EFFECT OF SPECIMEN SIZE, FIBER TYPE AND CONCRETE STRENGTH ON THE FLEXURAL PERFORMANCE OF FIBER REINFORCED CONCRETE

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

EFFECT OF SPECIMEN SIZE, FIBER TYPE AND CONCRETE STRENGTH ON THE FLEXURAL PERFORMANCE OF FIBER REINFORCED CONCRETE

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Master of Science, Civil Engineering
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To overcome the brittleness of concrete, fiber reinforcement is a commonly used material, which highly increases the toughness of concrete in a cost-effective way. The aim of this study is to assess the effect of different fiber parameters on the flexural behavior of fiber reinforced concrete. Bending tests were performed on two different beam sizes made of 20 different concrete batches. The type and amount of the fibers along with the grade of the concrete were changed to form this batch combination. The force vs. displacement and energy vs. displacement data were obtained by a displacement-controlled test setup. The effect of the specimen size, fiber type, fiber length, and fiber amount were compared to better understand their effect on the toughness. The results showed that smaller specimens yield to higher values than bigger ones due to size effect, for all fiber types and concrete batches tested.

Keywords: Fiber Reinforced Concrete, Toughness, Energy Absorption Capacity, Flexural Testing

ÖZ

NUMUNE BOYUTU, FİBER TİPİ VE BETON DAYANIMININ FİBER DONATILI BETONUN EĞİLME PERFORMANSINA ETKİSİ

Güzelce, Aydinç
Yüksek Lisans, İnşaat Mühendisliği
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Fiber donatı, betonun gevrekliğini azaltmak için sıkça kullanılan bir malzeme olup, betonun tokluğunu ekonomik bir şekilde önemli ölçüde yükseltir. Bu çalışmanın amacı çeşitli fiber parametrelerinin, fiber donatılı betonun eğilme davranışı üzerine etkilerini değerlendirmektir. 20 farklı beton karışımından elde edilmiş iki farklı kiriş boyutu kullanılarak eğilme deneyleri yapılmıştır. Bu beton kombinasyonunu elde etmek için fiber tipi ve miktarı ile birlikte beton sınıfı da değiştirilmiştir. Deplasman kontrollü deney düzeneği kullanılarak yük-deplasman ve enerji-deplasman verileri elde edilmiştir. Tokluğa etkilerini daha iyi anlamak için numune boyutunun, fiber tipinin, fiber uzunluğunun ve fiber miktarının etkileri karşılaştırılmıştır. Sonuçlar, boyut etkisinden dolayı, test edilen tüm fiber tipleri ve beton karışımları için, küçük numunelerin büyük numunelerden daha yüksek değerler verdiğini göstermiştir.

Anahtar Kelimeler: Fiber Donatılı Beton, Tokluk, Enerji Yutma Kapasitesi, Eğilme Deneyi

To My Family,

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INTRODUCTION

1.1. General

Concrete owes its widespread use as a structural material to its many appealing mechanical properties. On the other hand, concrete has also some limitations in terms of its mechanical properties. Those limitations are addressed by the developing materials science technology. One of the developments in the field of construction materials is the addition of fibers (steel or synthetic) to concrete in order to improve its mechanical properties, especially under tension. The improvements that can be provided by fibers are related to the type, shape, length, and amount of the used fiber. Throughout the years, different variations of fiber reinforcement were used for different needs and design criteria.

To measure the improvements of the mechanical properties of the fiber reinforced concrete (FRC), there are different standards and different test procedures. However, the most common criteria measured by those different tests are the flexural strength and the properties related to it. This is mainly because the fiber addition improves the tensile strength more than the compressive strength, yet it is easier to measure the behavior of concrete specimens subjected to an indirect tension (bending) than perform a direct tensile test. There are many types of tests developed for measuring the performance of FRC, like point loading plate tests (BS EN 14488-5, ASTM C1550 etc.), or bending tests of beams (BS EN 14488-3, ASTM C78, C1018, C1609 etc.). Plate tests tend to give more consistent results compared to tests performed on beams (Minelli & Plizzari, 2015). On the other hand, testing beam specimens is a lot easier than testing heavy plates.

1.2. Objective of the Study

Brittleness of concrete has always been a constraint when concrete is used as a structural element. Addition of fibers to concrete is the most feasible way of increasing its ductility and toughness. There are many studies focusing on the effects of fiber types and fiber dosage in the literature. Moreover, different test procedures, and standards regarding the fiber reinforced concrete are available.

This study aims to measure the effect of specimen size along with the fiber types, properties, and amount on the performance of FRC by applying third-point bending tests. Two different concrete grades were used as the main mixtures to measure the difference in the behavior of small and large beam specimens under bending. The concrete mixtures were produced by adding three different types of fibers, two steel and one synthetic, with 3 different amounts for each fiber type.

There are five chapters in this work, including this one. The second chapter presents a brief literature review about fibers and FRC, along with the common and popular tests and work done in these fields. In the third chapter, the properties of the materials used, and a detail description of the experimental work are presented. The fourth chapter contains the general test results with the discussions and comments made on them. In the final chapter, the conclusions and recommendations for future studies are listed. Moreover, the test results of each test specimen are presented in the appendices.

CHAPTER 2

BACKGROUND AND LITERATURE REVIEW

2.1. History of Fiber Reinforced Concrete

With all the advantages that concrete has, it also has a major disadvantage which is its brittleness, because of its relatively low tensile strength (approximately 10% of its compressive strength) and its weak post-crack performance (J. Lee, Cho, Choi, & Kim, 2016). In order to improve those shortcomings of concrete, reinforcement materials are used in different forms such as steel reinforcement bars, and reinforcement fibers that can be made of a variety of materials. The practice of using organic fibers (like straw and animal hair) to prevent cracks in brittle materials such as bricks, dates back to ancient ages and in modern times, the use of steel reinforcement bars in portland cement concrete is the most common application to improve the tensile strength. Even though the material and labor costs for steel reinforcement are high, it is still feasible, in most of the cases, to obtain the desired properties of the concrete structure. However, steel reinforcement has some major drawbacks such as corrosion that can negatively affect the durability of the structure in the long run.

As an alternative, fiber reinforcement is the other commonly used method to provide tensile strength and toughness for concrete. During the early 1900s, asbestos fibers were used to develop FRC plates by Ludwig Hatschek. (Ikai, Reichert, Rodrigues, & Zampieri, 2010). However, in the second half of the 20th century, health concerns regarding the use of asbestos resulted in efforts of searching for different materials to be used as fiber reinforcement. Later, glass-fibers started to be used as a fiber reinforcement. The utilization of steel fibers did not start until the 1960s. Since then, steel fibers have become widely available in different shapes and lengths, and they were used all around the world in various construction projects. Nowadays, synthetic fibers, which are made of different materials such as polypropylene, nylon, carbon-fiber, polyvinyl alcohol-PVA, and polyethylene, etc., are also used for producing fiber reinforced concrete along with steel fibers.

The use of fibers in concrete is becoming more important as the modern concretes are more brittle than they were 50 years ago, because of higher strength values and higher heat of hydration (Brandt, 2008). Nowadays fiber reinforcement is an important ingredient especially for high strength concretes, whether it is used for preventing cracks or increasing the ductility and the energy absorption capacity of concrete. When short fibers are randomly dispersed in the concrete medium, it is possible to control the cracks opening and propagation at early ages, thus, obtaining a concrete that is not only less brittle but also more durable. Whereas, when long fibers are used, the energy absorption capacity (toughness) of FRC can be significantly increased compared to plain concrete (Banthia, Majdzadeh, Wu, & Bindiganavile, 2014). That higher toughness value of FRC helps preventing brittle failure, which leads to safer structures and safer construction materials. Not to mention that with the use of fibers, impact resistance of concrete could be greatly increased, so that safer structures that would withstand explosions and ballistic attacks can be constructed. It should be also noted that for architectural purposes, thin but strong concrete elements can be constructed, thanks to fiber reinforcement. Moreover, the use of fibers allows concrete to be used in high performance structural applications, such as long span bridges and high-rise buildings. Structures which are safer, more durable, and more economical would be constructed.

2.2. Properties of Fiber Reinforced Concrete

The better performance of FRC can be attributed to the fibers' ability to transfer the tensile and shear loads within the cracks in concrete, when aggregates and the cement paste fail (Jaroslava & Pavel, 2014). Plain concrete could be simply modeled as a heterogeneous material, consisting of an aggregate medium held together by cement paste, and that structure is known for its sturdiness under compression. Yet, there are many flaws in concrete such as pores, air voids, lenses of water under aggregates, and shrinkage cracks (M. K. Lee & Barr, 2004). Those flaws are the main reason why concrete performs worse under tensile and flexural loads, as the flaws lead to micro-cracks and they are interconnected to form macro-cracks and then the failure of concrete.

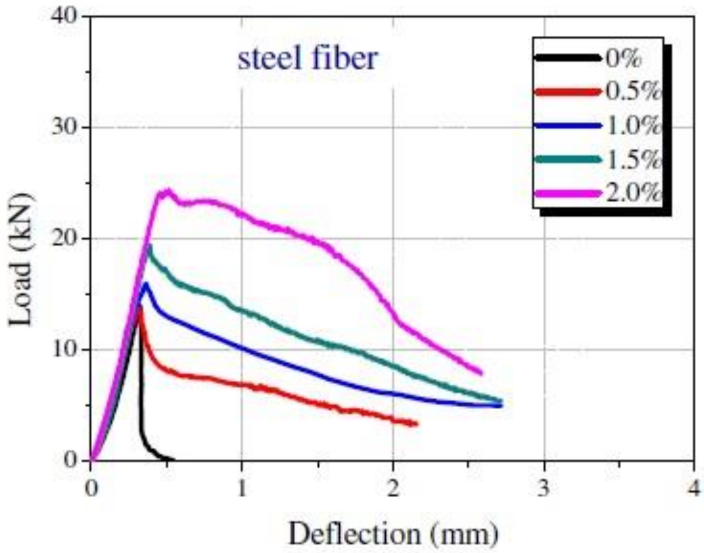


Figure 2.1 Effect of fiber content on toughness of concrete, load-deflection curves of steel fiber reinforced concrete under flexural bending (B. Li et al., 2018)

The load carrying mechanism of FRC under compression is similar to the one of plain concrete. The compressive strength of FRC is expected to be the same as plain concrete. However, introducing fibers helps the concrete to be kept intact under tensile and flexural loads up to some extent (Yehia, Douba, Abdullahi, & Farrag, 2016). Under the loading, the effect of fiber reinforcement is limiting the occurrence of macro-cracks caused by the flaws of concrete, and it is also transferring the loads after the cracks occurred. Beyond the ultimate strength of concrete matrix, fiber reinforcement will still carry and distribute the loads within the concrete (Figure 2.1, flexural bending test of steel FRC), so the force which concrete can withstand, does not drop dramatically, hence brittle failure is prevented (Pająk & Ponikiewski, 2013).

FRC mixtures are expected to have fresh and hardened properties different than plain concrete. Workability of FRC, for example, is different because of the friction created by the fibers within the concrete. It reduces the flow-ability of the concrete ingredients and it makes concrete harder to be mixed and cast. Therefore, in most cases, especially when the fiber amount is high, superplasticizers are used to improve workability (Felekoğlu, Tosun, & Baradan, 2009). It should be also noted that with the increased amounts of fiber, mixing concrete becomes harder, and the desired homogeneity be obtained. This situation will cause problems at hardened state, such as lower strength and worse durability. For that, when using fiber reinforcement, it is highly important to make an adequate mix design to ensure the proper homogeneity at mixing, so that better mechanical performance will be achieved. Even though reduction of workability is a handicap for FRC, a superior concrete both in hardened and fresh states can be obtained by using FRC with self-compacting concrete (SCC) (Sahmaran, Yurtseven, & Yaman, 2005).

Strength and other properties of FRC highly depend on its mix design and the properties of the concrete ingredients. Fiber type and amount, as well as cement, aggregate and admixture type and proportions are the most affecting factors. To satisfy some special requirements, it is now possible to produce a suitable concrete by using different fiber types and even by blending them in various quantities. Fiber reinforcement is a flexible ingredient which allows it to be used in many different amounts or types to meet a desired property for concrete. The possibility of using various types and amounts of fiber reinforcement, can provide an opportunity for concrete to achieve many desired performance criteria such as durability or safety (Tabatabaeian, Khaloo, Joshaghani, & Hajibandeh, 2017). When a low amount of fiber might in some cases improve the workability and prevent early age cracks, higher amounts of fiber dosage leads to higher toughness, if it can be mixed and placed correctly. The optimum fiber amount for a specific purpose or project should be determined by doing trial batches, for performance and economic reasons as well. It should be also noted that fiber reinforcement would be used to partly substitute the conventional steel reinforcement, which might also help reducing the labor and the costs (Soutsos, Le, & Lampropoulos, 2012).

2.3. Fiber Types and Properties

Fibers that are used as a reinforcement material in modern concrete can be listed under two main categories; synthetic fibers and steel fibers. Each category has some advantages and disadvantages. The need to use a specific type of fiber can be related to a specific desired property. Also it is possible to have hybrid fiber reinforcement, by mixing fibers of different properties or types (Banthia & Sappakittipakorn, 2007).

Besides the material from which the fiber is made of, fiber length and fiber diameter can be considered as the two most important parameters affecting the mechanical properties of FRC (Table 2.1). As the fiber length increases, generally the toughness of concrete also increases (Yoo, Zi, Kang, & Yoon, 2015). Longer fibers result in letting the concrete absorb more energy, as it requires higher loads to tear off the fibers from the concrete. Use of shorter fibers might contribute to the compressive strength, whereas longer fibers would contribute to the tensile strength. And it can be said that fiber geometry affects both fresh and hardened properties of concrete (Sahmaran & Yaman, 2007). Since longer fibers have higher surface area, more friction is created on their surface when the load is applied. However, longer fibers make it harder to mix the concrete.

Fiber diameter also has a large effect on the mechanical properties of FRC. Like the fiber length, the friction increases as the fiber diameter increases (Noushini, Hastings, Castel, & Aslani, 2018). Moreover, the tensile load that a single fiber can carry increases more with the increased fiber diameter, as the cross-sectional area of the fiber increases. However, increasing the diameter reduces the number of fibers for the same amount.

Table 2.1 Fiber Properties (Johnston, 2000)

Fiber Type	Steel	Polypropylene	Nylon	Polyethylene
Tensile Strength (MPa)	300 - 2600	450 - 750	750 - 1000	100 - 600
Modulus of Elasticity (GPa)	210	3.5 - 10	4.2 - 5	5
Elongation (Percent %)	0.5 - 3.5	15 - 25	16 - 20	3 - 100
Density (g/cm^3)	7.8	0.9	1.1	0.9
Diameter (μm)	100 - 1000	20 - 400	25 - 400	25 - 1000

For all of that, a term called aspect ratio, which is the ratio of length to diameter of a fiber, is often used when referring to the fibers. While longer fibers tend to withstand more interfacial friction, if they are small in diameter, they would fail due to tensile loads. Whereas, if a fiber is chosen to have a large diameter but it is not long enough, it would be pulled out of the concrete upon cracking, which would limit the concrete's load carrying capacity. For an economical mix design, the same toughness values of FRC can be obtained by using lesser amounts of a fiber with higher aspect ratio, and higher length. (Yoo et al., 2015) Yet, the length of fiber is limited by the efficiency of mixing and placing of concrete.

Moreover, fiber shape is another important factor that can hugely affect the bonding characteristics of the fibers with the concrete medium (Figure 2.2). Fibers with hooked ends or non-straight shapes can create more interfacial friction. Thus, the loads can be more easily transferred to the fibers. This allows the fibers to carry more tensile loads without being pulled out from the concrete, and results in higher toughness values.

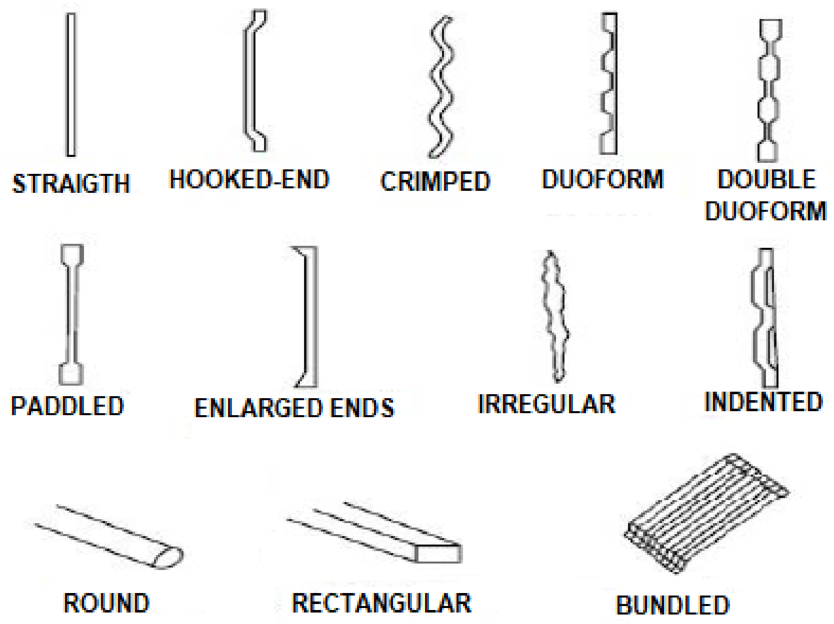


Figure 2.2 Different fiber shapes (Alqenai, 2018)

In addition to all of that, the bonding characteristics can be also affected by the surface texture of the fibers. This texture mainly depends on the material from which the fiber is made of, as well as the applied surface treatments at the stage of manufacturing. Fibers with rougher surfaces have more interfacial friction between the fiber and the concrete. However, the rougher surfaces can also make it harder to mix the concrete.

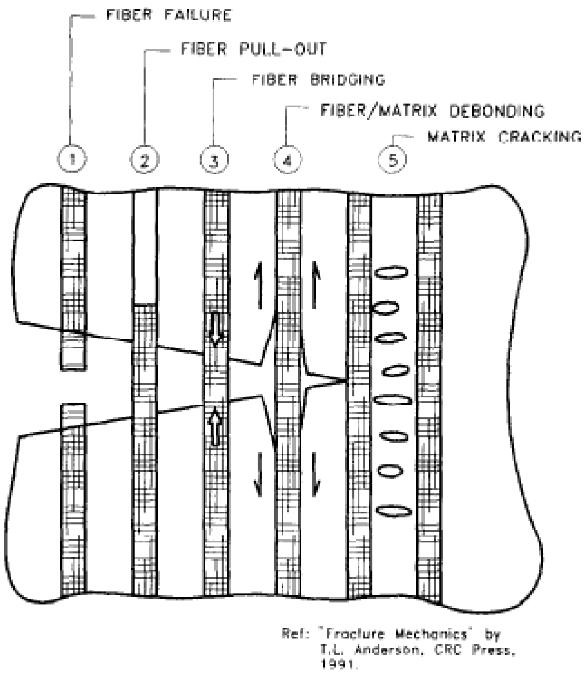


Figure 2.3 Fiber's bonding mechanism (T.L. Anderson, 1991)

For all of that, it can be said that creating more friction and bonding between the fibers and concrete in order to transfer the loads to the fibers as efficiently as possible should be the goal (Figure 2.3). At the same time, the fresh properties of the concrete need to be considered so that an optimum fiber type and amount could be chosen for a specific application.

2.4. High Performance Concrete

High performance concrete (HPC) is defined by American Concrete Institute (ACI) as the "concrete that meets special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practices" in concrete terminology (ACI CT-13, 2013). Those special requirements, for a concrete to be considered as HPC can be related to either hardened properties such as durability and strength; or fresh properties like workability, rheology/viscosity, and heat of hydration.

In 1990s, to foster the use of HPC in highway applications, Federal Highway Administration in the USA defined HPC by eight parameters, four of them related to strength with the other four related to durability (Goodspeed, Vanikar, & Cook, 1996). Strength related parameters are compressive strength, elasticity, shrinkage, and creep. Whereas durability related parameters are scaling resistance, abrasion resistance, freeze/thaw durability, and chloride permeability.

Fiber reinforced concrete can be considered as high performance concrete, whether it is used for better durability, or for limiting shrinkage cracks, or it is used for its mechanical properties such as high energy absorption capacity, higher tensile strength etc. that cannot be achieved by using conventional concrete. In this sense, both normal strength and high strength concretes with fiber reinforcement can be called high performance concrete.

High performance concretes are generally designed for higher strength or durability requirements. However, this does not mean that they cannot also be more economical. In fact, having more durable structures with longer service life would result in less repair and maintenance costs, and in less economical losses due to being out of service for repairs. Moreover, the longer service life a structure has, its impact on the environment would be lower.

2.5. Application of Fiber Reinforcement in Concrete

Fiber reinforcement has been used in normal strength concrete for more than five decades, especially for pavements and industrial floors/slabs, where surface cracks are not desirable. If fiber reinforcement is not used, shrinkage will cause tensile stresses to develop in the early age concrete, which may result in cracking of the concrete surface. Moreover, due to occurrence of repetitive loading and unloading on those types of structures, fatigue cracks may occur if fiber reinforcement is not used.

