs proposed here. Each energy absorption level will cover a region in this design graph as shown in Fig. 9. Thus three regions with three levels of energy absorption and three mix design data can be highlighted on the graph with the tentative details of the support shown below Fig. 9. As discussed above the proposed composite liner is very economic compared to conventional designs and can also be comparable to the conventional steel reinforced cast concrete lining.

Higher energy absorption levels may also be obtained by following a similar procedure as was performed this study. Note that, although more fibers results in more energy absorption up to a certain level, the failure mechanism and structural behavior does not change, thus the same objectives can be met by minimum amounts of the fibers.

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Massoumeh Farjadmand, is a senior lecturer and the course leader for Building Engineering course, in the University of Westminster got BS, MSC and PhD in structural engineering at City University and University of Westminster in London, UK. She joined the University of Westminster as research assistant in concrete structures in 1996 with professional interest in the field of concrete structures. She is currently involved in further research in the behavior of Fiber Reinforced Concrete, FRC, to investigate the effects of various chemical additives with varying degrees of slump to arrive at an optimum position for sprayed concrete by shotcrete method. She has been involved in a number of design projects ranging from bridge assessment to concrete frame building. Dr Farjadmand is an active graduate member of the Institution of Structural Engineers, IStructE, and aiming to become a charted Engineer soon. Also she is a cooperated member of Charted Institute of Building.

Mohammad Safi, is an assistant professor at the Power and Water University of Technology got his BS and MSC in structural engineering at Tehran University and PhD at Tehran Poly-technique, Iran and Post Doctorate at university of Waterloo, Canada. He has joined the Power and Water University of Technology as a faculty member in structural engineering group since 2001. He is now the deputy of Natural Disasters Research Center at this university and working in the field of research in strengthening and retrofit of engineering structures, leading several projects to date and has published more than 60 papers in international journals and conferences. He is also the head of structures and concrete dam department at Moshanir power engineering consultants. He has 1st grade PE and is a member of Iranian Building Engineering Organization and also an active member of Iranian Commission on Large Dams, Iranian Hydropower Association, National Retrofit Center of Iran and the ACI Iran chapter.