As for high strength concrete, although it has much higher compressive strength, its tensile strength still not that high compared to normal strength concrete. Moreover, increasing the strength of concrete without using reinforcement makes it more brittle, which brings concerns about the structural safety. In this scope, fiber reinforcement is a very useful and economical way of increasing ductility. Fibers provide a medium to transfer the tensile loads through concrete, which makes it less brittle. Moreover, fibers could bear the tensile loads even after the concrete is cracked. This helps preventing the concrete from sudden failures, which is a valuable property in terms of safety.

Fiber reinforced high strength concrete (FRHSC) can be used to economically construct high rise structures, bridges, or other types of structures that has large span length between columns, such as shopping malls and concert halls. For the safety of public and government buildings FRHSC can also be utilized as the fibers in concrete helps concrete to be kept intact. Walls made of FRHSC can protect the structure from ballistic attacks, and also shelters made of FRHSC can provide better protection (Drdlová, 2015).

2.6. Test Methods Used to Evaluate the Performance of FRC

Some of the tests that are used for ordinary concrete may not be applied to specific kinds of high-performance concretes, or in other words, some tests are only meaningful when applied to some types of high-performance concretes. For instance, self-compacting concrete uses some special test methods to measure its consistency or rate of flow. For FRC, measuring the occurring displacements under loading to determine the energy absorbed by concrete is much more meaningful when compared to plain concrete. High quality concrete may need better quality control, which leads to more tests to be performed to ensure the desired properties and the required safety.

For FRC, apart from the durability standpoint, the most important performance criterion is energy absorption capacity. To measure this capacity, flexural strength tests are usually performed. Some of the standardized bending test methods for of FRC are as follows:

- ASTM C1018 (withdrawn standard)

This standard is named Standard Test Method for Flexural Toughness and First-Crack Strength of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading). In this test method, molded or sawn beams made of FRC are tested using the third-point loading arrangement (Figure 2.4) as specified in ASTM C78. Load-Deflection curve is obtained. The first-crack load and deflection are used to determine the first-crack flexural strength and to establish end-point deflections for toughness calculations. Computations of toughness and toughness indices are based on areas under the load-deflection curve up to the first-crack deflection and up to the specified end-point deflection.

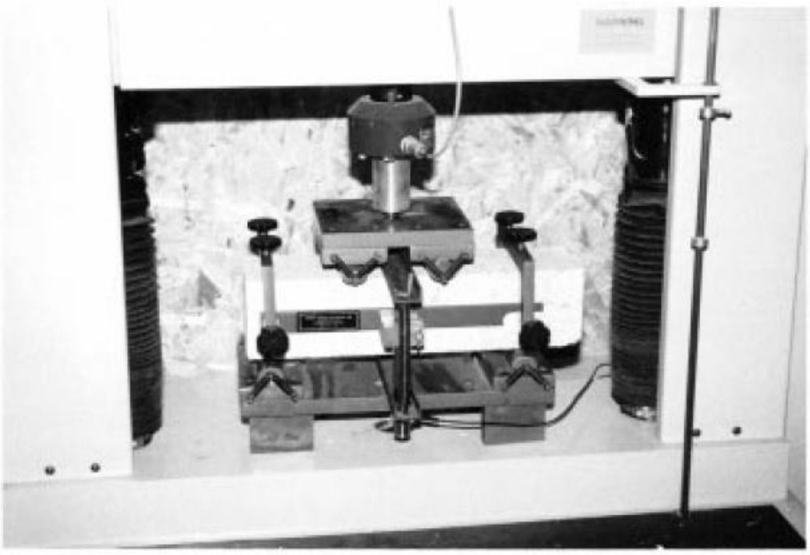


Figure 2.4 Testing according to ASTM C1018

- ASTM C1399

Standard Test Method for Obtaining Average Residual Strength of Fiber-Reinforced Concrete. In this standard, a load arrangement similar to C1018 is used, but the test method C78 is modified by a steel plate used to assist in support of the concrete beam during an initial loading cycle, in order to help control the rate of deflection when the beam cracks (Figure 2.5). After the beam has been cracked in the specified manner, the steel plate is removed, and the cracked beam is reloaded to obtain data to plot a reloading load–deflection curve. Load values at specified deflection values on the reloading curve are averaged and used to calculate the average residual strength of the beam.

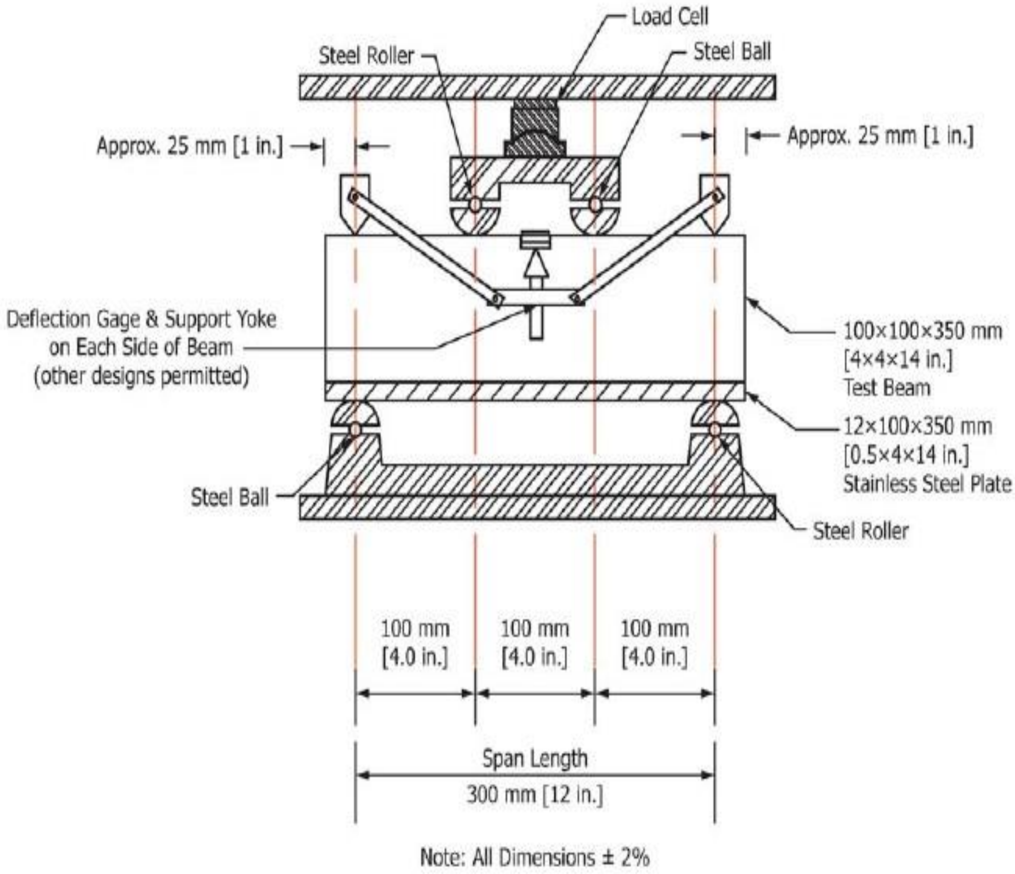


Figure 2.5 Testing according to ASTM C1399

- ASTM C1609

Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) This standard is similar to C1018, but it uses a closed-loop, servo-controlled testing system and roller supports that are free to rotate on their axes (Figure 2.6). The results of this standard test method are dependent on the size of the specimen.

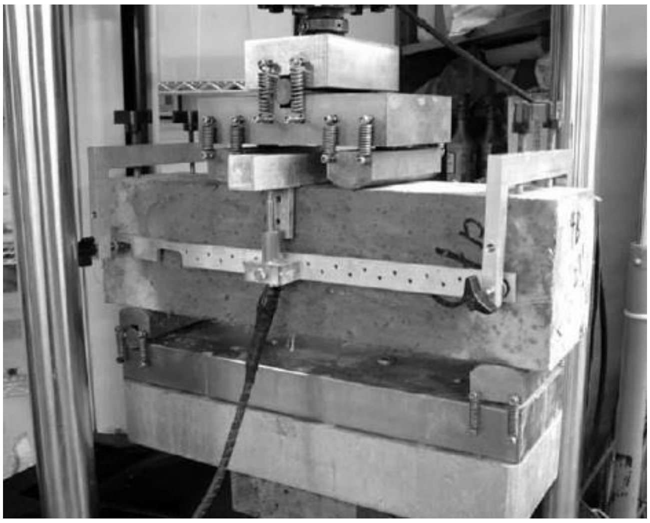
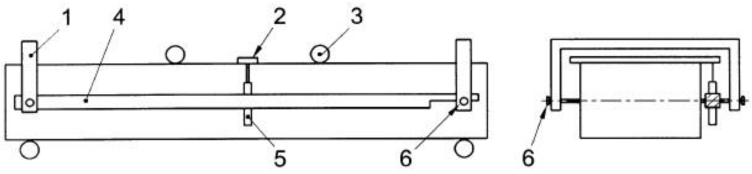


Figure 2.6 Testing according to ASTM C1609

- BS EN 14488-3

This standard is called Testing sprayed concrete – Flexural strengths (first peak, ultimate and residual) of fibre reinforced beam specimens. Prismatic beam specimens are subject to a bending moment by the application of load through upper and lower rollers (Figure 2.7). The first peak, maximum and residual loads sustained are recorded and the corresponding flexural strengths are calculated.



Key

1 Cramp
2 Reference bar (clamped or glued)
3 Loading roller
4 Yoke
5 Transducer
6 Locating screw

NOTE A yoke/transducer may be fixed at each side of the beam, instead of at only one as it is represented in the section of the beam.

Figure 2.7 Testing according to EN 14488-3

2.7. Review of Flexural Strength Tests on FRC

There are many studies in the literature on performance of FRC by using flexural strength tests. Those studies use different flexural test methods such as four point bending or three point bending tests, on many different sizes of specimens, and with or without notched specimens. In this chapter, a summary of the previous studies on flexural testing of FRC will be made. In general, most of the studies conclude that, the behavior of FRC beams up to cracking was similar to the beams without fibers, and after cracking, beams with fibers shows not only higher strength but also enhanced ductility and stiffness (Biolzi & Cattaneo, 2017). There are some studies focusing on comparing different fiber types. For instance, a study (Buratti, Mazzotti, & Savoia, 2011) compares three different types of synthetic fibers with steel fiber reinforcement by using 2 different dosages for each fiber and testing the notched concrete specimens (150x150x550 mm^3) by three point flexural test. The study concludes that steel fibers perform better than synthetic fibers in terms and toughness, but it also states that there is variability between the results due to used test method. Another study focuses on steel fiber use for high strength concrete, with comparing four dosages of steel fiber reinforcement (Song & Hwang, 2004), and indicates that toughness increases with increased dosage. Four point flexural tests on beams (100x100x400 mm^3) are conducted in another study (J. Li, Wan, Niu, Wu, & Wu, 2017) to evaluate the toughness of steel FRC on five different fiber dosages, and concludes that there is an optimum dosage for steel reinforcement, and beyond that dosage toughness is not improved.

Three different matrices of concrete with different strength (25, 35, and 45 MPa) was tested for four point flexural strength in another study (J. Lee, Cho, & Choi, 2017) conducted on steel FRC with three fiber dosages for comparing the flexural toughness at 3mm deflection (1/150 of span length) suggests that, even though the toughness increases with higher fiber dosage, it is highest for 35 MPa sample and decreases for sample with the highest strength. A more comprehensive study on steel FRC (Abbass, Khan, & Mourad, 2018) shows that failure mode might differ due to concrete strength as well as fiber dosage. Findings indicate that for low dosages failure is due to fiber rupture, but as the fiber amount increases it is due to fiber pull-out. On the other hand, as the concrete strength increases, the failure mode changes from fiber pull-out to fiber rupture. Another study conducted on steel FRC for measuring the effect of fiber dosage and aggregate size (Jang & Yun, 2018) suggests that flexural toughness is more dependent on fiber content rather than the aggregate size, but smaller aggregate size is more helpful in terms of proper mixing and placing when high amounts of fibers are used. Another study on residual flexural strength of steel FRC investigates the effect of concrete strength along with fiber content (Lee, 2017). Three different concrete matrixes with strengths of 25, 35, and 45 MPa was used for the study along with three fiber volume fractions. The study concludes that the energy absorption capacity of higher strength FRC would decrease as the crack propagates.

One study conducted by using three point testing method, comparing steel fibers and polypropylene fibers (Bencardino, Rizzuti, Spadea, & Swamy, 2010) shows that, increasing the fiber amount increases the fracture energy for both fiber types, but improvements are higher for the steel FRC. That study also shows a decrease in the compressive strength when polypropylene fibers are used.

To understand the effect of the specimen size and fiber configuration on the mechanical behavior of steel FRC, a study (Sarmiento, Geiker, & Kanstad, 2016) by using both full scale beams (200x300x3000 mm^3), and test specimens (150x150x550 mm^3) is conducted. The study found that there is a major difference in results between the two specimen sizes. Namely, the smaller specimens show higher flexural performance due to fiber orientation and distribution. Study concludes that testing of smaller specimens results in overestimation than the real life conditions; hence they should not be used for estimation of the capacity, but they should be used for quality control and comparison purposes. Another study on specimen size effect (Fládr & Bílý, 2018) states that, different strength levels and different mix compositions result in variable influence from the size effect. Also, for very high strength levels, performance is found to be almost independent from the specimen size, but in general it can be concluded that the smaller beams exhibit higher flexural strength than the bigger beams. Another study conducted to measure the fracture properties of steel FRC uses work of fracture method and size effect method (Kazemi et al., 2017). In this study, it is suggested that the wall-effect of the mold sides on the fibers' orientation needs to be considered as the fiber content increases, more fibers are oriented parallel to the mold sides. The study concluded that size effect method gives more accurate results for lower fiber amounts.

A recent study utilizes artificial intelligence to assess flexural and splitting tensile strength of FRC (Paul et al., 2019). The input parameters such as aspect ratio, fiber amount and compressive strength was used to predict the flexural and splitting tensile strength of concrete with steel fiber reinforcement. It was stated that the automated neural network search model could be further developed to include more parameters such as toughness and modulus of elasticity.

CHAPTER 3

EXPERIMENTAL STUDY

3.1. General

In this study, the effect of fiber type, fiber amount and fiber length are investigated through two different concrete grades. The first one being high performance concrete (HPC), which is a high strength self-compacting concrete, with an average 28 days strength of 63 MPa. The second one is a normal performance concrete (NPC) that has relatively lower design strength compared to the first one, with an average 28 days strength of 39 MPa. Three different fibers, two steel and one synthetic were used in different amount to create a total of 18 FRC mixtures. Two plain concrete mixtures were also used for comparison purposes. The evaluation of the mixtures was done through the third-point flexural test. All the experiments were conducted in the Materials of Construction Laboratory of the Department of Civil Engineering at Middle East Technical University.

3.2. Materials

For all concrete batches, CEM I 42.5R Portland Cement, and Class F fly ash were used alongside crushed limestone aggregates. For HPC, silica fume and a polycarboxylate based high range water reducer were also used, whereas for NPC, normal range water reducer was used. The cement amounts used were 250 kg/m^3 and 400 kg/m^3 for NPC and HPC respectively.

The crushed limestone aggregates used were of three different sizes: 0-4 mm fine aggregate, 4-12 mm medium-coarse aggregate and 12-22 mm coarse aggregate. Moreover, Dramix 3D steel fibers in two different lengths (30 mm and 60 mm) were used as the steel fiber reinforcement and Forta Ferro 54 mm fibers were used as the synthetic fiber reinforcement (Figure 3.1). The fibers were used in the two concrete groups, NPC and HPC, in dosages of 30, 60, and 90 kg/m^3 for steel fibers and 3, 6, and 9 kg/m^3 for synthetic fibers. The properties of the fibers are presented in Table 3.1. Moreover, the mix designs of the concrete batches are shown in Table 3.2 .

Table 3.1 Properties of the Fibers Used

	Steel Fiber		Synthetic Fiber
Name	Dramix 3D 30 mm	Dramix 3D 60 mm	FortaFerro 54
Material	Steel		Polyethylene / Polypropylene Copolymer
Shape	Hooked Ends – Glued		Twisted Bundle
Length (mm)	30	60	54
Diameter (mm)	0.62	0.75	0.34
Aspect Ratio	48	80	158.8
# of Fibers per kg	13000	4700	220000
Tensile Strength(MPa)	1225		550 - 750
Modulus of Elasticity(GPa)	200		5.75

Figure 3.1 Fibers Used

Table 3.2 Mix Design

Mix ID	Cement (kg/m^3)	Silica Fume (kg/m^3)	Fly Ash (kg/m^3)	W/B (%)	Water reducer (%)	Fiber (kg/m^3)	Fine Agg. (kg/m^3)	Coarse Agg.1 (kg/m^3)	Coarse Agg.2 (kg/m^3)	Density (kg/m3)
NPC Control						0	890	461	461	2342
NPC 30 kg						30	936	484	484	2406
NPC 60 kg						60	931	481	481	2426
NPC 90 kg	250	0	63	50%	1%	90	926	479	479	2446
NPC 3 kg						3	936	484	484	2380
NPC 6 kg						6	932	482	482	2375
NPC 9 kg						9	928	480	480	2369
HPC Control						0	819	423	423	2370
HPC 30 kg						30	816	422	422	2396
HPC 60 kg						60	811	420	420	2416
HPC 90 kg	400	30	100	32%	1%	90	806	417	417	2436
HPC 3 kg						3	817	423	423	2370
HPC 6 kg						6	811	420	420	2362
HPC 9 kg						9	808	418	418	2358

3.3. Experimental Procedure

A total of 20 batches, including the control ones, were prepared in this study. All the materials were added to a rotary mixer in the following order; aggregate, cement and fly ash, fibers, and finally the water mixed with the chemical admixture. For HPC mixtures, silica fume was mixed with water. The mixing process continued until a homogenous mixture was obtained. The slump value for each mixture was determined (Figure 3.2), as presented in Table 3.3. After that, the concrete was cast into beam molds (Figure 3.3) of two sizes, 325×75×75 mm^3 and 600×150×150 mm^3. For the mixtures with low slump values, a mechanical vibrator was used during the filling process. The fresh concrete was kept in the molds for 24 hours then removed from the molds and cured in a wet condition at room temperature till the test day, at 28 days.

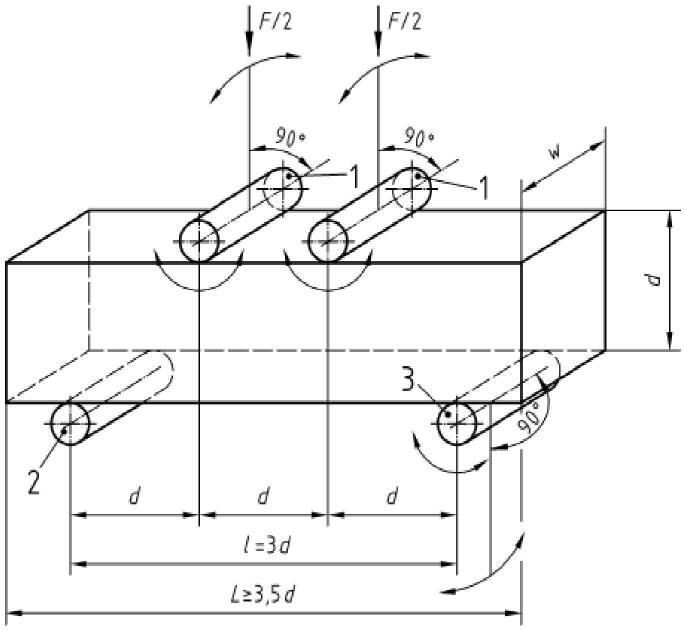
Figure 3.2 Slump Test is Performed with Rotary Mixer in the Background

Figure 3.3 Placing of Concrete into Big Beams and Small Beams

Table 3.3 Properties of Concrete Batches

Concrete Matrix	Fiber Type	Fiber Amount	Volume Fraction (%)	Slump (cm) (* Flow)
HPC	Control	0 kg/m3	0	70*
	30 mm Steel Dramix 3D	30 kg/m3	0.38	75*
		60 kg/m3	0.75	57*
		90 kg/m3	1.13	62*
	60 mm Steel Dramix 3D	30 kg/m3	0.38	56*
		60 kg/m3	0.75	18
		90 kg/m3	1.13	0
	Synthetic FortaFerro54	3 kg/m3	0.34	20
		6 kg/m3	0.68	18
		9 kg/m3	1.02	5
NPC	Control	0 kg/m3	0	23
	30 mm Steel Dramix 3D	30 kg/m3	0.38	17
		60 kg/m3	0.75	18
		90 kg/m3	1.13	18
	60 mm Steel Dramix 3D	30 kg/m3	0.38	12
		60 kg/m3	0.75	0
		90 kg/m3	1.13	0
	Synthetic FortaFerro54	3 kg/m3	0.34	0
		6 kg/m3	0.68	0
		9 kg/m3	1.02	0

At test day, the third-point bending test was applied to the specimens in order to determine their flexural performances, Figure 3.4. For each mixture, three beam specimens of each size were tested using an MTS Landmark device with a capacity of 250 kN. The tests were conducted under the displacement control mode, with a loading rate of 1 mm/min. Two linear variable displacement transducers (LVDT) were attached to both sides of the specimens in order to measure the deflections directly from the specimens, as seen from Figure 3.5 for big beams and Figure 3.6 for small beams. The average deflection values of the two LVDTs were used in order to obtain the mid-point deformations of the specimens. The load-deflection curve for each specimen was obtained at the end of the test. Based on this curve, the energy absorption capacity of each specimen was determined as the area under that curve.



Key

1 Loading roller (capable of rotation and of being inclined)

2 Supporting roller

3 Supporting roller (capable of rotation and of being inclined)

F is the load (P_{fp} or P_{ult}) defined above in newtons

l is the span

w is the average beam width

d is the beam height

L is the beam length

Figure 3.4 Third-Point Flexural Bending Test (Reference: BS EN 14488-3)

Figure 3.5 Testing of Big Beams

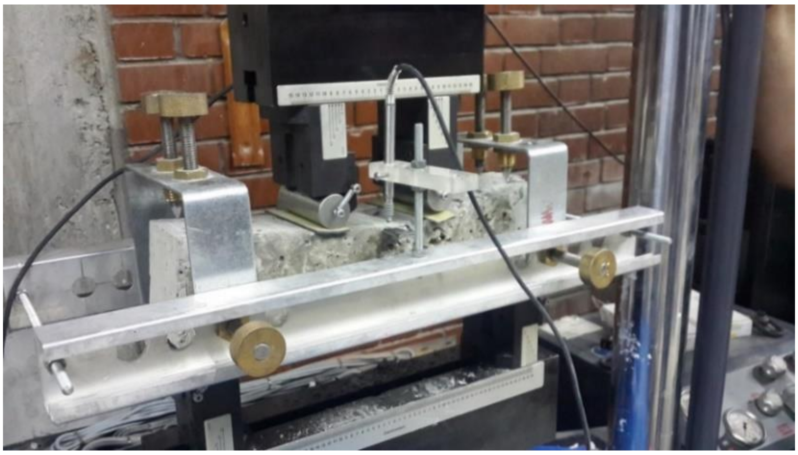


Figure 3.6 Testing of Small Beams

3.4. Analysis Procedures

3.4.1. Averaging

After testing all three specimens of each batch, the data were used for computing average force vs. displacement of the concrete batch. MATLAB was used for converting the raw data of the performed tests into equal interval in terms of deflection. By doing so, it became possible to calculate the average force values for the corresponding displacement values needed to obtain the arithmetic average from the three specimens tested. As an example, first few rows of data obtained from big beam HPC specimens made with 30mm/60kg steel fibers are shown in Table 3.4, and corresponding force-deflection curves can be seen in Figure 3.7.

Table 3.4 Average Force Data of HPC Big Beam (BB) 30mm-60kg/m³

Force 1	Force 2	Force 3	Average Force (N)	Deflection Δ (mm)
6192	6720	6240	6384	0.005
11833	13124	11644	12200	0.010
17470	18936	17011	17806	0.015
22820	24447	22251	23173	0.020
27991	29716	27386	28364	0.025
33023	34772	32178	33324	0.030
37882	39385	36333	37867	0.035
41935	43672	40198	41935	0.040
46190	47333	43879	45801	0.045
49887	50518	46600	49002	0.050
52825	52673	47935	51144	0.055

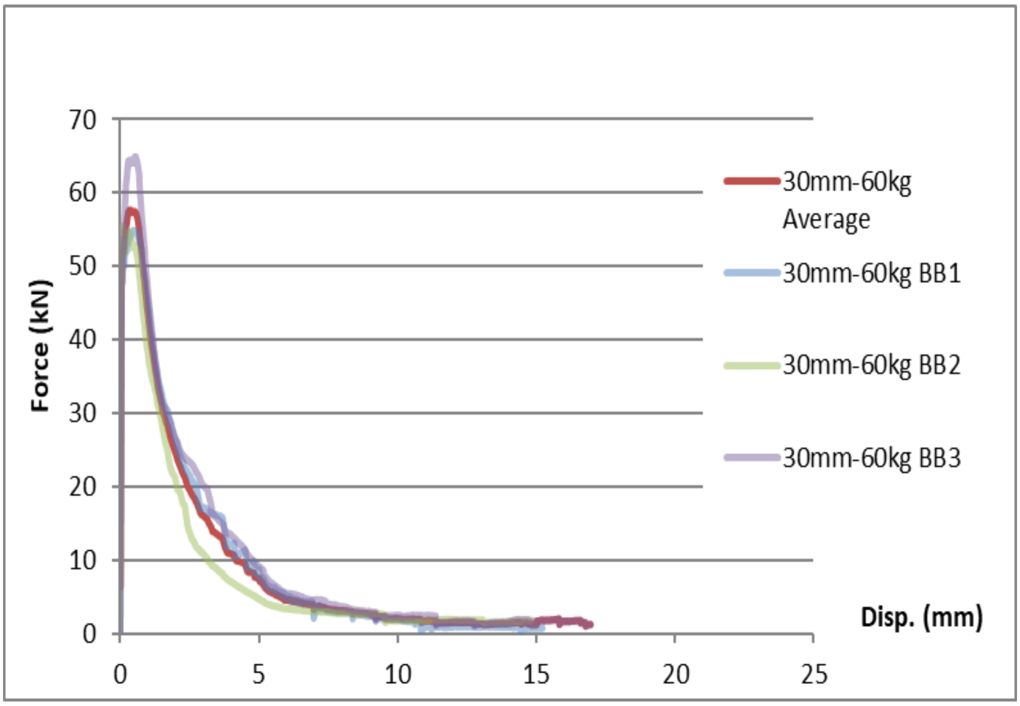


Figure 3.7 HPC 30mm-60kg/m³ Steel FRC Force-Displacement Graph

3.4.2. Calculation of Energy

Energy absorption capacities are also calculated by using average force vs. displacement data, as the area under the average force vs. displacement curves gives the energy absorption, and the areas are obtained by using the trapezoidal rule. First few rows of data used for calculating the energy absorption of big beam HPC specimens made with 30mm/60kg steel fibers are shown at the Table 3.5, where trapezoidal area for every row is calculated and total energy absorbed is obtained by adding those areas up to 15 mm deflection for small beam (SB) and 25 mm deflection for big beam (BB). For instance, the total energy absorbed at 0.055mm deflection at the table below equals to 1.607 Joules as an example. HPC SB energy-displacement curves are also shown as an example on Figure 3.8.

Table 3.5 Energy Data of HPC Big Beam (BB) 30mm-60kg/m³

Average Force (N)	Deflection Δ (mm)	Trapezoidal Area (N.mm)	Total Area (Energy)
6384	0.005	16	16
12200	0.010	46	62
17806	0.015	75	137
23173	0.020	102	240
28364	0.025	129	369
33324	0.030	154	523
37867	0.035	178	701
41935	0.040	200	900
45801	0.045	219	1120
49002	0.050	237	1357
51144	0.055	250	1607

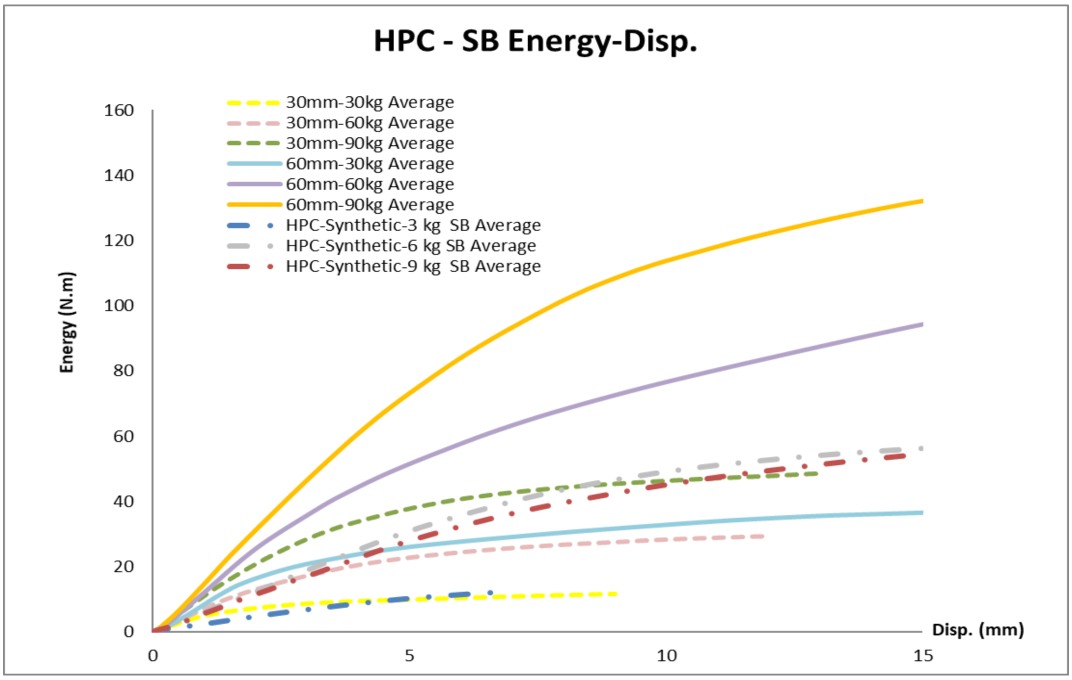


Figure 3.8 HPC Small Beam (SB) Average Energy vs. Displacement Graphs

3.4.3. Calculation of Stress and ∆/L

After obtaining average force vs. displacement curves (Figure 3.7), the average stress values are calculated by using $F=(P*L)/(b*d^2)$ formula for flexural stress, where F is stress, P is force, L is span length, b is width and d is height of the specimen (note that for the square cross-sectioned specimens tested b=d). Moreover, ∆/L is obtained by dividing the displacement values by the span length of the tested specimen (Table 3.6). The stress values are calculated for the whole force-displacement data even though the formula is intended to be used only until the specimen is cracked. The reason for that is to better compare the performance of the fibers, as the fibers are actually starting to redistribute the loads after the concrete cracks. Reason why force vs. displacement results are converted to stress vs. ∆/L can be better understood by observing Figure 3.9 and Figure 3.10 below, as the SB and BB specimens are better compared in the latter.

Table 3.6 Data of HPC BB 30mm-60kg/m³

Average Force (N)	Average Stress (MPa)	Deflection ∆ (mm)	∆/L	Trapezoidal Area (N.mm)	Total Area (Energy)
6384	0.851	0.005	1.11E-05	16	16
12200	1.627	0.010	2.22E-05	46	62
17806	2.374	0.015	3.33E-05	75	137
23173	3.090	0.020	4.44E-05	102	240
28364	3.782	0.025	5.56E-05	129	369
33324	4.443	0.030	6.67E-05	154	523
37867	5.049	0.035	7.78E-05	178	701
41935	5.591	0.040	8.89E-05	200	900
45801	6.107	0.045	1.00E-04	219	1120
49002	6.534	0.050	1.11E-04	237	1357
51144	6.819	0.055	1.22E-04	250	1607

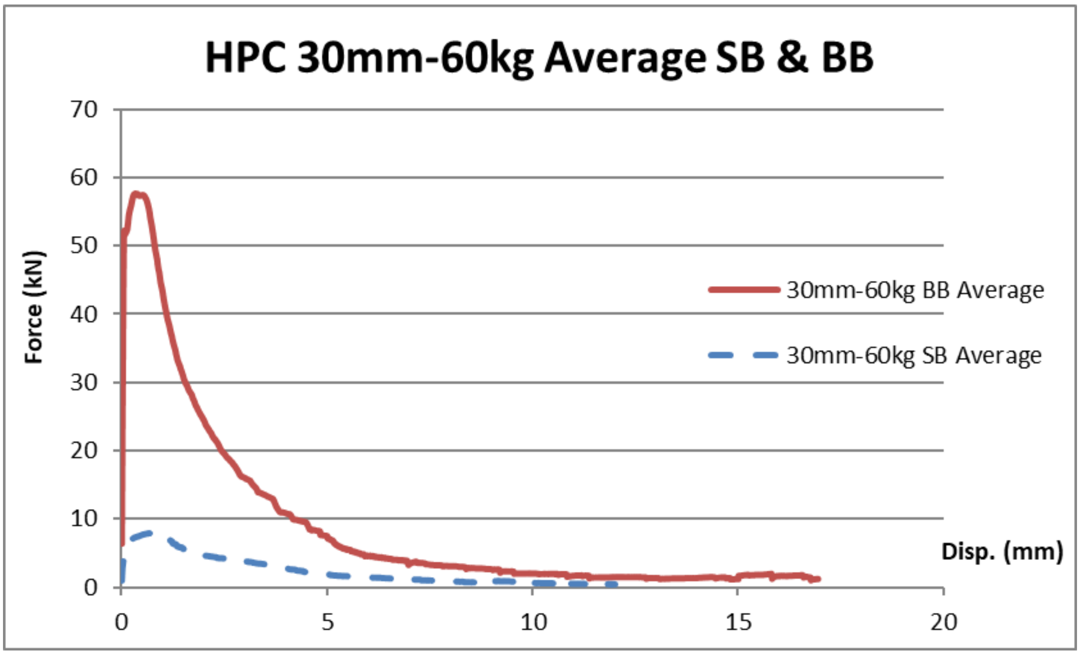


Figure 3.9 HPC 30mm-60kg/m³ Steel FRC Average SB & BB Force vs. Displacement

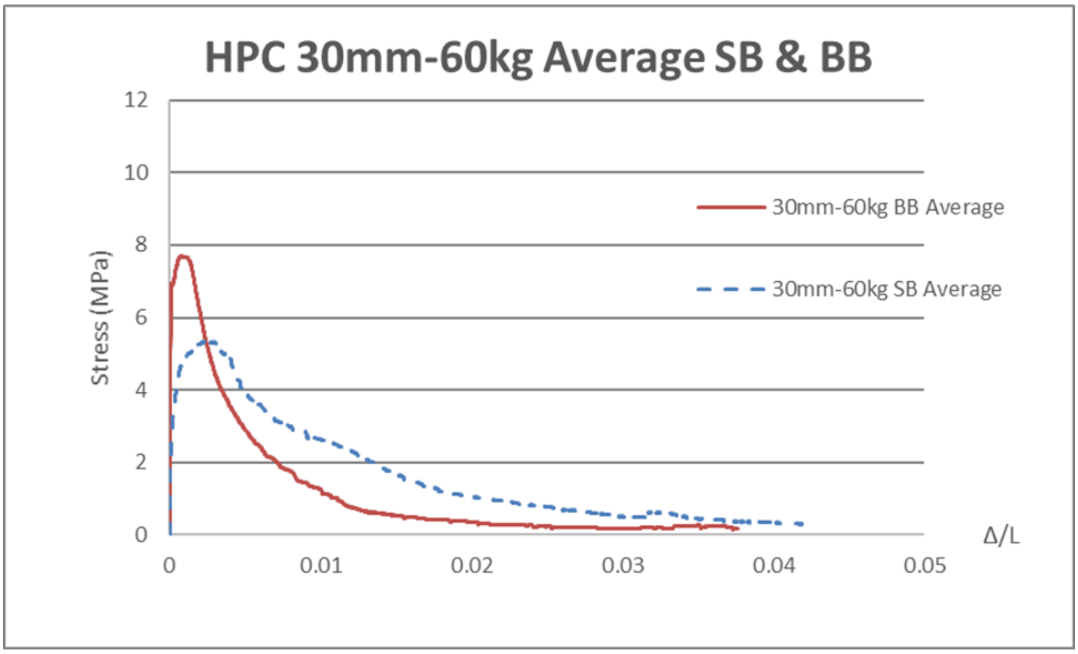


Figure 3.10 HPC 30mm-60kg/m³ Steel FRC Average SB & BB Stress vs. Δ/L

3.4.4. Modulus of Toughness

From the energy values calculated as discussed in part 3.4.2, it is not possible to make comparisons between different specimen sizes as it can be seen from Figure 3.11 and Figure 3.12 below.

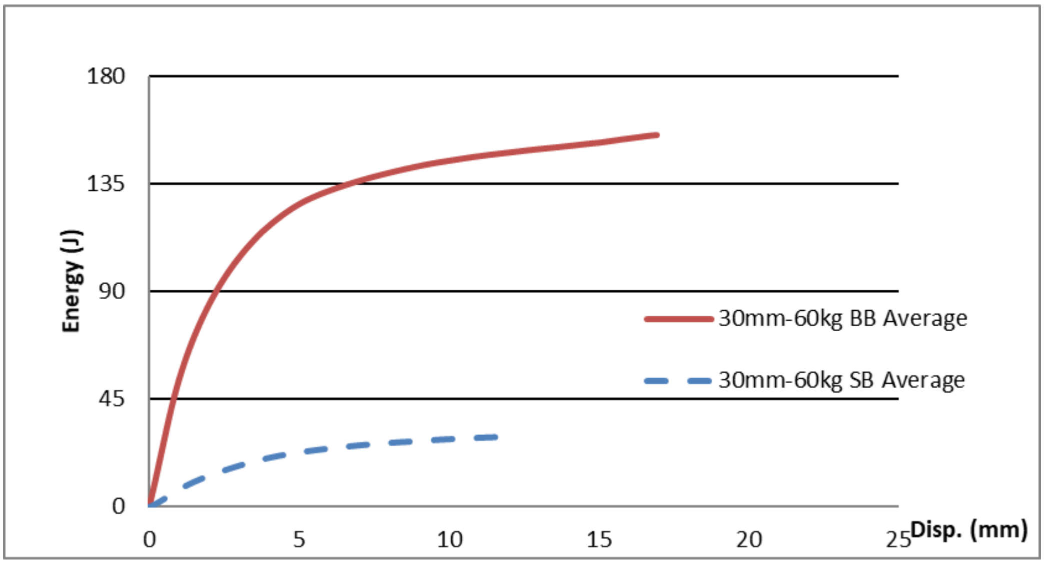


Figure 3.11 HPC 30mm-60kg/m³ Steel FRC Average SB & BB Energy vs. Displacement

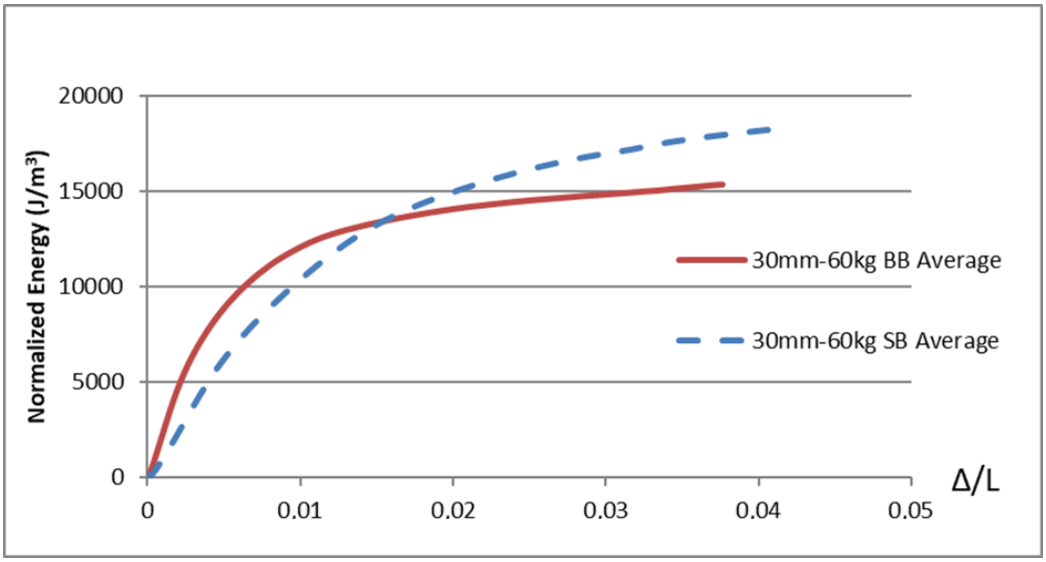


Figure 3.12 HPC 30mm-60kg/m³ Steel FRC Average SB & BB Modulus of Toughness vs. Δ/L

Moreover, energy at 0.05 Δ/L values, instead of energy at specific displacement values are also calculated for having better comparisons between big beam and small beam specimens. Finally, that energy values are normalized by dividing them into volume of the tested specimens to obtain modulus of toughness. The procedure to do that calculation involves calculating the cross section area of the tested specimen and multiplying it with the span length of it for obtaining the volume. Then the previously calculated energy values are divided by this volume, and all of that energy results are tabulated as discussed on the Chapter 4.

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the average test results of each mixture and for each specimen size are presented. Those results are the average Stress vs. Δ/L graphs which are derived from the average Load-Deflection data, and the average energy absorption capacities at specific deflection values. Moreover, the test results of each specimen and average Load-Deflection curves for each fiber type tested are presented in the appendices. The effects of the fiber type, properties, and amount along with the concrete strength and specimen size are evaluated based on the obtained test results. Test results obtained from Control specimens are shown in Figure 4.1 for comparison purposes.

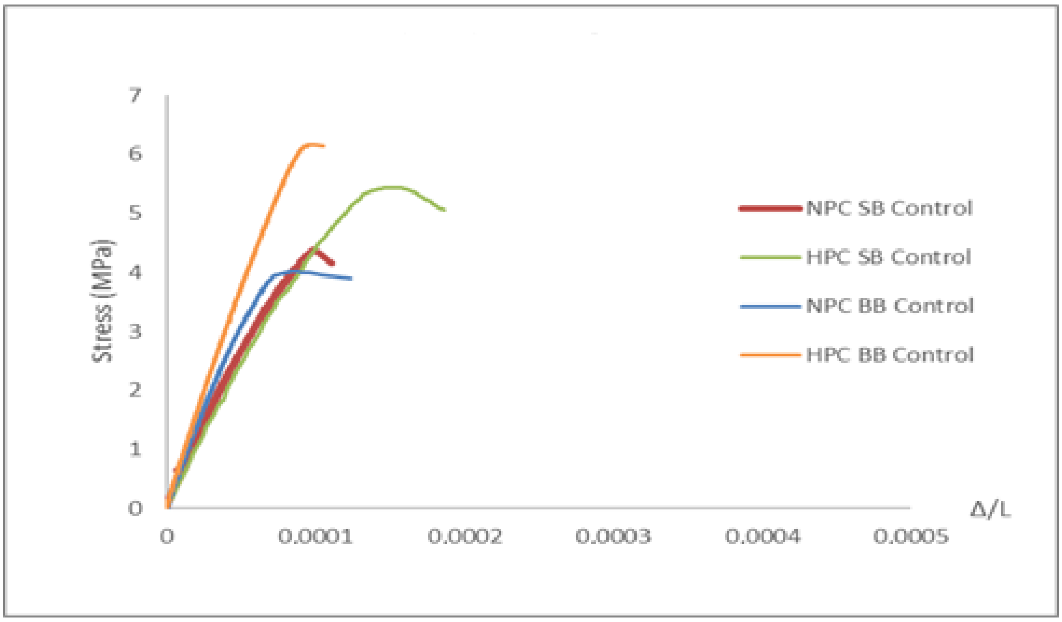


Figure 4.1 Control Specimens Stress vs. Δ/L

4.1. Tests Performed on Small Beams

4.1.1. NPC

From the flexural bending tests performed, the stress vs. Δ/L; (where Δ:Displacement, L:Span Length) graphs are obtained from average load-displacement data for NPC mixtures are presented in Figure 4.2 to Figure 4.4. The ultimate strength and energy absorption values at specific displacements for NPC SB are presented in Table 4.1.

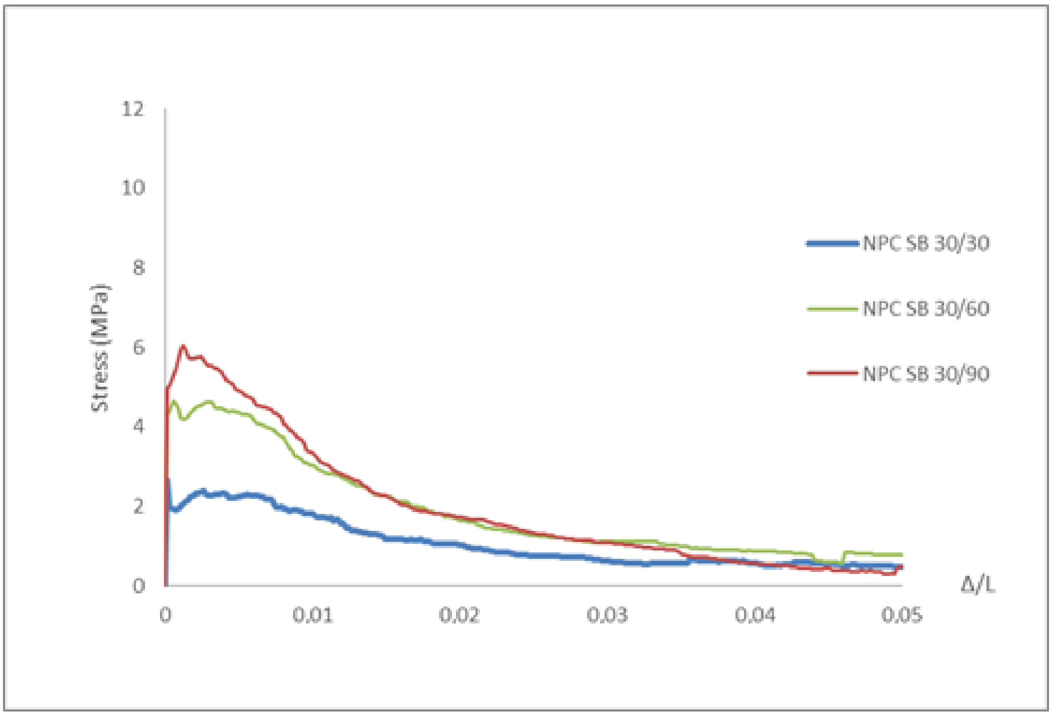


Figure 4.2 Stress vs. Δ/L of NPC SB 30mm Steel Fibers

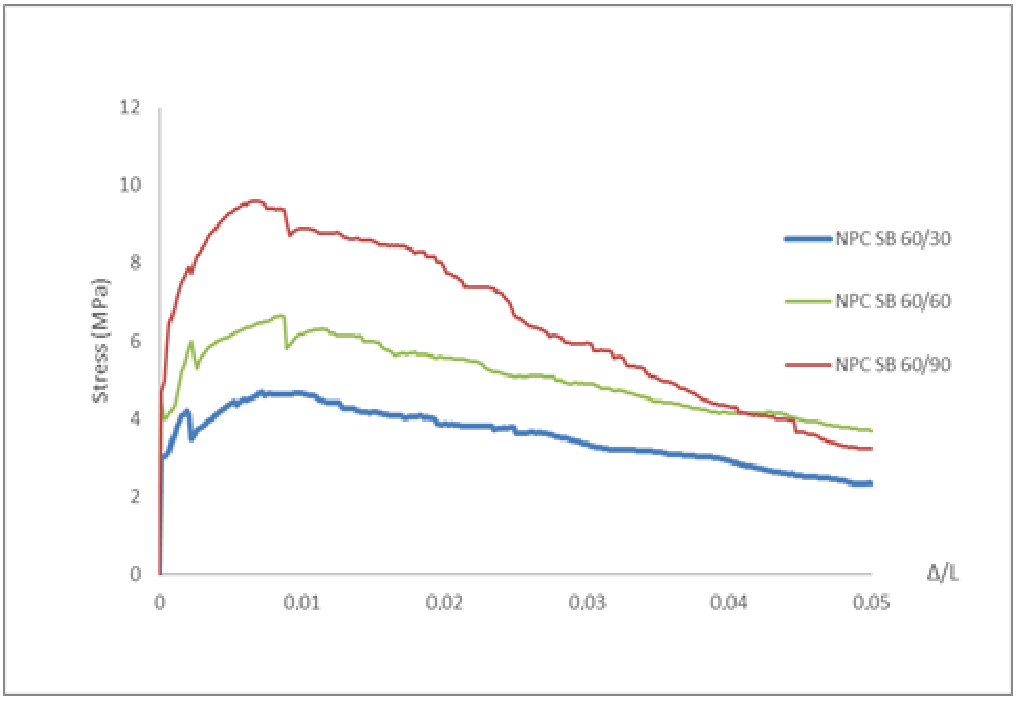


Figure 4.3 Stress vs. Δ/L of NPC SB 60mm Steel Fibers

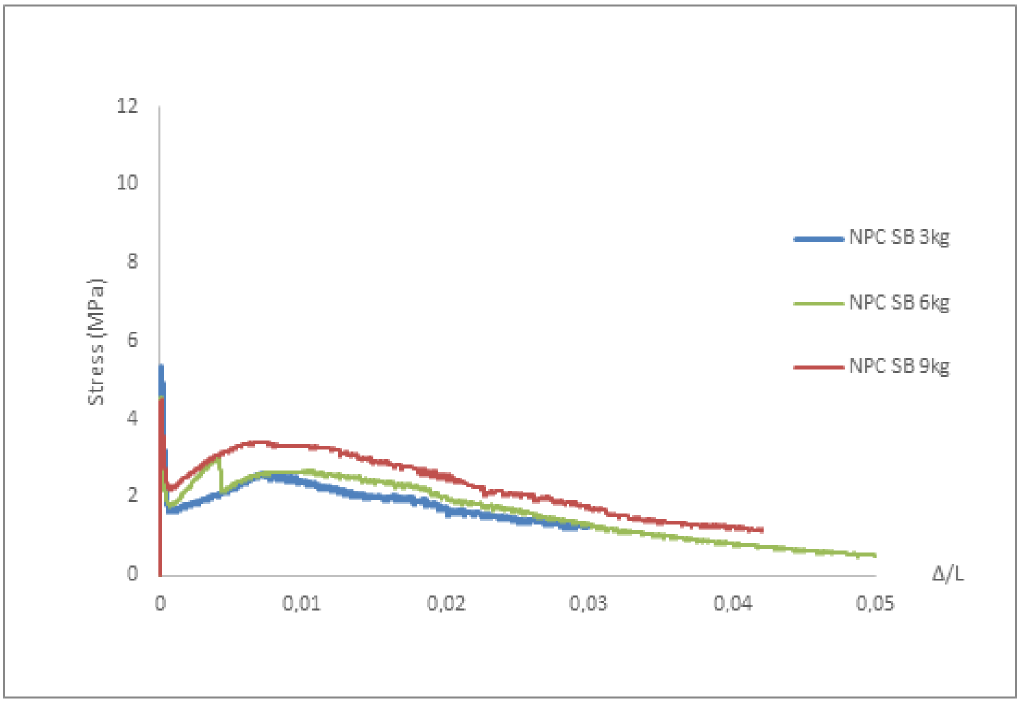


Figure 4.4 Stress vs. Δ/L of NPC SB Synthetic Fibers

Table 4.1 Test Results of NPC Small Beam

Small Beam	NPC Control	NPC 30-30	NPC 60-30	NPC Synthetic 3 kg	NPC 30-60	NPC 60-60	NPC Synthetic 6 kg	NPC 30-90	NPC 60-90	NPC Synthetic 9 kg
Max Force (kN)	6.41	4.65	7.41	7.91	7.50	10.05	6.73	9.2	14.26	6.64
Ultimate Flexural Strength (MPa)	4.33	3.14	5.01	5.34	5.07	6.79	4.55	6.22	9.63	4.49
Displacement At Max Strength (mm)	0.03	0.27	1.88	0.04	0.37	1.88	0.03	0.53	2.00	0.04
Cracking Stress (MPa)	4.33	2.16	3.06	5.34	4.06	5.53	4.55	5.60	6.06	4.49
Displacement At Cracking (mm)	0.03	0.20	0.65	0.04	0.22	0.25	0.03	0.18	0.27	0.04
Energy at 15 mm Disp. (N.m)	0.5*	22.7	77.3	24.2*	40.0	111.1	35.1	41.6	141.1	41.2*
Energy @ 0.05 Δ/L (N.m)	0.5*	22.5	74.8	24.2*	39.3	107.1	34.5	41.1	137.6	41.2*
Normalized Energy @0.05 Δ/L (N/m^2)	311.9*	14035.1	46658.9	15095.5*	24514.6	66807.0	21520.5	25637.4	85832.4	25699.8*

* Specimen is broken before reaching indicated displacement or Δ/L.

From the data obtained from testing of NPC small beams, it can be clearly seen that, with 60 mm steel fiber use, the ultimate strength increases after the cracking due to the effect of fibers. Whereas, for 30 mm steel fibers, it is only observed for higher fiber dosages (60 kg/m^3 and 90 kg/m^3). On the other hand, for specimens containing synthetic fibers, this has not happened even for the highest dosage tested. For all fiber types it is observed that increasing the fiber dosage leads to better recovery performance after the initial cracking. Also, from the energy absorption comparison, it can be seen that 30 mm steel fibers and 54 mm synthetic fibers perform similarly, while 60 mm steel fibers show much superior results than them.

4.1.2. HPC

From the flexural bending tests performed, the stress vs. Δ/L graphs are obtained from average load-displacement data for HPC mixtures are presented in Figure 4.5 to Figure 4.7. The ultimate strength, and energy absorption values at specific displacements for HPC SB are presented in Table 4.2.

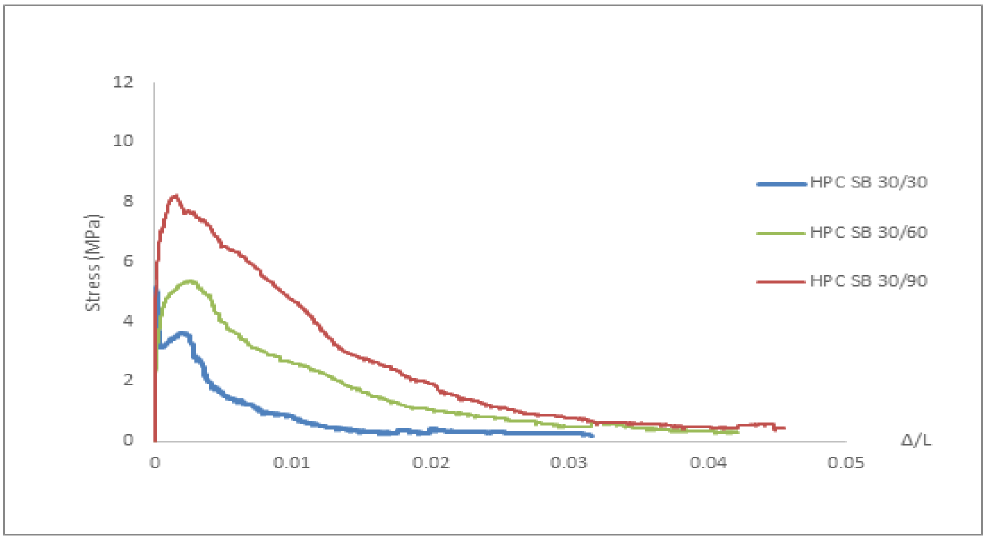


Figure 4.5 Stress vs. Δ/L of HPC SB 30mm Steel Fibers

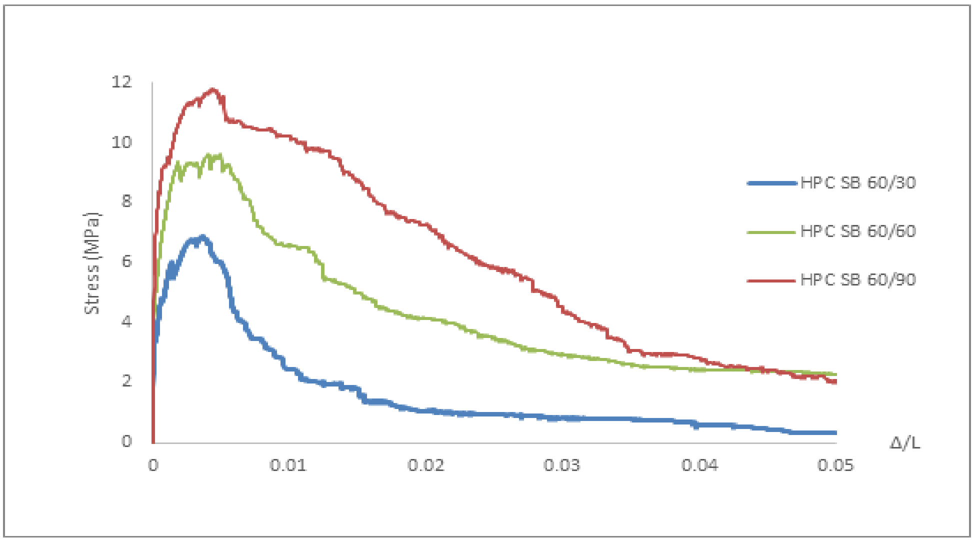


Figure 4.6 Stress vs. Δ/L of HPC SB 60mm Steel Fibers

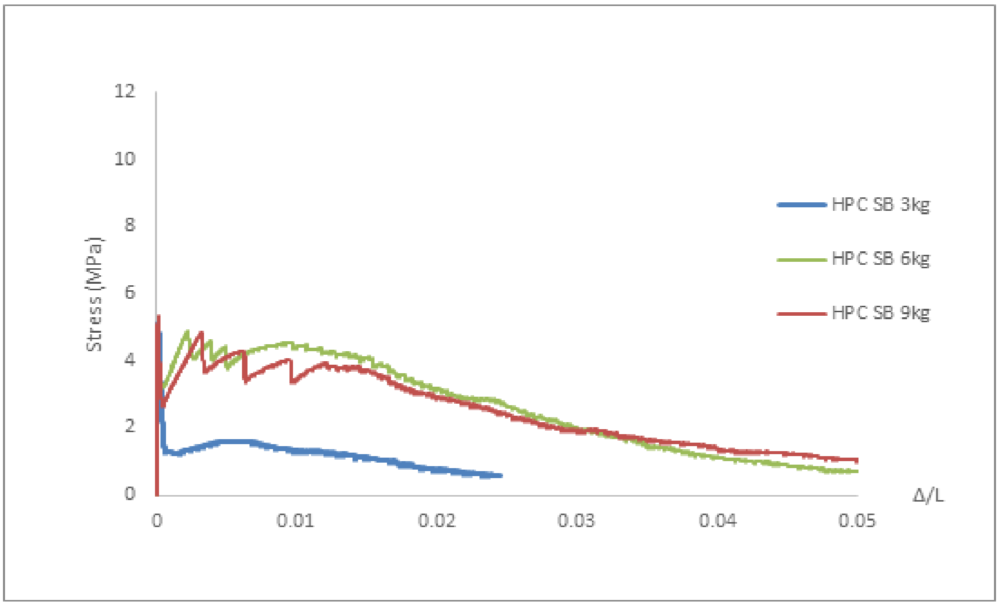


Figure 4.7 Stress vs. Δ/L of HPC SB Synthetic Fibers

Table 4.2 Test Results of HPC Small Beam

Small Beam	HPC Control	HPC 30-30	HPC 60-30	HPC Synthetic 3 kg	HPC 30-60	HPC 60-60	HPC Synthetic 6 kg	HPC 30-90	HPC 60-90	HPC Synthetic 9 kg
Max Force (kN)	8.1	7.60	10.20	7.54	7.90	14.20	7.23	12.20	17.40	7.88
Ultimate Flexural Strength (MPa)	5.47	5.13	6.89	5.09	5.34	9.59	4.88	8.24	11.75	5.32
Displacement At Max Strength (mm)	0.04	0.04	1.04	0.04	0.76	1.41	0.64	0.46	1.25	0.04
Cracking Stress (MPa)	5.47	5.13	4.80	5.09	4.86	9.39	4.49	7.03	9.19	5.32
Displacement At Cracking (mm)	0.04	0.04	0.19	0.04	0.28	0.54	0.04	0.14	0.25	0.04
Energy at 15 mm Disp. (N.m)	1.3*	11.7*	36.6	12.4*	29.4*	94.3	56.3	48.6*	132.1	54.5
Energy @ 0.05 Δ/L (N.m)	1.3*	11.7*	36.2	12.4*	29.4*	91.8	55.5	48.6*	130.0	53.4
Normalized Energy @0.05 Δ/L (N/m^2)	810.9*	7298.2*	22580.9	7734.9*	18339.2*	57263.2	34619.9	30315.8*	81091.6	33309.9

* Specimen is broken before reaching indicated displacement or Δ/L.

Based on the test results of HPC SB specimens, the huge improvement of adding fibers can be clearly seen when the results are compared with the control mixtures. All the specimens showed a recovery at the post-crack phase. The amount of recovery was increased by the increase in the fiber dosage, as it can be seen from the stress vs. Δ/L curves. Moreover, the effect of increasing the fiber length, from 30 mm to 60 mm in steel fibers, can be best noticed from the increase in the ultimate stress when longer fibers are used. In a similar way, the effect of the fiber type can be also seen through the difference in the ultimate load of the synthetic and steel fibers mixtures, the latter being higher. In addition to that the recovery in the post-crack region for all steel fiber reinforced specimens except the 30mm-30kg/m^3 one, reached a load higher than the first crack load, while this was not valid for any of the synthetic fiber reinforced specimens. The increase in the fiber dosage for all the fiber types lead to a better recovery, with an exception of the synthetic 9 kg/m^3 one. This might be due to mixing and placing problems stemming from the high fiber dosage of that particular specimen.

From Table 4.2 it can be said that, energy absorption capacities of specimens containing 60 mm steel fibers are considerably higher than that of the other two fiber types. Moreover, if the specimens with 30 mm steel fibers are compared with synthetic ones, they are very close in terms of energy absorption capacities, but the latter ones have slightly higher capacity.

4.1.3. NPC vs. HPC

Based on the results presented in the tables above, as well as the Figure 4.8 and Figure 4.9, the effects of the fiber type, length, and amount along with the effect of the concrete strength can be all clearly seen. The energy absorption capacity was generally increased when longer fibers, steel fibers instead of synthetic, and a larger amount of fibers was used. On the other hand, for the small beams, there is no significant difference in energy absorption capacity when a stronger concrete is used. Even though the ultimate strength values for HPC specimens are higher than NPC specimens, their energy absorption capacities are obtained to be generally close to each other, or even lower than NPC. The most extreme case is when 60mm-30kg/m^3 dosage is tested, its results indicate that the NPC specimen can achieve twice the HPC specimen can achieve in terms of energy absorption.

For both NPC and HPC specimens, the longer steel fibers required larger loads to be applied in order to tear the fibers off the concrete, which increased the energy absorption capacities between 2 to 3 times compared to that of the shorter steel fibers. In a similar way, the stronger fibers (steel fibers) were able to handle larger loads or stresses before they fail, compared to the weaker synthetic fibers. However, due to the larger length of the used synthetic fibers, the energy absorption capacities were close or even better than the ones of 30 mm steel fibers. Moreover, the increase in the fiber dosage showed a proportional increase in the energy absorption values in most of the cases. However, for some of the mixtures, the improvement was not that significant, mainly because the workability of the mixtures containing higher amount of fibers was not good enough to obtain a proper compaction. That would be the case when NPC 30mm-90kg/m^3 and HPC Synthetic 9 kg/m^3 are tested.

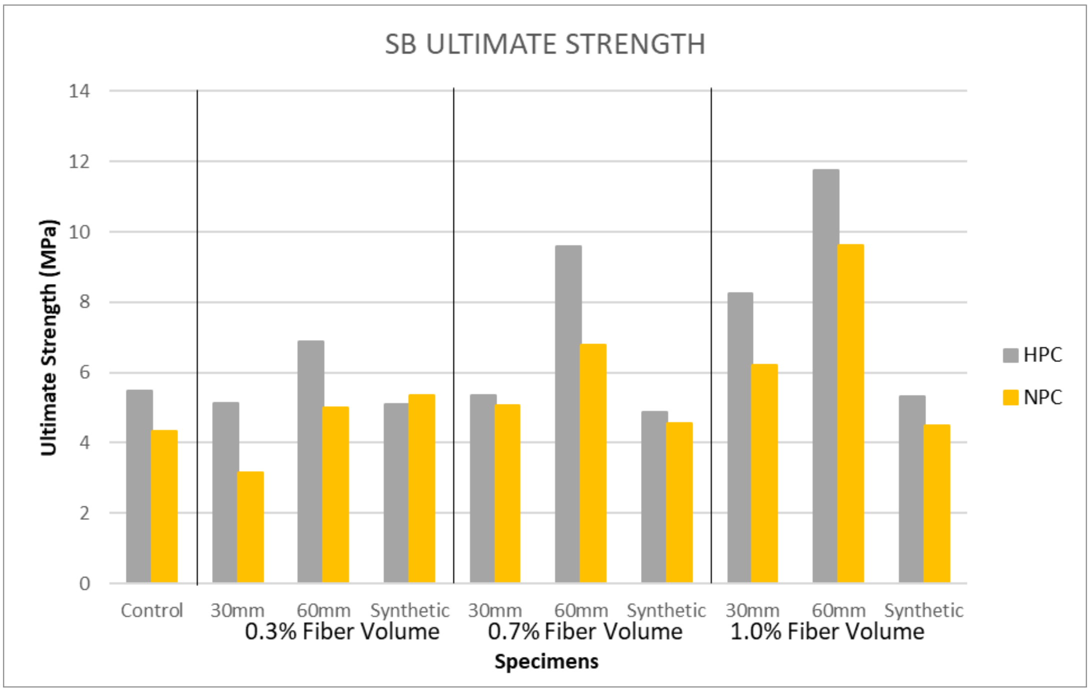


Figure 4.8 Strength Comparison of NPC and HPC for SB

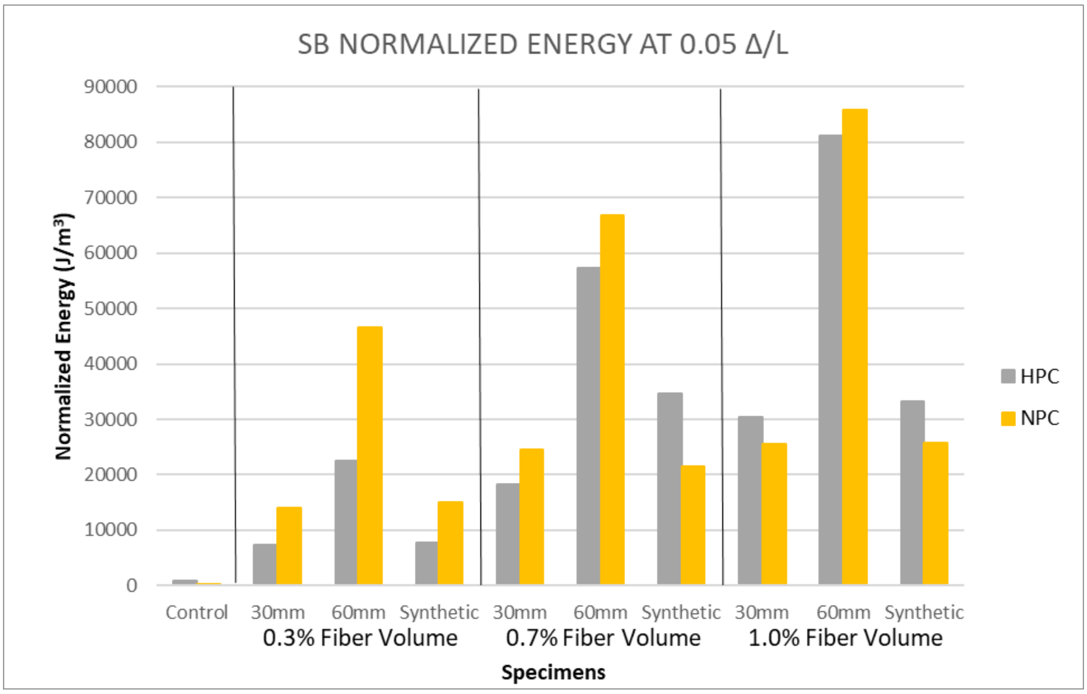


Figure 4.9 Energy Comparison at 0.05 Δ/L of NPC and HPC for SB

4.2. Tests Performed on Big Beams

4.2.1. NPC

From the flexural bending tests performed, the stress vs. Δ/L; graphs are obtained from average load-displacement data for NPC mixtures are presented in Figure 4.10 to Figure 4.12. The ultimate strength, and energy absorption values at specific displacements for NPC BB are presented in Table 4.3.

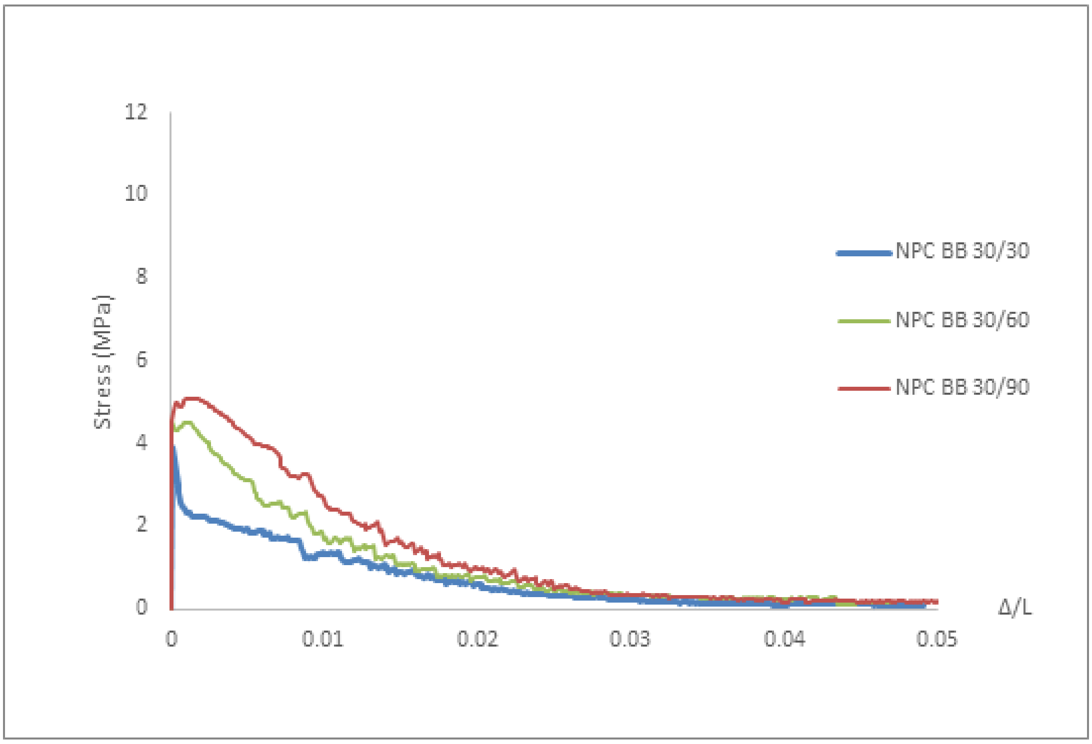


Figure 4.10 Stress vs. Δ/L of NPC BB 30mm Steel Fibers

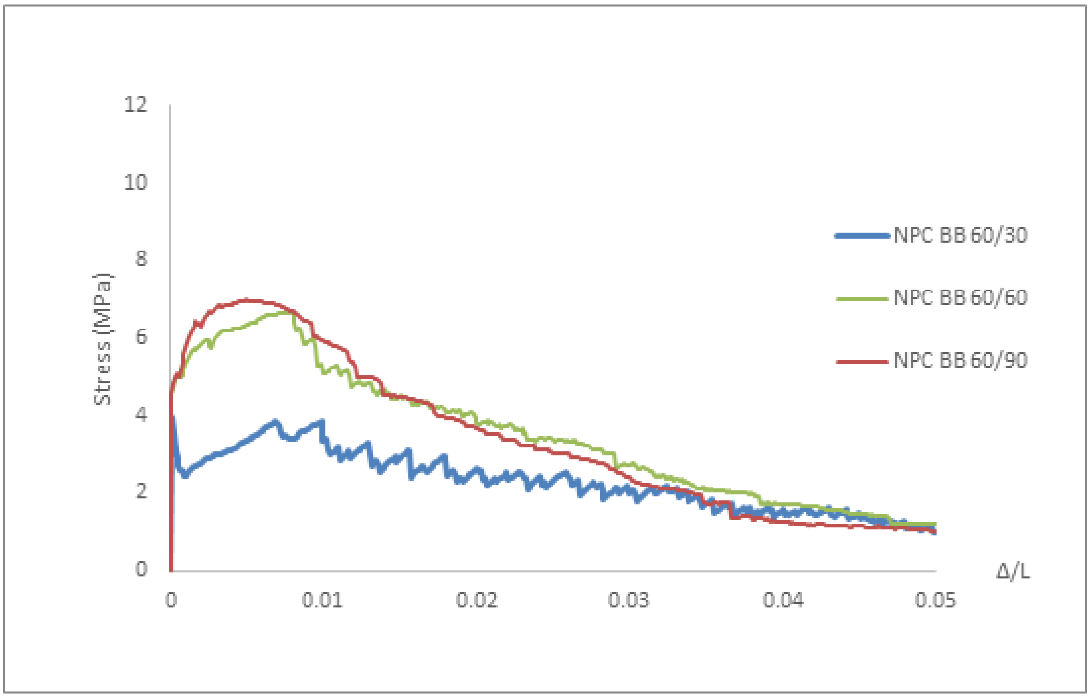


Figure 4.11 Stress vs. Δ/L of NPC BB 60mm Steel Fibers

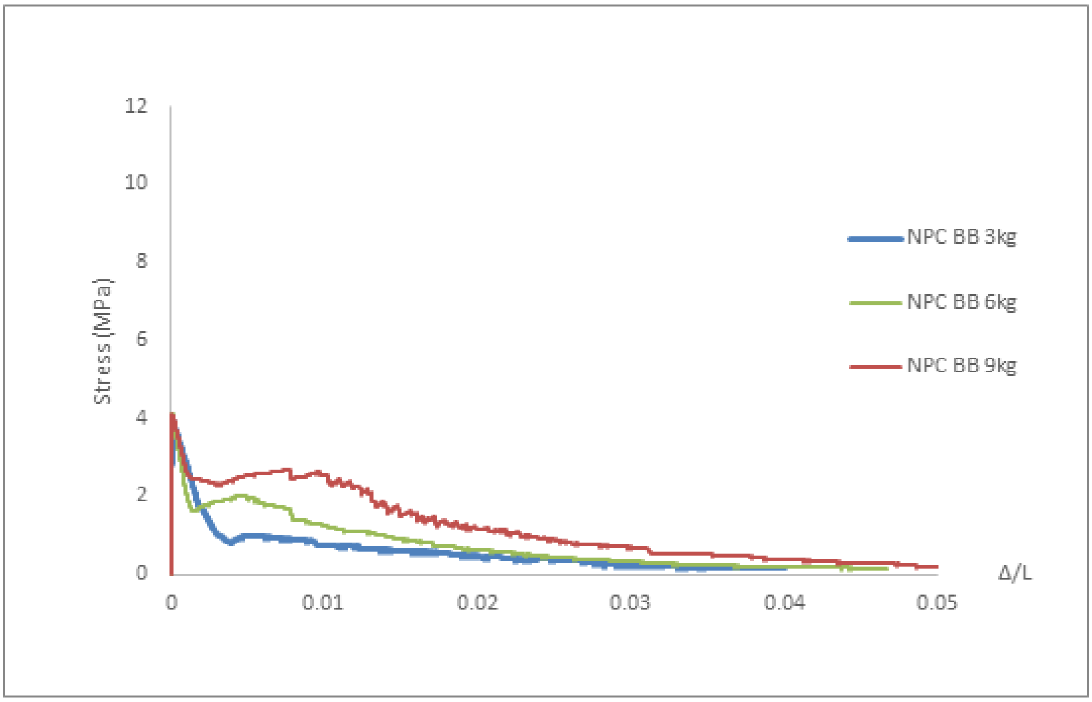


Figure 4.12 Stress vs. Δ/L of NPC BB Synthetic Fibers

Table 4.3 Test Results of NPC Big Beam

Big Beam	NPC Control	NPC 30-30	NPC 60-30	NPC Synthetic 3 kg	NPC 30-60	NPC 60-60	NPC Synthetic 6 kg	NPC 30-90	NPC 60-90	NPC Synthetic 9 kg
Max Force (kN)	30.20	29.40	31.54	30.26	35.38	50.75	30.99	38.97	53.37	30.74
Ultimate Flexural Strength (MPa)	4.03	3.92	4.21	4.03	4.72	6.77	4.13	5.20	7.12	4.10
Displacement At Max Strength (mm)	0.04	0.05	2.35	0.05	0.32	3.33	0.05	0.38	2.58	0.05
Cracking Stress (MPa)	4.03	2.24	2.87	4.03	4.42	4.79	4.13	4.89	4.93	4.10
Displacement At Cracking (mm)	0.04	0.04	0.28	0.05	0.23	0.12	0.05	0.25	0.08	0.05
Energy at 15 mm Disp. (N.m)	1.2*	110.5	304.8	80.35	165.5	497.6	112.5	218.1	503.3	182.5
Energy at 25 mm Disp. (N.m)	1.2*	116.5*	406.4	84.4*	176.8*	612.5	121.4*	233.2	594.2	203.9*
Energy @ 0.05 Δ/L (N.m)	1.2*	116.5*	387.4	84.4*	176.8*	591.7	121.4*	230.2	577.3	203.1
Normalized Energy @0.05 Δ/L (N/m^2)	118.5*	11496.3*	38261.7	8335.8*	17461.7*	58439.5	11990.1*	22735.8	57017.3	20059.3

* Specimen is broken before reaching indicated displacement or Δ/L.

Test data obtained from NPC BB specimens show that, even though there is recovery after the cracking of the concrete, there is ultimate strength increase for only steel fiber reinforced samples. None of the synthetic ones reached a higher stress than initial cracking stress. It is also noted that 30 mm steel fibers perform better than synthetic ones, and 60 mm steel fibers perform better than 30 mm ones, as well as there is performance increase with the increasing fiber dosage. One exception of this performance increase is for 60 mm steel fibers when dosage is increased from 60 kg/m^3 to 90 kg/m^3. That might be due to mixing and placing problems taking place with the higher fiber dosage tested. Moreover, if the energy absorption of those two specimens are compared from the table above, it can be seen that the value is slightly lower for the 90 kg/m^3 one. Another point that could be made is when those big beam specimens are tested until 25 mm deflection, none of the synthetic FRC beams could reach that deflection.

4.2.2. HPC

From the flexural bending tests performed, the stress vs. Δ/L graphs are obtained from average load-displacement data for HPC mixtures are presented in Figure 4.13 to Figure 4.15. The ultimate strength, and energy absorption values at specific displacements for HPC BB are presented in Table 4.4.

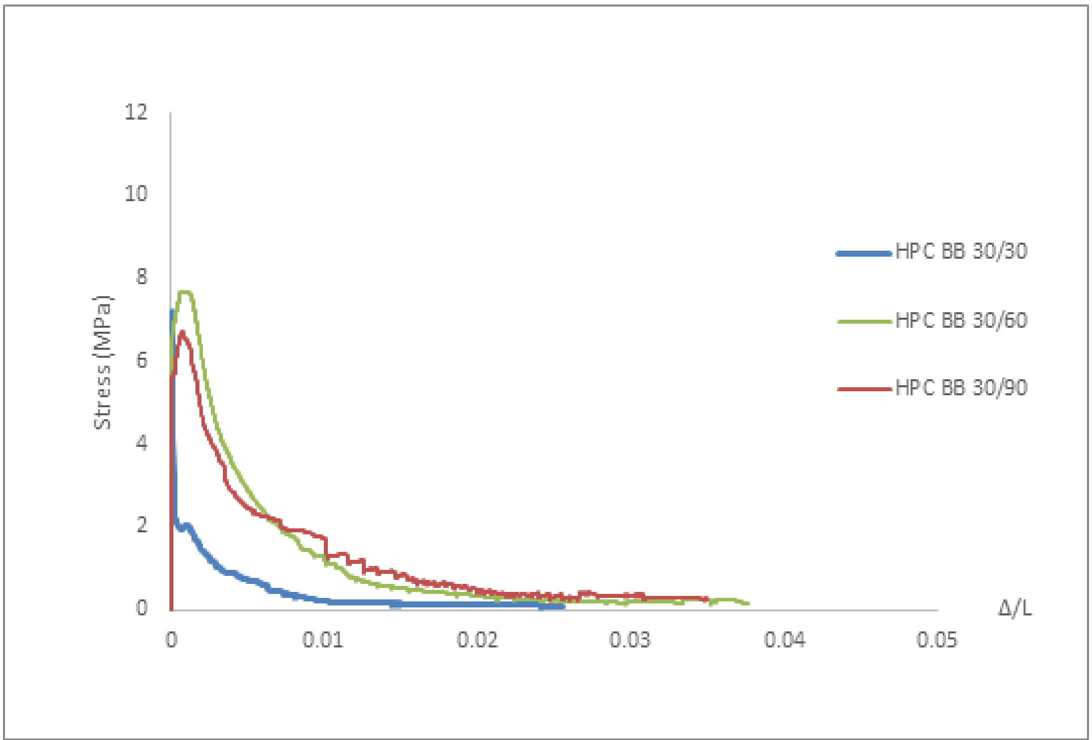


Figure 4.13 Stress vs. Δ/L of HPC BB 30mm Steel Fibers

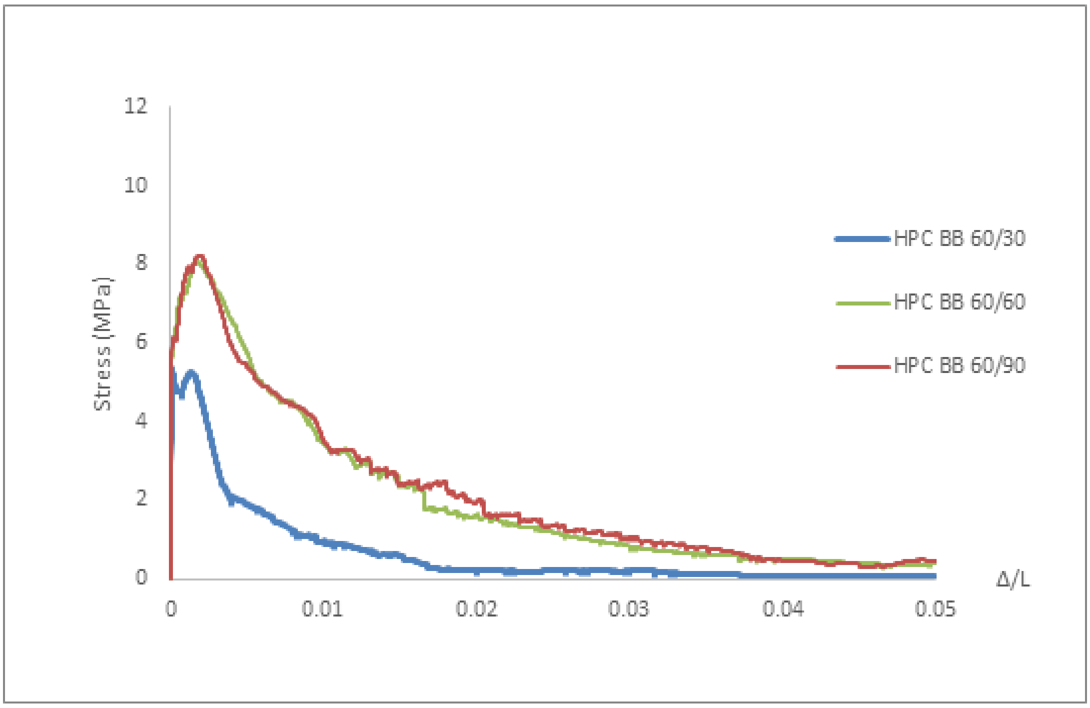


Figure 4.14 Stress vs. Δ/L of HPC BB 60mm Steel Fibers

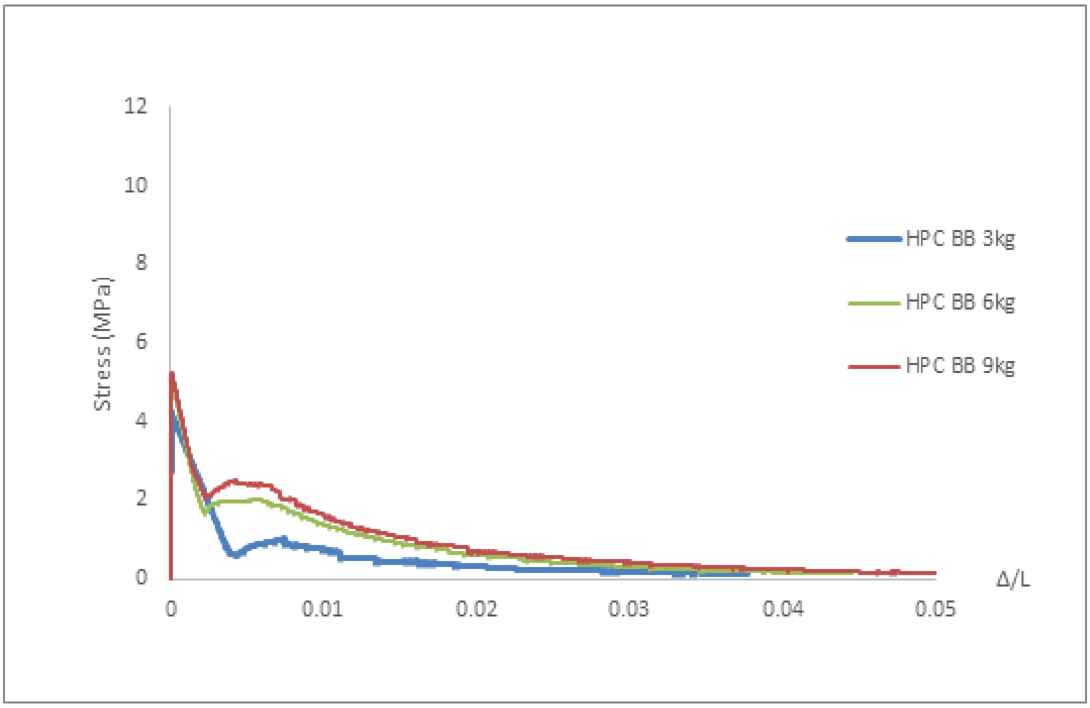


Figure 4.15 Stress vs. Δ/L of HPC BB Synthetic Fibers

Table 4.4 Test Results of HPC Big Beam

Big Beam	HPC Control	HPC 30-30	HPC 60-30	HPC Synthetic 3 kg	HPC 30-60	HPC 60-60	HPC Synthetic 6 kg	HPC 30-90	HPC 60-90	HPC Synthetic 9 kg
Max Force (kN)	46.30	53.90	40.10	31.80	57.60	60.50	37.86	50.40	61.70	39.39
Ultimate Flexural Strength (MPa)	6.17	7.19	5.35	4.24	7.68	8.07	5.05	6.72	8.23	5.25
Displacement At Max Strength (mm)	0.04	0.06	0.05	0.05	0.33	0.83	0.06	0.34	0.82	0.05
Cracking Stress (MPa)	6.17	7.19	5.35	4.24	6.95	5.75	5.05	5.76	6.16	5.25
Displacement At Cracking (mm)	0.04	0.06	0.05	0.05	0.06	0.08	0.06	0.06	0.07	0.05
Energy at 15 mm Disp. (N.m)	1.3*	38.9*	111.1	74.4	152.2	324.6	121.3	153.7	339.2	142.3
Energy at 25 mm Disp. (N.m)	1.3*	38.9*	117.8	76.5*	155.4*	358.1	128.2*	155.3*	374.6	156.8
Energy @ 0.05 Δ/L (N.m)	1.3*	38.9*	116.4	76.5*	155.4*	351.5	128.2*	155.3*	367.9	155.3
Normalized Energy @0.05 Δ/L (N/m^2)	128.4*	3841.9*	11496.3	7555.6*	15348.1*	34716.0	12661.7*	15338.3*	36335.8	15338.3

* Specimen is broken before reaching indicated displacement or Δ/L.

The HPC big beam specimens showed a recovery after the post-crack phase. The amount of recovery was increased by the increase in the fiber dosage, as it can be seen from the stress vs. Δ/L curves, but for steel fibers of both lengths, 60 kg/m^3 specimens perform as good as 90 kg/m^3 specimens. This similar performance between medium and highest dosage of tested steel FRCs could be explained by decreased workability of the high fiber dosages, which results in mixing and placing problems. Moreover, the effect of increasing the fiber length, from 30 mm to 60 mm in steel fibers, can be best noticed from the increase in the ultimate stress when longer fibers are used, with the exception of 30mm-30 kg/m^3 FRC specimen, which has a high ultimate strength, but after the initial cracking of concrete, there is a sudden drop in stresses until the recovery phase. The effect of the fiber type can clearly be seen through the difference in the ultimate stress of the synthetic and steel fibers mixtures, the latter being higher.

From the energy absorption results, it is observed that 60 mm steel fibers perform considerably better than the other two.

4.2.3. NPC vs. HPC

Results presented in Table 4.3 and Table 4.4 are used for obtaining Figure 4.16 and Figure 4.17 to better compare the effect of concrete strength on big beam specimens. From those graphs it is clearly seen that the ultimate strength values of HPC specimens are higher than the ultimate strength of NPC specimens. On the other hand, energy absorption capacity results of HPC BB specimens are lower than that of NPC BB specimens. The reason behind this might be the NPC matrix better utilizes the fiber amounts used, than the HPC matrix. There is a possibility that HPC might show its potential if higher fiber dosages are used with HPC matrix. While the energy absorption results for synthetic fibers are very close for all dosages of NPC and HPC specimens, steel fibers show higher energy absorption for NPC specimens. And that difference increases with the increased steel fiber length. Energy absorption results of both NPC and HPC big beams indicate that 60 mm steel FRC batches perform much better. While 30 mm steel FRCs performs slightly better than synthetic FRCs in terms of toughness. It should be also noted that synthetic FRCs tend to fail earlier with lower displacement values than steel FRCs. That might be due to exceeding tensile loads a synthetic fiber can carry or due to difference of surface texture and shape between synthetic and steel fibers.

The increase in the fiber dosage showed a proportional increase in the energy absorption values in most of the cases. Especially when comparing the lowest fiber volume with the medium one, the energy absorption capacity increase could be observed for all fiber types tested with both NPC and HPC mixtures. The energy absorption capacity for all steel fibers tested with HPC matrix is observed to be three times when the used fiber amount is doubled (i.e. 60 kg/m^3 compared to 30 kg/m^3) and also, if the tested matrix is NPC the energy amount is twice as much in this case.

For synthetic fibers tested with BB, energy absorption capacity increase of 1.5 times for both NPC and HPC matrix with increasing fiber dosage is observed. However, for some of the mixtures, the improvement was not that significant, mainly because the workability of the mixtures containing highest amount of fibers was not good enough to obtain a proper compaction, which was also seen in stress vs. Δ/L results.

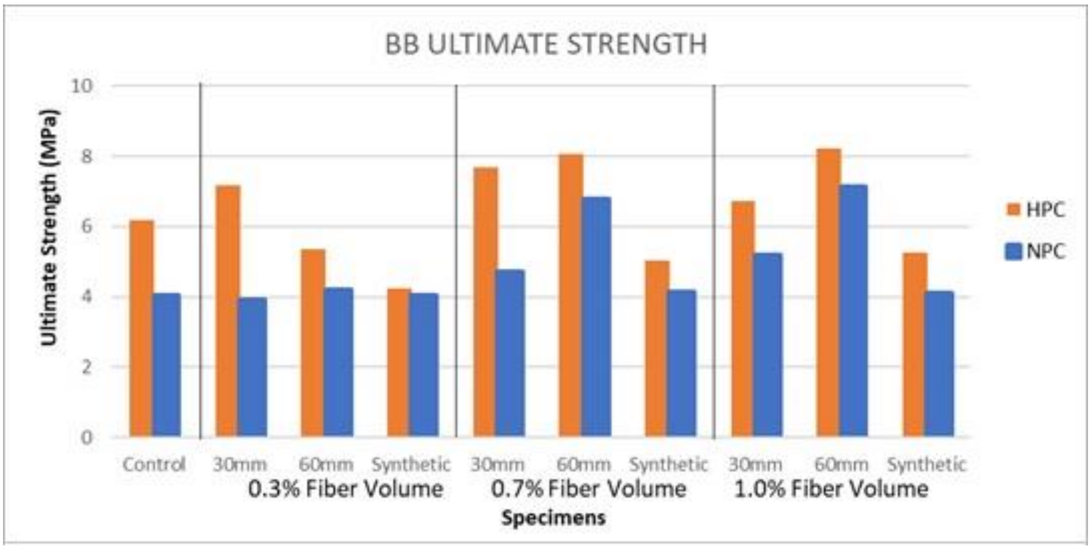


Figure 4.16 Strength Comparison of NPC and HPC for BB

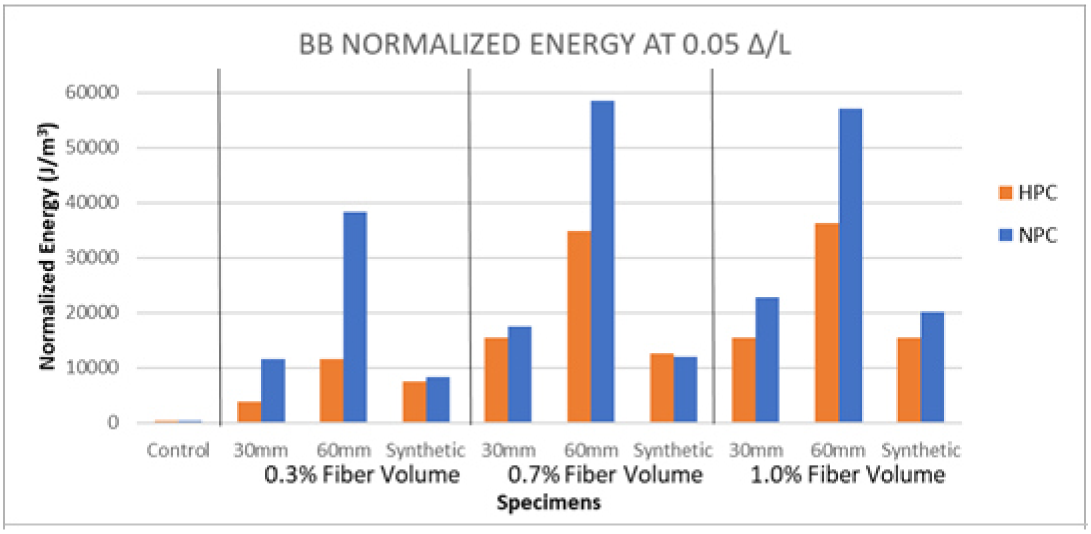


Figure 4.17 Energy Comparison at 0.05 Δ/L of NPC and HPC for BB

4.3. Effect of Specimen Size

When comparing small beam and big beam tests, mostly similar results such as the huge improvement of adding fibers could be seen for both of the tested specimen sizes, and the general comments and arguments made about the small beams are also true for the large beams. Namely, the energy absorption capacity was generally increased when longer fibers, steel fibers instead of synthetic, and a larger amount of fibers was used. Comparison graphs shown below at Figure 4.18 to Figure 4.21 are obtained from Table 4.1 to Table 4.4 in order to better understand the effect of specimen size.

Ultimate strength comparisons seen from Figure 4.18 and Figure 4.19, for NPC and HPC respectively, shows that the general trend is SB specimens achieve higher strength than BB specimens, which is logical due to the size effect: bigger specimens have more probability for defects. However, for NPC samples only 30mm-30kg/m^3 steel FRC does not fit the trend and it shows lower strength for SB. On the other hand, for HPC, there are some samples that have lower strength values for SB, two of which shows considerable difference in strength, namely 30 mm short steel fibers with two of the lower dosages (30 kg/m^3 and 60 kg/m^3). This might be due to when low length fibers used in low dosages in SB samples, the amount of fibers on the cross section where the specimen is broken would not be sufficient enough to redistribute the loads efficiently.

The energy absorption comparisons can be seen from Figure 4.20 to Figure 4.21 for NPC and HPC respectively. Energy absorption values used in the comparison graphs are normalized values from the last row of the tables and obtained by dividing the energy values at 0.05 Δ/L by the volume of the specimen for its span length. It is clearly seen from both graphs that the SB specimens gives higher modulus of toughness (in other words, normalized energy absorption capacity) results compared to BB specimens for both NPC and HPC mixtures. Generally, the difference between the SB and BB in terms of energy is higher in HPC mixtures, whereas for NPC the energy values are considerably closer between SB and BB specimens.

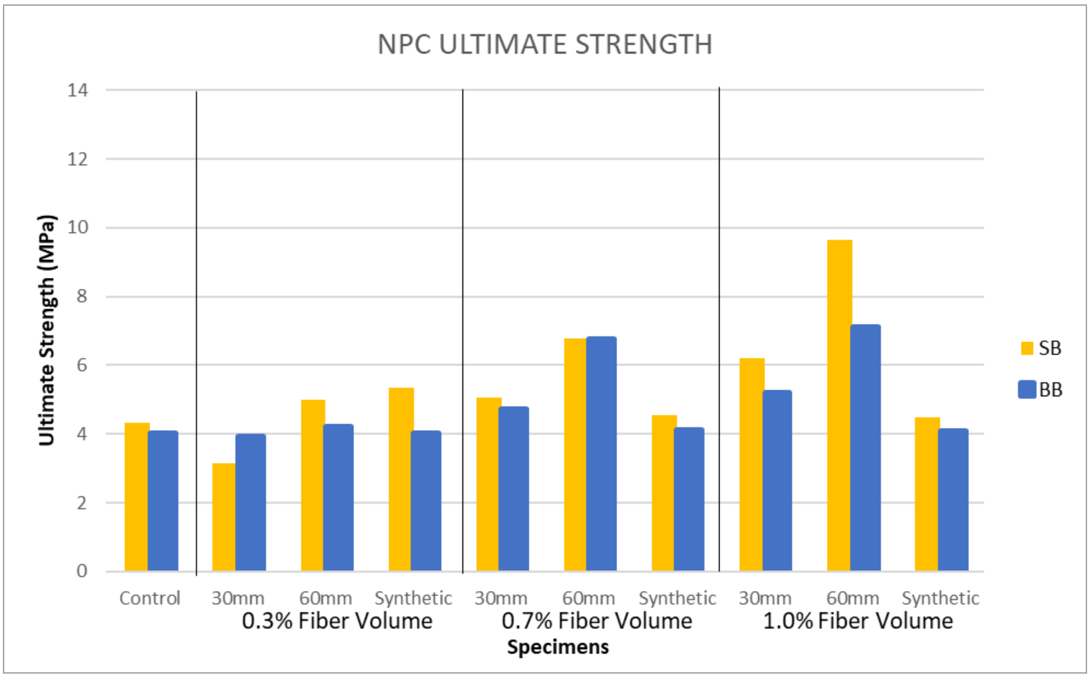


Figure 4.18 Strength Comparison of SB and BB for NPC

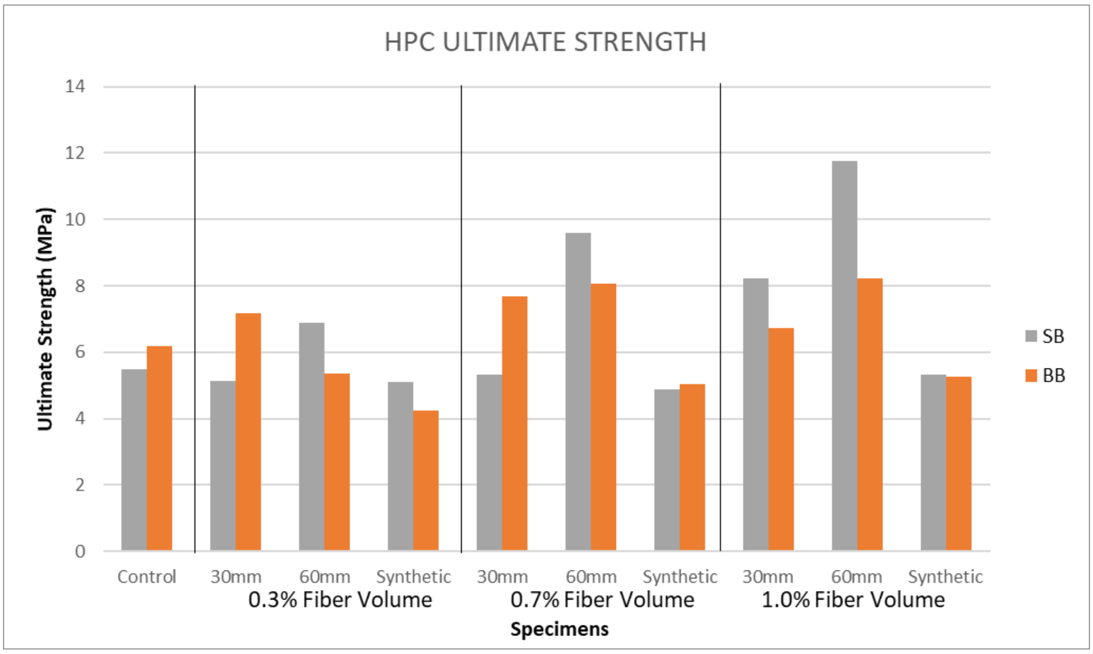


Figure 4.19 Strength Comparison of SB and BB for HPC

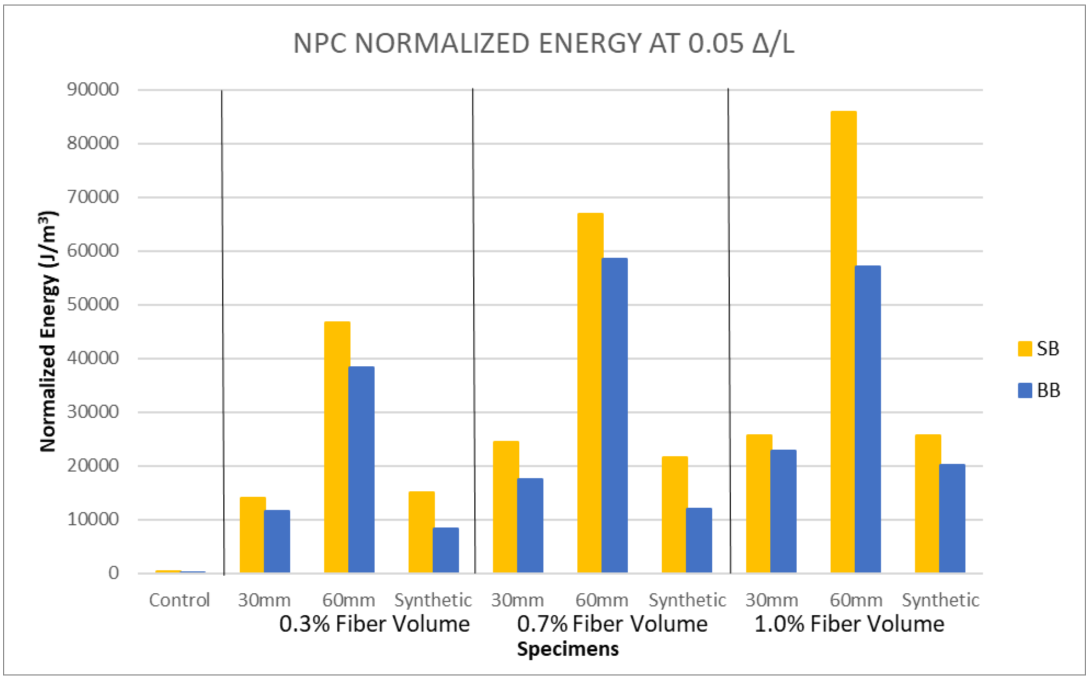


Figure 4.20 Energy Comparison at 0.05 Δ/L of SB and BB for NPC

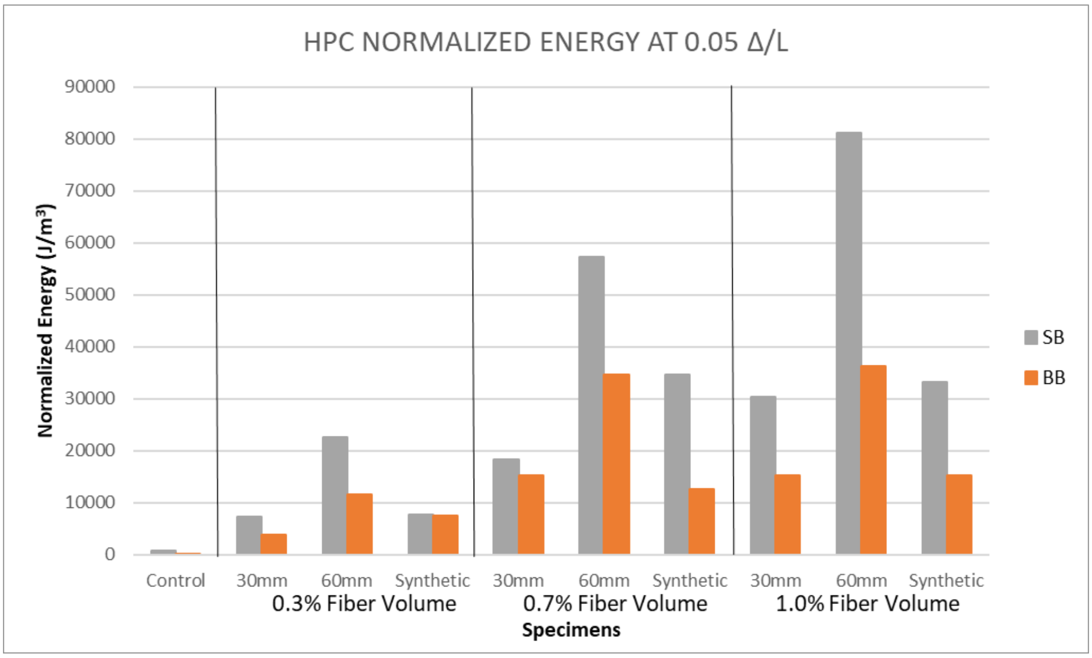


Figure 4.21 Energy Comparison at 0.05 Δ/L of SB and BB for HPC

It is also evident from the above graphs that, 60 mm steel fibers perform much better than 30 mm steel and 54 mm synthetic fibers. Similarly, the effect of the fiber dosage is also clearly seen from the normalized energy graphs, as the fiber dosage increases the energy absorption capacity increases for both SB and BB samples.

If we make the specimen size comparison for the 60 mm steel fibers used with both NPC and HPC matrixes, we can conclude that the SB specimens continued the growth trend in the energy absorption capacity when the fiber dosage increases. On the other hand, for the same 60 mm steel fiber reinforcement, the BB specimens' energy absorption does not increase for the highest fiber dosage. This corresponds to the 50% difference in SB and BB results of NPC mixture, and more than 100% difference in SB and BB results of HPC mixture. The reason why the difference between SB and BB varies depending on the concrete matrix used, might be due to the different mixing characteristics of the two mixtures. But it is clear that for both mixtures with highest dosages of the long steel fibers, it is possible to have mixing and placing problems to some extent. In this case using 60 kg/m^3 fiber dosage would be more economical, if the mixing problems cannot be overcome when using 90 kg/m^3 dosages, as both gave similar toughness values if we consider the BB test results.

Another similar conclusion can be made about the use of highest fiber dosage regarding the synthetic fibers. This time increasing fiber dosage but not achieving considerable increase in the energy absorption capacities are seen for both NPC and HPC matrixes if the SB test result of medium and highest fiber dosages are compared, but there is an increase in the BB test results, especially for NPC mixture. All in all, it is possible to conclude that, when using high amounts of fiber reinforcement, mixing and placing plays an important role independent of the specimen size, concrete strength and fiber type.

CHAPTER 5

CONCLUSION

In this work, the effect of beam sizes along with the type and amount of fibers on the flexural performance of concrete was investigated. The following conclusions can be highlighted:

- The flexural performance increases with the increase of fiber amount, as long as attention is paid to mixing and placing problems that might be encountered while using high fiber amounts.
- Steel fibers tested show better performance than synthetic fibers, and this is not only due to their higher strength but also due to differences in the shape and surface texture. However, 54 mm synthetic fibers' comparable performance with 30 mm steel fibers suggest that synthetic fibers would be an economical alternative to steel fibers, if much higher toughness values are not desired. It should also be mentioned that the synthetic fibers would be more desirable if the durability is considered as they are not prone to corrosion, like the steel fibers.
- The increase in the fiber length lead to an increase in the performance, when considering the 30mm and 60mm steel fibers. The energy absorption capacity of the latter is found to be up to three times higher than the shorter one.
- It is also noted that with increasing fiber amounts, the workability decreases and for NPC mixing and placing becomes harder with higher amounts of fibers used. However, for HPC, chemical admixtures provide much better workability and ease of placing of the concrete. But better workability does not always guarantee the homogeneous mixing, especially when higher fiber dosages are utilized.

- For the tested fiber dosages NPC matrix performed better than the HPC matrix in terms of energy absorption capacity, even though the HPC matrixes had shown higher ultimate strength than the NPC matrixes. This might be due to the fact that for the tested amounts of fiber, NPC matrix is better at utilizing the fibers, whereas the higher ultimate strength of HPC might result in more dramatical drop in stresses as the fibers are being pulled-out more rapidly. To overcome this, using higher fiber dosage for HPC matrix would be suggested. Further studies can be conducted with higher amounts of fiber to investigate the issue with HPC matrix.
- It can be concluded that, in terms of both ultimate strength and modulus of toughness, small beams give higher results than the big beams, for both NPC and HPC matrixes. This could be explained by size effect, bigger the size of a specimen higher the probability of occurrence of a defect is the case.
- Even though, in general the performance of the concrete increases with the increasing fiber amount, some specimens show that there might be some mixing errors while using higher amounts of fibers. This can be observed as some of the batches with 60 kg/m^3 fibers can achieve the same toughness values as 90 kg/m^3 samples. It would be expected for NPC to have such an issue especially due to lower workability of the 90 kg/m^3 samples. But it was also observed for HPC that batches with 60 kg/m^3 of used fiber amount shows nearly as high performance as batches with 90 kg/m^3 fibers.

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APPENDIX A

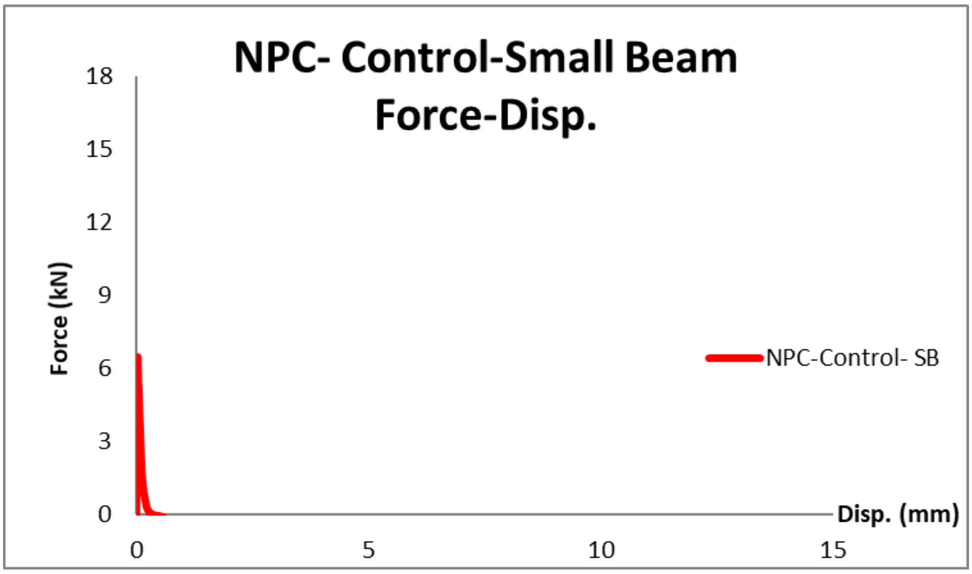

Figure A0.1 NPC Control SB Load-displacement

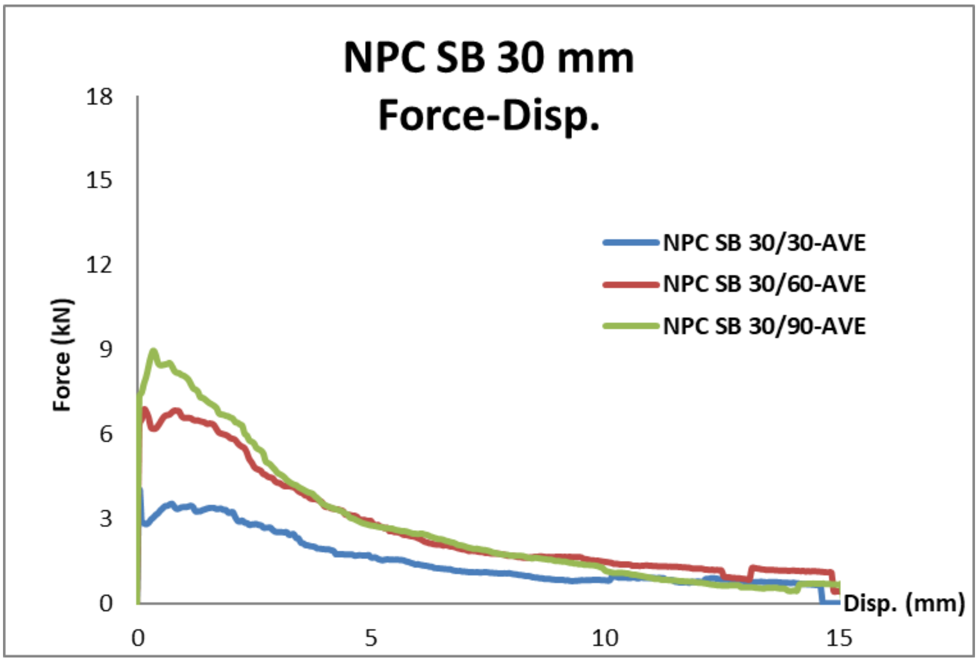

Figure A0.2 NPC 30 mm Steel Fiber Load-displacement

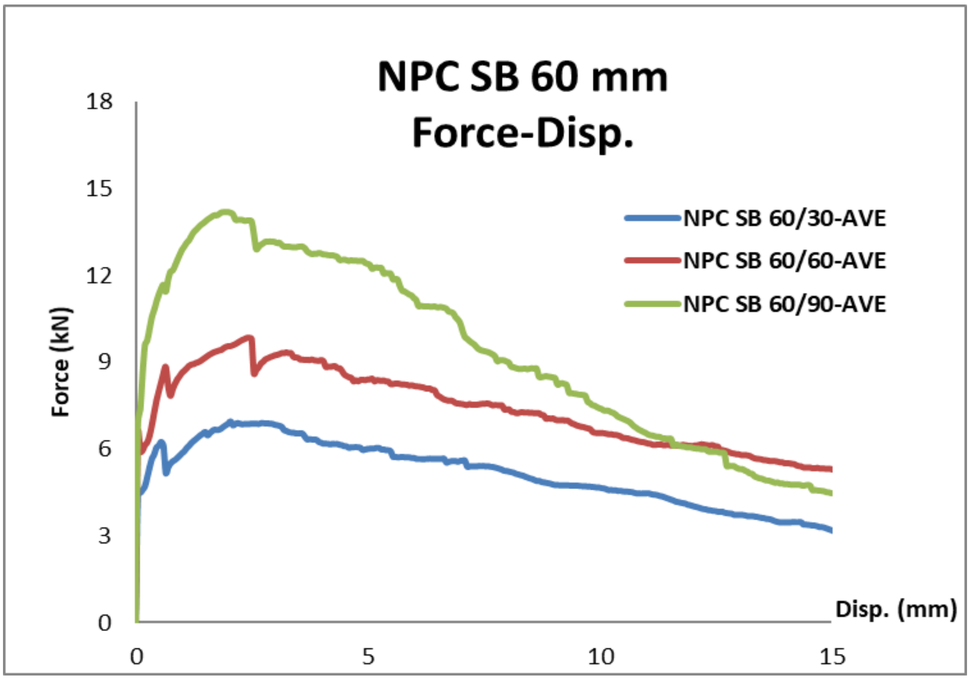

Figure A0.3 NPC 60 mm Steel Fiber Load-displacement

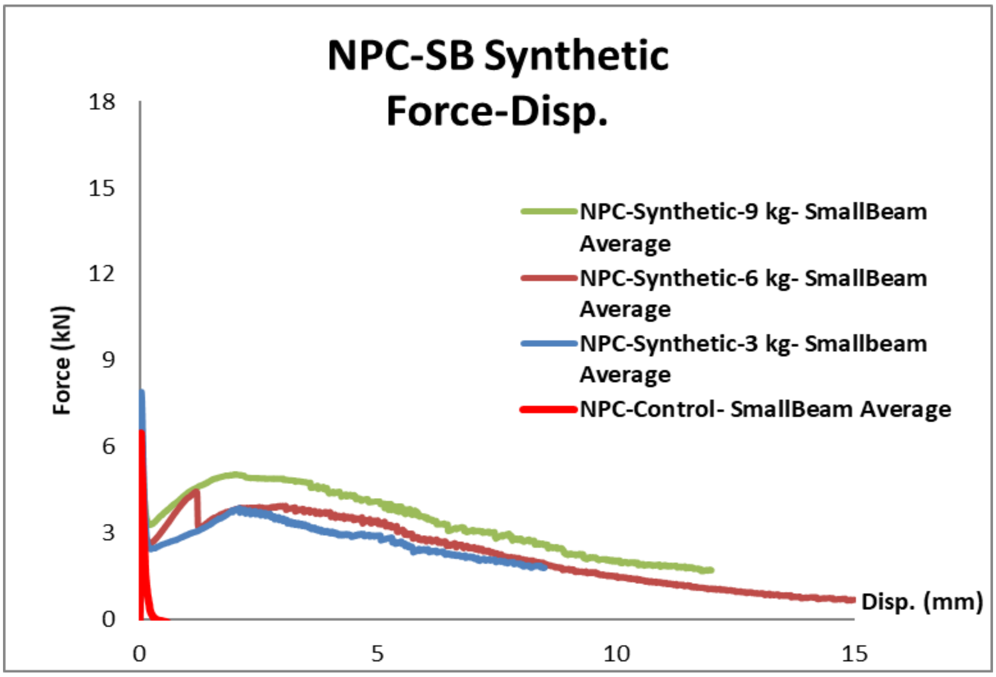

Figure A0.4 NPC Synthetic Fiber Load-displacement

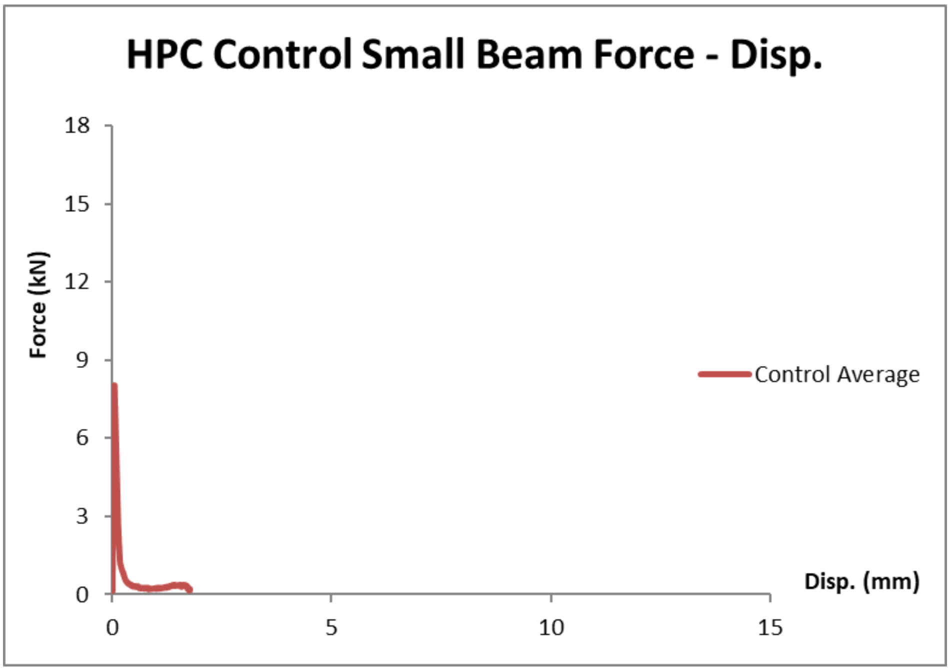

Figure A0.5 HPC Control SB Load-displacement

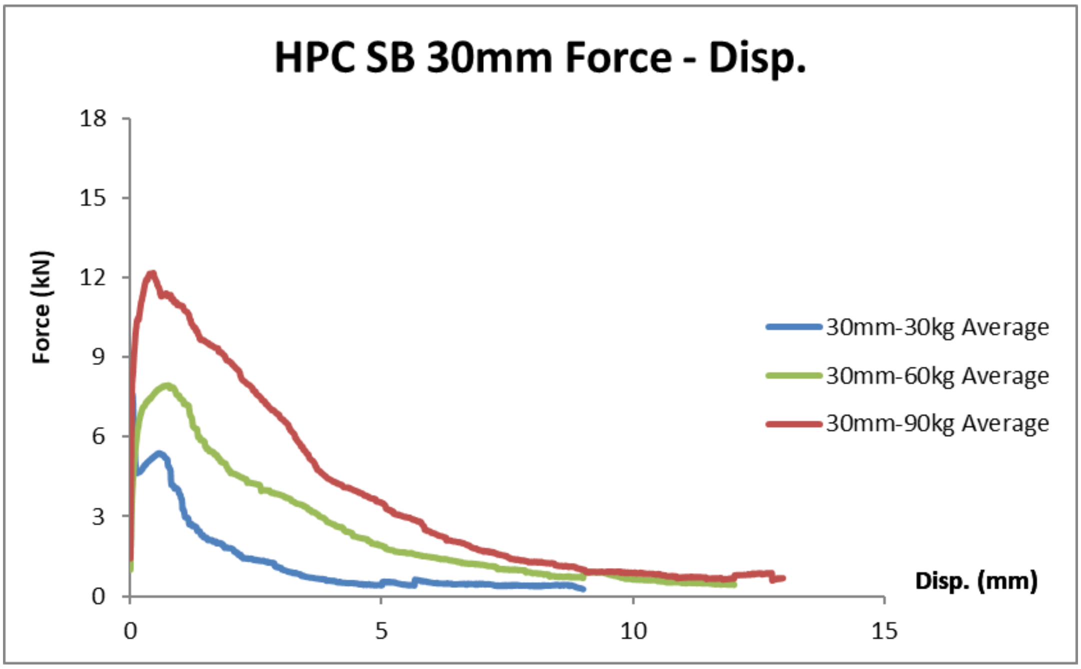

Figure A0.6 HPC 30 mm Steel Fiber Load-displacement

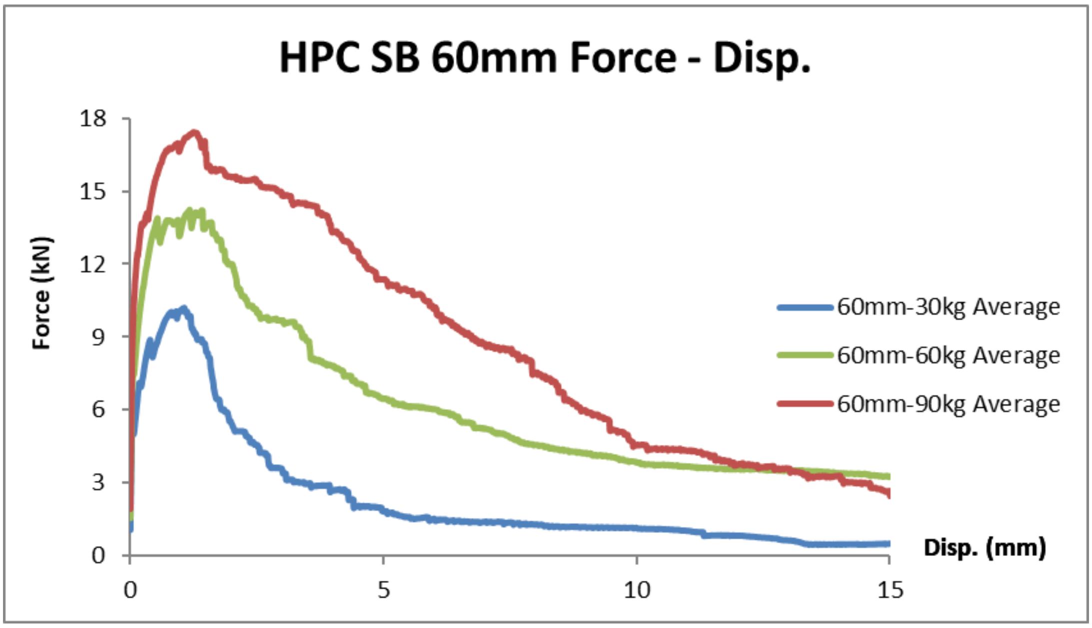

Figure A0.7 HPC 60 mm Steel Fiber Load-displacement

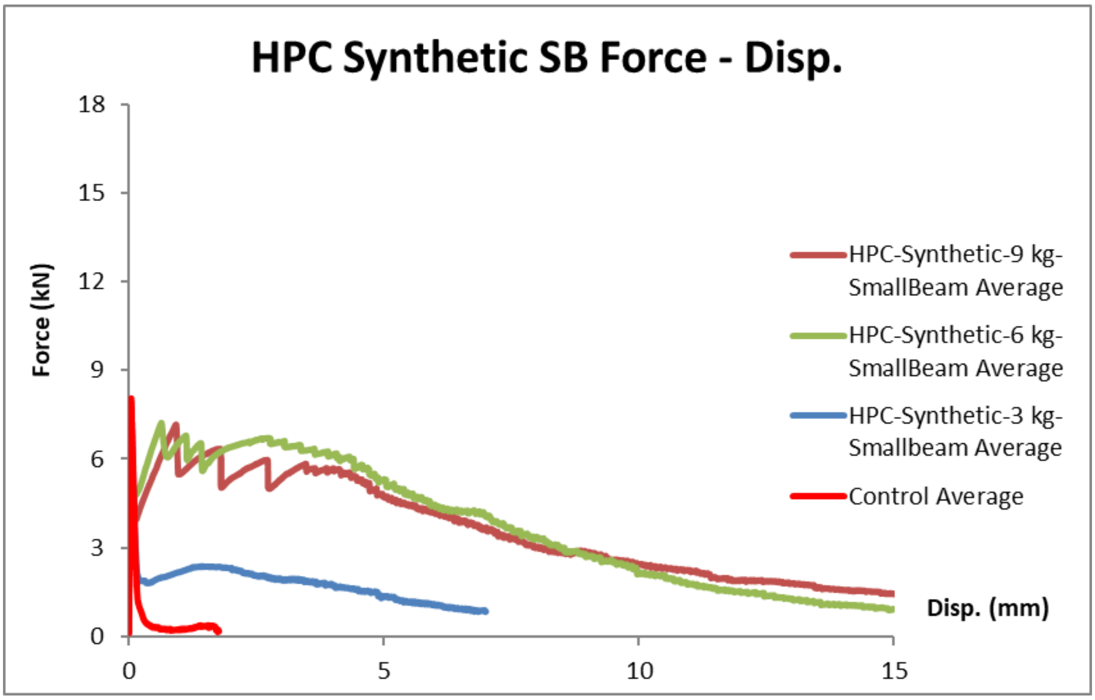

Figure A0.8 HPC Synthetic Fiber Load-displacement

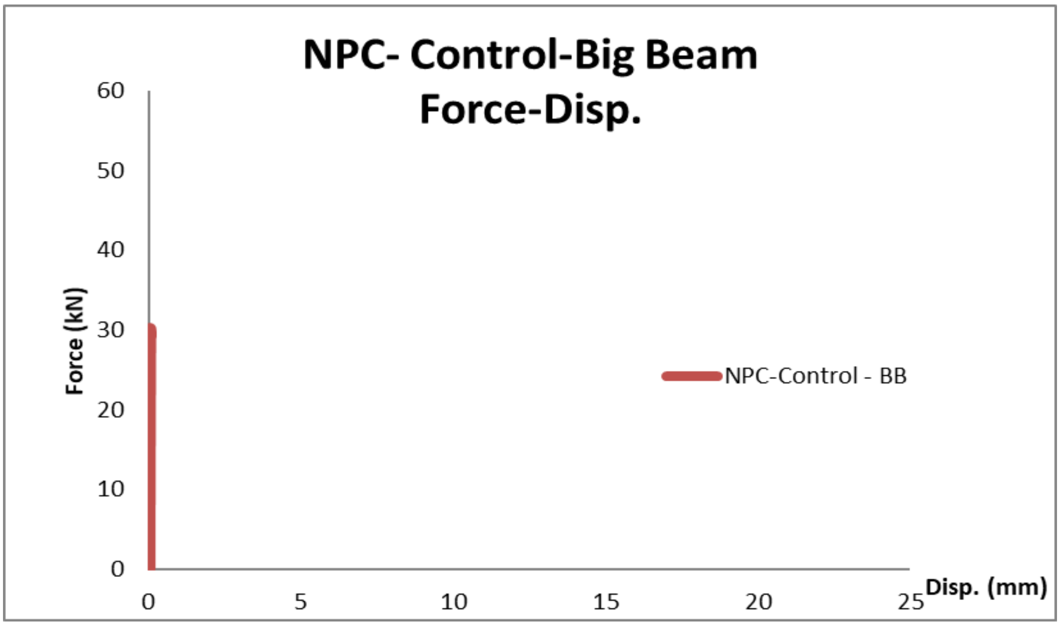

Figure A0.9 NPC Control BB Load-displacement

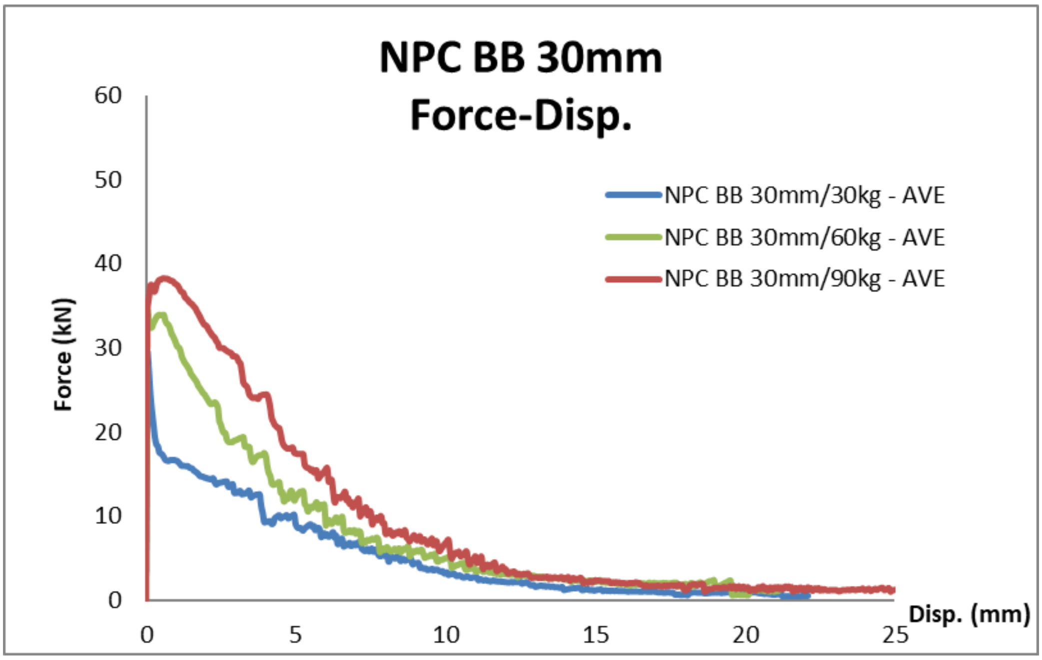

Figure A0.10 NPC 30 mm Steel Fiber Load-displacement

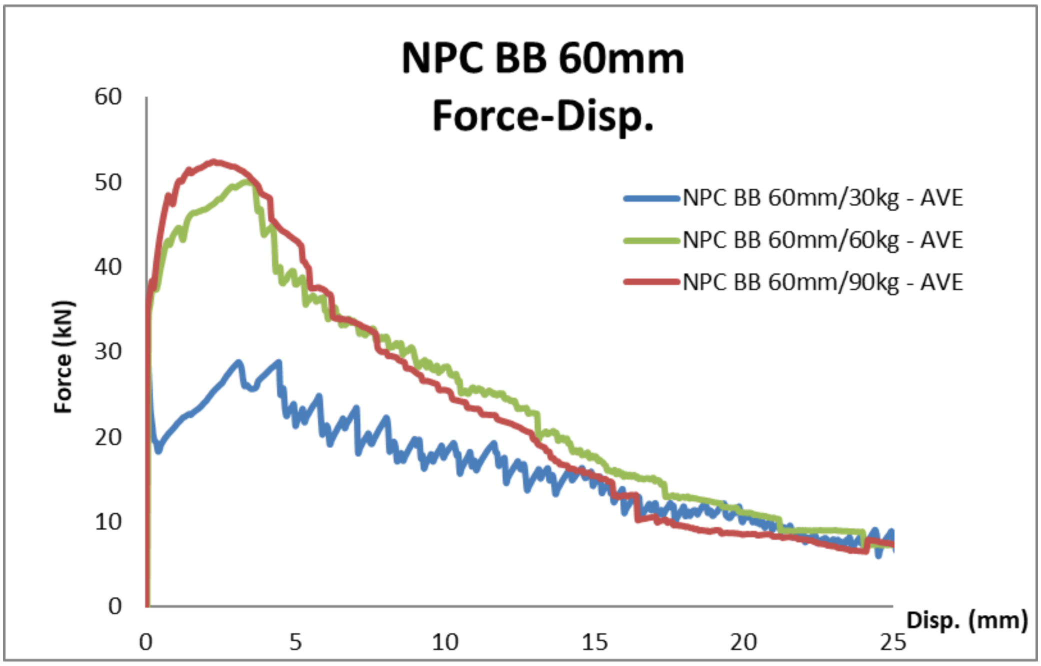

Figure A0.11 NPC 60 mm Steel Fiber Load-displacement

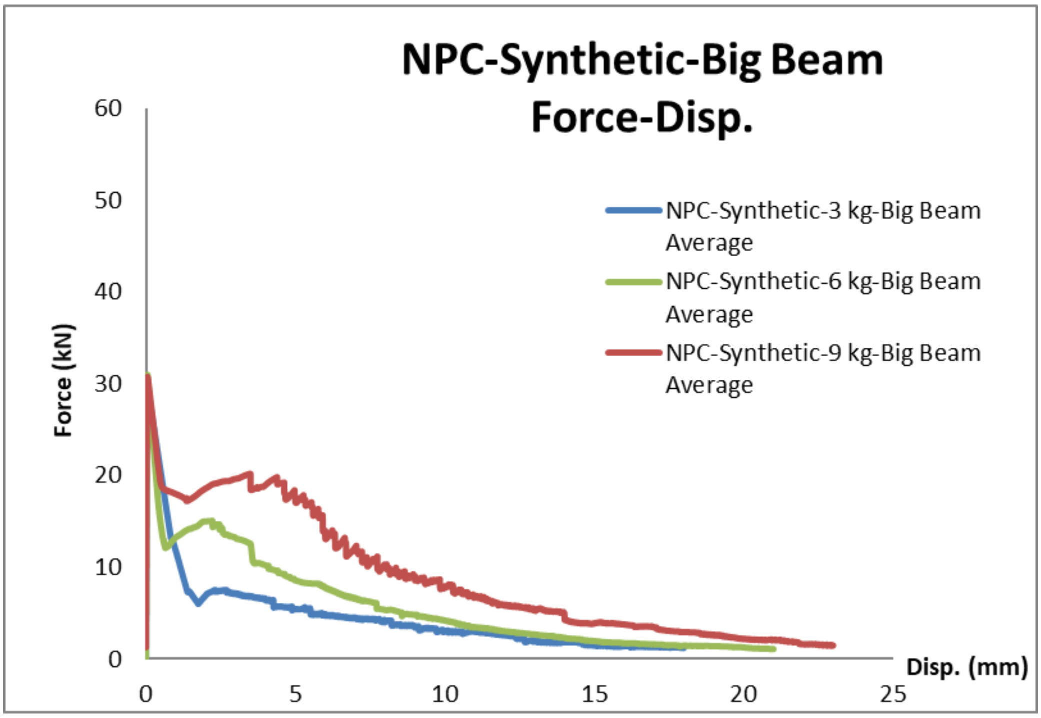

Figure A0.12 NPC Synthetic Fiber Load-displacement

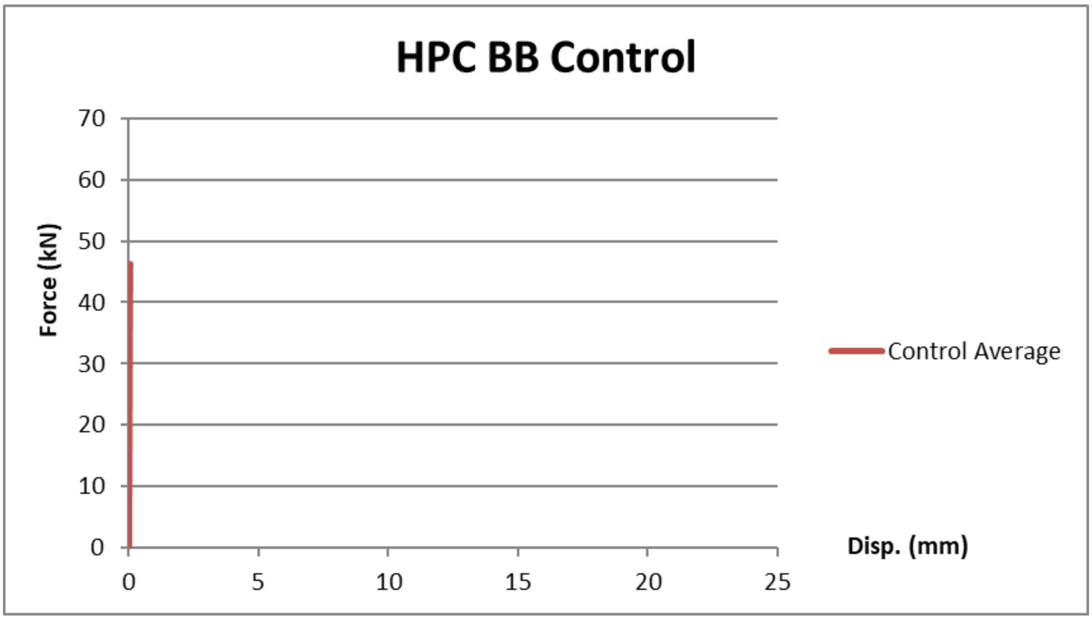

Figure A0.13 HPC Control BB Load-displacement

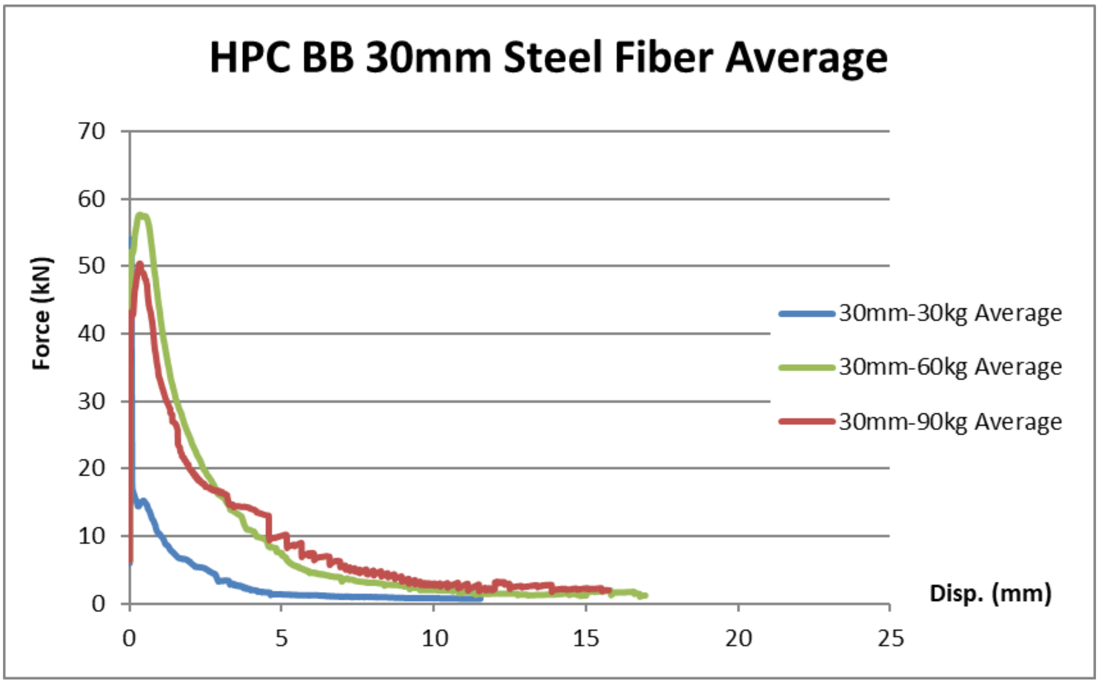

Figure A0.14 HPC 30 mm Steel Fiber Load-displacement

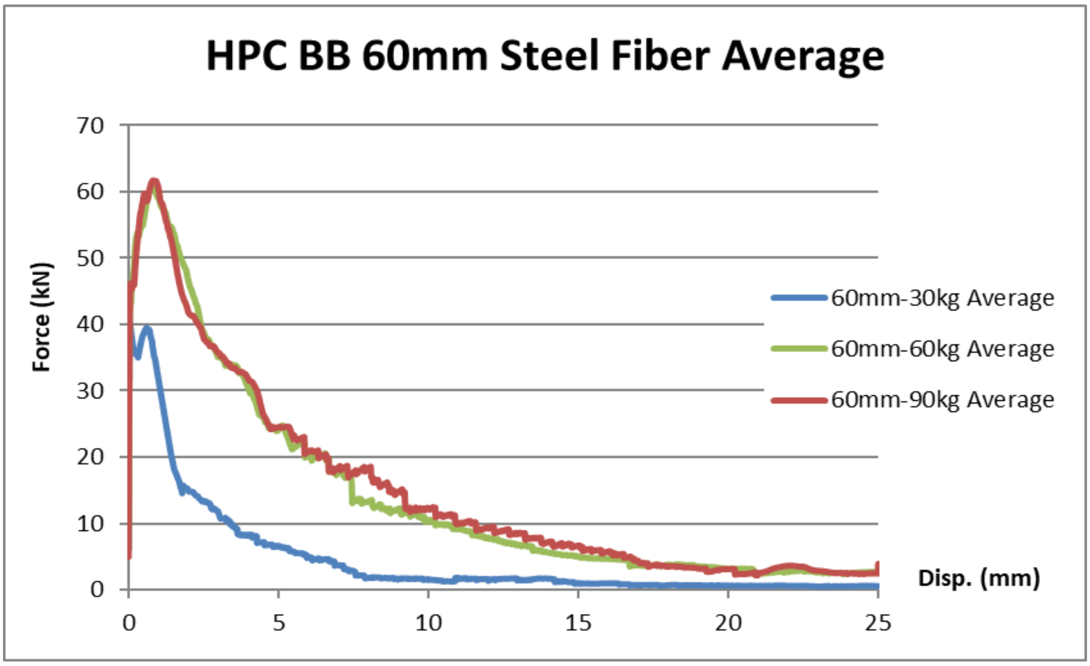

Figure A0.15 HPC 60 mm Steel Fiber Load-displacement

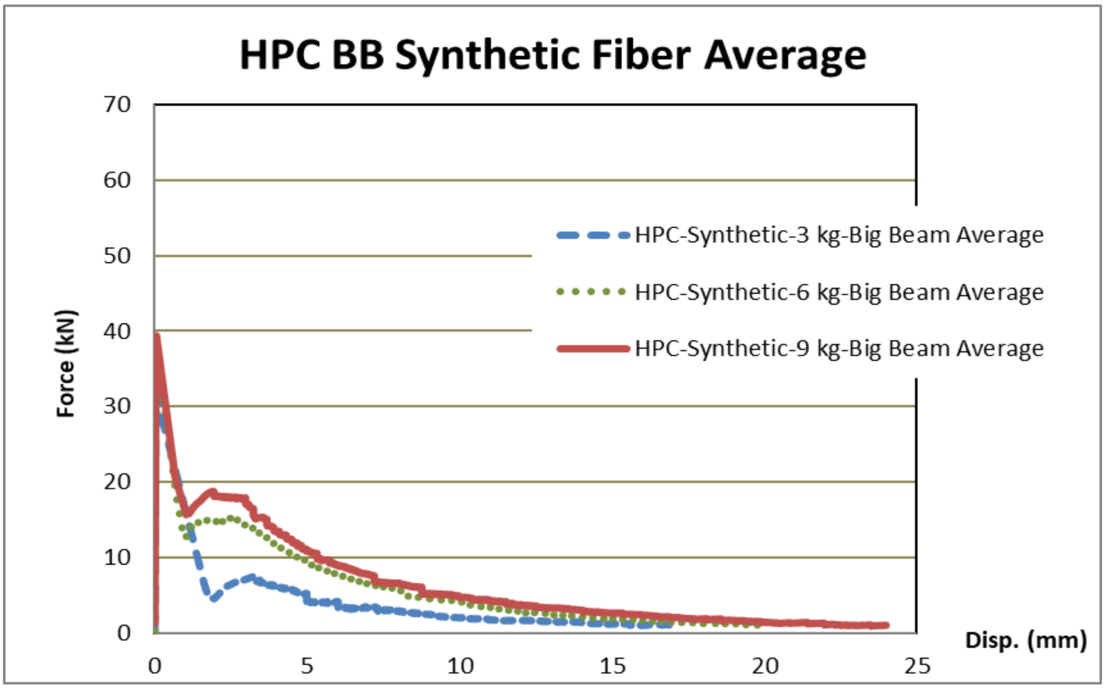

Figure A0.16 HPC Synthetic Fiber Load-displacement